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When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors

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ABSTRACT

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. We argue that, although these two trends cannot be considered an industrial revolution, Industry 4.0-associated technologies nevertheless have the unique potential to unlock environmentally-sustainable manufacturing. 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. 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 – we also propose an integrative framework containing twelve research propositions. We hope this will stimulate the debate on the intersection of manufacturing waves, in particular the integration of Industry 4.0 and environmentally-sustainable manufacturing.

1. Introduction

Based on the emerging cutting-edge discussion on the integration of Industry 4.0's technologies and corporate sustainability (Dubey et al., 2017), this work argues that the principles and practices of Industry 4.0 will unlock the full potential of sustainable organisations, moving towards a more sustainable society as well as world-class sustainable manufacturing (Dubey et al., 2015; Dubey et al., 2016). This is possible because, in general, the development of technology is related to a country's sustainability (Gouvea et al., 2017) and environment-based technical progress can stimulate improvements in environmental quality (Song and Wang, 2016). For instance, Jabbour et al. (2017a, 2017b) have argued that big data – a key technology of Industry 4.0 – can contribute to the development of a circular economy.

Industry 4.0 and sustainability are considered major trends in the current system of production. We propose that, while they cannot individually be considered new industrial revolutions, through their overlap and synergy they may together comprise a distinct industrial wave that will change worldwide production systems forever. This is due to the potential that Industry 4.0 has to fully unlock industrial sustainability through its technology, moving towards a more sustainable society, as defined by Dubey et al. (2017).

Parallel to the development of Industry 4.0, organisational sustainability has flourished through the integration of economic and environmental issues (Elkington, 1994) into organisations' operations management decision-making processes (Gunasekaran and Irani, 2014). The implementation of sustainability in production and consumption processes aims to mitigate negative pressures on the ecosystem generated by products, services, and transportation (Esmaeilian et al., 2016; Sarkis, 2001). The search for a more sustainable production and consumption system is so relevant today that the United Nations have selected it as one of their paramount societal objectives for sustainable development (UN, 2015), due to the risks that environmental challenges, such as climate change, pose to society (Kim, 2015).

Industry 4.0 is oriented towards digital and virtual technologies and is service-centred (Drath and Horch, 2014). It is driven by real-time data interchange and flexible manufacturing, enabling customised production (Li et al., 2017; Thoben et al., 2017). Industry 4.0 can be understood through its fundamental components: cyber-physical systems (Drath and Horch, 2014; Hozdić, 2015; Schlechtendahl et al.,

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2015), the internet of things, cloud manufacturing, and additive manufacturing (Kang et al., 2016).

While recognising that other topics are also currently relevant, we argue that a joint analysis of these two major trends – Industry 4.0 and environmentally-sustainable manufacturing – has yet to be suitably realised, as studies dealing with the complex integration of Industry 4.0 technologies and sustainability are rare (Dubey et al., 2017). Consequently, the primary questions driving this research are: can Industry 4.0 boost the effects of the environmentally-sustainable manufacturing wave, and what are the critical success factors capable of unlocking this process? This research has three objectives:

- To present arguments in favour of considering the interface of Industry 4.0 and environmentally-sustainable manufacturing as a robust new industrial wave;
- To discuss the critical success factors (CSF) of the integration of Industry 4.0 and environmentally-sustainable manufacturing;
- To present an original framework capable of systematising previous debate on this topic and to provide a research agenda for the future integration of Industry 4.0 and environmentally-sustainable manufacturing, considering the CSF. This research agenda contains propositions that could further develop the body of knowledge on the nexus of Industry 4.0 and environmentally-sustainable manufacturing.

This work is organised as follows. Following the introduction (Section 1), a brief literature review is presented covering the topics of environmentally-sustainable manufacturing (Section 2) and Industry 4.0 (Section 3). Thereafter, the main critical success factors for integrating Industry 4.0 and environmentally-sustainable manufacturing are discussed (Section 4). Section 5 presents an integrative framework and a number of research propositions to add to the growing body of work on this topic. Final remarks are presented in Section 6.

2. Environmentally-sustainable manufacturing

Organisational sustainability has come to prominence in recent research, with a special focus on the environmental aspect of sustainability (Marcus and Fremeth, 2009). Despite this, analysis of the integration of economic and environmental issues into sustainable operations management has remained limited (Gunasekaran and Irani, 2014). However, manufacturing decisions are paramount in sustainable development (Garetti and Taisch, 2012; Sangwan and Mittal, 2015) due to their influence on the natural environment through production of products and services (Esmaeilian et al., 2016; Sarkis, 2001). To highlight the relevance of sustainable manufacturing, the United Nations selected sustainable consumption and production as one of society's major goals in tackling poverty and creating environmental equilibrium (UN, 2015). The ultimate objective of incorporating sustainability into manufacturing is to move industry towards world-class sustainable manufacturing (Dubey et al., 2015; Dubey et al., 2016).

The term ‘sustainable manufacturing’ has a number of definitions, due to a lack of consensus in the associated literature (Moldavska and Welo, 2017). In this work we discuss environmentally-sustainable manufacturing with a focus on green issues, rather than approaching sustainability from the “triple bottom line” perspective, which focuses on the environmental, social, and economic dimensions. Possible definitions include: (a) production which integrates processes, decision-making, and environmental concerns to simultaneously maximise economic returns and reduce negative environmental impacts without depleting natural resources (Moldavska and Welo, 2017); (b) creation of products and services using production systems which take into account the negative impacts of production on the environment (Garretson et al., 2016); (c) operational strategies, tactics, and policies which further sustainability targets (Gunasekaran and Irani, 2014); and (d) the integration of environmental impact awareness into the traditional orientation of operations management (Kleindorfer et al., 2005).

Environmentally-sustainable manufacturing decision-making comprises system design and system operations (Gunasekaran et al., 2014), which are related to the green design of products and processes, and to the environmental management of supply chain operations, respectively (Abdul-Rashid et al., 2017). González-Benito and González-Benito (2006) have identified and classified practices addressing environmentally-sustainable manufacturing decision-making. These are: (a) design for environment, which refers to the creation of products that require less natural resources and hazardous pollutants, minimise waste, and can later be disassembled in order to reuse, recycle and remanufacture the component parts; (b) cleaner production, which is based on production, planning and control of processes orientated towards reducing the consumption of resources and the generation of waste; and (c) green supply chain management initiatives, which include green purchasing, logistics decisions to reduce environmental impact (e.g. packaging, mode of transportation, shipments consolidation), and responsible disposal and recycling systems.

O'Brien (1999) and Alayón et al. (2017) have proposed principles to guide environmentally-sustainable manufacturing decisions. They recommend the use of the 3Rs (reduce, reuse, recycle), support to extend the life cycle of products – for instance, remanufacturing and recycling – and the use of clean technologies to reduce pollution.

Technology is a fundamental component of environmentally-sustainable manufacturing decisions, as it is necessary to lower the resources used in production, which in turn causes less damage to the environment (Dubey et al., 2017). Both software and hardware can provide efficient solutions for energy savings, control of emissions, machine maintenance, real-time order monitoring, and so on (Garetti and Taisch, 2012). Environmentally-sustainable manufacturing also requires the combined analysis of buildings and facilities to support manufacturing operations (Despeisse et al., 2013). Walker et al. (2014) have identified an avenue for future research, exploring the impact of recent business trends, such as the digital manufacturing era, on environmentally-sustainable manufacturing. It can therefore be argued that understanding the connections and mutual benefit between environmentally-sustainable manufacturing and Industry 4.0 is worthwhile, due to the relevance of technology in pursuing environmentally-sustainable manufacturing decisions.

3. Industry 4.0

For many, Industry 4.0 signifies a new and powerful industrial wave, which is oriented towards digital and virtual technologies and is service-centred. This movement resulted in the advent of the term “Industry 4.0”, coined by the German government according to Drath and Horch (2014). The principles of Industry 4.0 are the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customised production (Li et al., 2017; Thoben et al., 2017). The most significant components of Industry 4.0 are cyber-physical systems (Drath and Horch, 2014; Hozdić, 2015; Schlechtendahl et al., 2015), the internet of things, cloud manufacturing, and additive manufacturing (Kang et al., 2016).

Cyber-physical systems are technological systems which integrate cyberspace with physical processes and objects in order to transform machines and devices of production lines and cells into a network, so that real-time data is available for making decisions such as the prioritisation of production orders, optimisation of tasks, maintenance requirements, etc. (Lee et al., 2015). Sensors and actuators are employed to gather and distribute this data in real-time (Yu et al., 2015).

The internet of things is an information technology infrastructure which enables the collection and transmission of data between devices, resulting in identification, localization, tracking, and monitoring of objects (Li et al., 2017). Bar codes, wireless sensors and Radio Frequency Identification (RFID) are all examples of technologies which