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Digitalization Technologies for Industrial Sustainability

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Abstract

Digital technologies are shown to perform a potential role in developing a resource efficient industrial base. The effective adoption of them can help to deliver reduced costs and improve the flexibility and sustainability of manufacturing systems. However, these positive benefits are far from guaranteed and the way in which digital technologies favor the transition towards sustainable manufacturing systems has not been analyzed in detail yet, so more conceptual and empirical investigations are required in this field. This paper develops a conceptual framework, which explains the potential significance of using digital technologies toward efficiency, resilience and sustainability. It also includes evidence from various case studies, which illustrate the core technologies which can potentiality contribute to a sustainable industrial future. The findings show some impressive results concerning the sustainable implications of the digitalization of manufacturing processes. If the predicted benefits can be achieved through digital technologies, they could massively impact on sustainability.

Keywords: Digital technologies, Industrial sustainability, conceptual framework

1. Introduction

According to the World Economic Forum, the term "sustainable development" can be defined as development that increases the living standards of current generations without sacrificing that of future generations. This addresses issues such as economic and resource efficiency, environmental accountability and social equity. Sustainability is

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viewed as a long-term goal of society, with the production of all that is manufactured being both a contributor to modern well-being but also a contributor to many of the industrial and environmental challenges recognized today. Industrial sustainability refers to the practice and study of how industry responds to current sustainability challenges and eventually becomes part of a larger and fully sustainable system [1]. By 2050, it is expected that manufacturing produces four times more goods and services added value than 2017, and it needs to be able to do this while aiming to zero waste, zero climate change emissions and using half its current resources. Digital technologies are shown to perform a potential role in developing a resource efficient industrial base. Their adoption can help to deliver benefits such as: i) establish which change is necessary at a firm level to enable improvements in sustainability performance, ii) improve the planning processes of companies to better account for demands and opportunities offered by industrial sustainability and iii) enable firm level experimentation with new business models. These requires awareness and transformation of the manufacturing processes to considerably reduce emissions and improve energy efficiency shifting towards the circular economy paradigm and adopting high-performance components, machines and robots that optimize the consumption of materials and energy. However, these positive benefits are far from guaranteed and the way in which digital technologies favor the transition towards sustainable manufacturing systems has not been analyzed in detail yet. So more conceptual and empirical investigations are required in this field. This paper develops a conceptual framework, based both on the literature and case studies to analyses innovative digital technology for sustainable strategies. To contribute to the building of knowledge on this aspect, this research introduces and explains the potential significance of using digital technologies toward efficiency, resilience and sustainability and goes on to offer case studies that illustrate companies' leadership in inventing and profiting from such technologies. The paper is structures as follows. Section 2 describes the research methodology adopted for this study, going through the literature and case study research. In section 3 the literature review and the conceptual framework are described while Section 4 presents the description and analysis of case studies. In Section 5, results and discussion are reported and finally, in Section 6 final consideration and future developments are discussed.

2. Research methodology

This research adopts a mixed research methodology based on a qualitative literature review and case study. The literature analysis provides a theoretical background for the conducted case studies, it is used to create a solid base from the best available evidence with respect to our topic. It aims at providing i) the theoretical framework and ii) the definition of key terms and topics related to this research. Literature review is considered a rigorous scientific investigation, limiting bias and random error through pre-planned methods and strategies. These strategies imply a search of all significant papers and the adoption of a selected criteria, which can be used by other researchers. Once the literature review is conducted, providing the main literature background, the next step is to choose the companies to be part of the research. Case study is one of the most powerful research methods used for theory building purposes, testing, extending or refining theories. In this research, case study is adopted for a better understanding of the digital transformation, as case studies often examine complex and non-repeatable circumstances and thus gather information, which can be used in theory building. This paper also provides evidence from various case studies from UK. The case studies are diverse and thus not structured similarly so as to gain as broader range of information as possible. An explanation of transformations that use digital technologies is then provided through examples, which attempt to present a scale of benefits achievable. These benefits are structured into two categories:

- Benefits felt by the industrial system as user of the technologies,
- Benefits felt by the industrial system as a supplier of digital technologies.

The first research step is based on the analysis of the existing body of literature on digital technologies selected to support a sustainable industrial system. Then a conceptual framework has been designed to define i) competitive dimensions and ii) the core technologies, both which can enable a sustainable industrial system. To explore how these dimensions and technologies deliver innovative capabilities into the industrial system, case study research (iii) was chosen as the other methodology for paper findings; these has been used to evaluate and validate the conceptual framework which aims to explain how digital technologies can potentially contribute to a sustainable industrial future.

3. Literature review

To achieve a thorough understanding of our topics of interest, the following sections are an overview of the relevant findings established on: i) a solid base from the best available evidence ii) a conceptual framework which defines the competitive dimensions and core technologies, both which can enable a sustainable industrial system.

3.1. Digital technologies and industrial sustainability

The literature review has been performed by selecting papers from Scopus due to its ample coverage of articles in this field. The qualitative literature review process was composed of two parts: firstly, an explorative unstructured one that had several different origins; and secondly, a more structured one involving searching databases using search strings and dashboards. The Authors' strategy was to identify articles that included "cyber physical manufacturing system" and "industrial sustainability" as keywords in all fields. The "cyber physical manufacturing system" set of keywords refer also to "industry 4.0" but focusses on the "manufacturing" orientation of the searching strategy. The search technique allowed the identification of 64 academic papers published until 2017, which were rigorously reviewed in order to evaluate their adherence to the study. Then the selected database was analyzed according to publication year and the country.

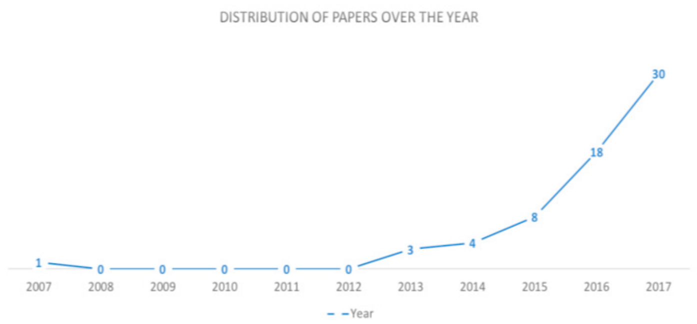

Figure 1 Distribution of papers over the year

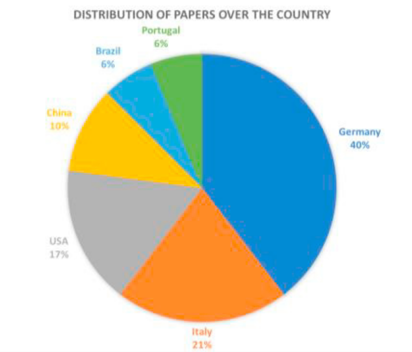

Figure 2 Distribution of papers over the country

The analysis on publication years reveals a sharp growing trend of articles on this subject over the past decade (Figure 1). The trend line illustrates the average number of articles published until the previous year. It reveals a ten-fold increase from 2013 to 2017. Regarding the geographical distribution of data (Figure 2), many different countries around the world contributed to this area of research and the papers were based on the main author's university affiliation. One country stands out, Germany (probably because of its strong focus on Industry 4.0 and manufacturing). So, this topic is primarily rooted in this country, and partially in countries throughout the rest of Europe and the world. Additionally, there is a considerable contribution from scholars in Italy and the USA. Hence, the aforementioned digital technologies are supposed to be implemented within the digital factory consisting of innovative technologies and distributed equipment with some smart production that forms a highly intelligent organism in the realization of data exchange, to achieve the integration of a virtual and physical world. In this way, the factory of the future can adopt, for instance, sensor networks during the final assembly. Indeed during product assembly, a network of wireless sensors can validate inventory and control, verifying that correct components have been used, and that they are exactly positioned in the correct locations [2]. In recent years, the demand for these intelligent sensors for improving flexibility and adaptability in manufacturing processes has been reported in many studies [3], as they are one of the main components of cyber physical manufacturing systems (CPMS). CPMS are based on embedded systems, which are able to communicate and create new production capabilities. CPMS are designed to be decentralized and self-organized, based on the integration of different elements which all are intelligent, therefore each production element knows its own skill, capability and position so there is no need of central coordination [4]. These systems can deliver significant benefits in flexibility, productivity and resilience within the production process (and also on the supplying and distribution logistics activities) by exploiting the increasing availability of manufacturing data and by optimizing the relationship between technological and social processes [5]–[7]. Furthermore, such digital technologies, also named as the Industrial Internet of Things (IIoT) and Data analytics, can support the product life-cycle and energy efficiency by collecting information from the design phase to the recycling phase and analyzing context information based on this data [8]. In this context, remanufacturing applications can be improved through new digital technologies, specifically the IIoT and Data Analytics can provide performance monitoring and optimize productivity. Digital technologies can adapt the manufacturing/remanufacturing operations through self-optimization and smart fixturing capabilities [9]. To conclude, the digital revolution with its innovative technologies, the concepts of CPMS and IIoT, can deliver relevant improvements concerning industrial sustainability. Factories can use network or matched technology to link their productions with suppliers and customers rapidly reacting to changes, reducing waste and overproduction and improving the efficiency of energy and resources through the adoption of intelligent management systems [10].

3.2. Conceptual framework

Digital technologies are expected to deliver many innovative capabilities into the industrial system as reported in the literature review. These have been studied to analyze their potentiality in contributing to a sustainable industrial future. Based on the literature above, a conceptual framework is constructed, as shown in Figure 4. The conceptual framework aims to introduce and explain the potential significance of adopting digital technologies towards specific competitive dimensions:

1. *Productivity:* factories could do more with less;
2. *Resilience:* industry could become more resilient to many disruptions;
3. *Sustainability:* the industrial systems operates within planetary limits.

As depicted in Figure 3 digital technologies have been characterized as “more data”, “more connectivity”, “more flexible automation” and “more analysis”. These abilities are predicted to be used in various combinations to change the system of manufacturing [4].

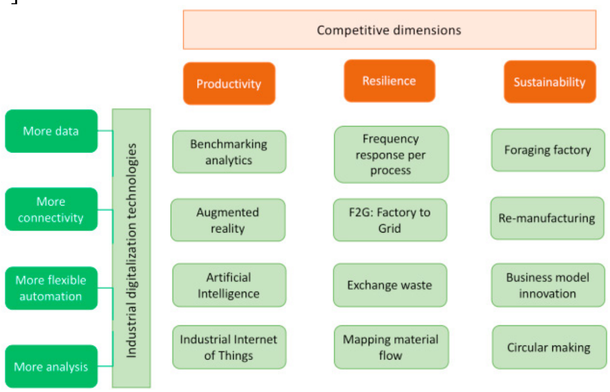

Figure 3 The conceptual framework

3.2.1. Productivity

Digital technologies enable a radical improvement in non-labor resource efficiency on a scale not yet achieved. They can improve resource productivity through benchmarking analytics, where a massive quantity of data from a single factory is used to identify “golden moments” which occurs when one product can be manufactured for half the energy or CO_2 emissions of the same product manufactured at a different time or use the same data for anonymous comparison between factories. Increased resource productivity can be achieved through the application of artificial intelligence (AI), augmented reality (AR), IIoT and data analytics. AR is important to this drive for productivity, as it enables engineers to see energy, water and waste flows in real-time in the factory setting. This allows them to bring their traditional skills of productivity improvement to play onto a real cost that has only previously been made visible in spreadsheets. AR technology is expected to eventually lead to improved factory design tools. The scale of benefits from using digital technologies to make previously hidden or messy situations visible is a significant reduction in total costs to manufacturing including benefits to the grid and to climate targets and the creation of new companies that export these great ideas.

3.2.2. Resilience

It is predicted that increasingly frequent and large disruptions will occur to supply chains, from material availability due to geo-politics to floods, droughts and energy disruptions. One strategy to mitigate such disruptions is to require less resource per unit of a manufacturing value added and the resource productivity drive will achieve this. In another strategy, many companies are using sensors to identify short term strain on the grid and uses IIoT technology to adjust the amount of electricity being consumed by industrial equipment for short bursts (such as refrigerators or heating systems). These have little or no effect on operational processes but perform a service to the grid in helping to balance electricity supply and demand. This "frequency response" service is a type of demand flexibility [11], and part of a wider shift to a smart energy system. The next stage of resilience advancement for such digital technologies is to connect sets of factories or supply chains, or even local clusters of factories, to the grid to deliver grid services such as demand shifting peak lopping and frequency response [12]. This is called factory-to-grid (F2G) as a useful analogue to vehicle-to-grid (V2G), but with much greater capacity availability than V2G. Material efficiency is also amenable to improvement through the use of digital technologies. Many factories are potentially able to use other factories waste as an input material, but the provenance, quality, and time availability of such materials preclude their easy inclusion into a carefully planned system where the factory does not want to stop production while waiting for raw material to arrive [13]. Digital technologies can better predict future waste availability and its qualities to accuracy never before possible. As such individual waste exchanges are increased in volume it also enables mapping and analysis of material flows which has been viewed as a massively powerful but unavailable tool for government and sector level planning.

3.2.3. Sustainability

The ultimate goal of the industrial system must be to work within the ability of the planet to offer its raw materials of energy, water and material. The alternative cannot be sustained. It is evident that many large and small manufacturers are engaging with this ambition with increasing seriousness. It is equally evident that this final drive to sustainability is not ubiquitous, yet leadership can be seen from many leading manufacturers such as Unilever, Toyota, and AB Sugar. A "foraging factory" uses similar technologies to the waste exchange factories described above. They can identify what raw materials are likely to become available locally and soon. Differently to the waste exchange factories they then search their order book to assess what product to make, and how to adjust the bill of materials for that product to allow it to be made from waste that is becoming available. This is only possible because of the extreme flexibility emerging from digital technologies, automation and process control technology. Many companies are using the power of increasing data availability to find products and materials and re-manufacture them. Some are the original manufacturers who rely on sensors to know when their products are under-performing in the field and get them back to the factory to be made as good as new. Furthermore, business model innovation and circular economy can provide advice to global industry on how to innovate their system of value exchange and how to begin the journey to becoming a circular organization. Though it is very early to predict the benefits from this drive toward sustainability, digital technologies are likely to deliver further reductions in downtime, increases in added value (as less resources are used across the system), plus cleaner air and cleaner energy systems. Re-manufacturing, even supported by advanced and flexible automation, is relatively labor intensive and will increase employment directly.

4. Case description and analysis

Recently, challenges to benefit from digitalization in practice have been increasingly discussed among companies. In this section, two examples from UK companies are introduced to provide understanding of the phenomenon and the research context. The cases are from companies that have been experiencing digitalization and changes caused by it.

4.1. Company Alfa

Company Alfa is a UK company that uses innovative digital technology to connect a range of distributed energy assets and aggregates and optimizes their electricity demand in real-time. This service illustrates business model innovation with triple bottom-line benefits. The technology platform is an example of a demand side response (DSR) service that helps the national grid to balance electricity supply and demand in real-time throughout the year. Monitors detect the frequency in the electricity system. If it is higher or lower than the balanced frequency, it will send a request to thousands of digital technologies devices across the country and ask if it can temporarily increase or reduce power consumption to restore the optimal balance between electricity supply and demand. The responses are aggregated and adjusted in real-time, creating a virtual power station, without compromising operational performance. Their technology also provides an interactive, customizable portal that helps identify energy savings. One of their largest customers is a water company, who has connected assets such as water pumps, motors and blowers at some of its largest wastewater treatment works. By 2020, Company Alfa aims to provide over 50MW of demand side response for national grid, equating to a reduction of over 100,000 tons of carbon for the UK per year. Furthermore, Company Alfa launched a new platform in 2017 further utilizing AI, machine learning, big data analytics and IIoT to deliver data-driven savings and revenues to its customers from multiple markets and services. However, several barriers hinder wide scale adoption by more companies across the UK. Many companies are confused by the complexity of the technology, processes and structures in the DSR sector. This can in turn make it challenging for businesses to evaluate commercial propositions and slow decision making. Potential ways to circumvent these barriers may be better regulation to enable a level playing field in still a relatively infant industry.

4.2. Company Beta

Company Beta is a market leader in the IIoT, machine learning and AI sector. It provides a range of applications and services through an innovative platform to help eliminate inefficiencies and improve productivity yields in plants, processes and people. Their platform utilizes key technologies such as machine learning and physical models that analyze real-time and historical data to predict and simulate future performance. They also use virtual sensors based both on their customers' data and sensor networks to plug data gaps as well as advanced analytics and automation outputs from statistical, physical and machine learning models. These allow firms to identify areas for improvement, for example, they are able to monitor the quality and safety status of materials during transportation, track the supply chain end-to-end and identify and respond to any bottlenecks more quickly. Reduced performance variability, less unplanned downtime, and optimized use of resources lead consequently to lower energy consumption and associated costs. Company Beta delivers to their clients' optimization as a service (OaaS) through a combination of software and networks, wherein the IIoT platform and big-data technologies are integrated to deliver it as ready-to-use software applications. Their client base is primarily in capital and asset-intensive industries and they have built substantive partnerships in the natural resources and mining industry. Examples of their customers include one of the largest copper and gold mines in Latin America, who have seen a 55% reduction in their variability and a uranium mining site in Kazakhstan who have seen a 15% increase in system efficiency and energy savings and a 7.5% increase in yield improvement. Existing technologies do not have the capability to manage continuously changing operating environments or the ability to predict the mineral composition of feed, significantly benefiting their customers in the mining industry, where input materials vary on an hour-by-hour basis and connectivity has been difficult in the harsh or extreme environments. Going forward, Company Beta hope to increase the number of their applications and services and expand their customer base.

5. Results and discussion

This study explores the potential significance of adopting digital technologies towards specific competitive dimensions and evaluates and analyzes differences with regard to varying company characteristics and the conceptual framework. The two considered companies have a sustainability strategy in place and expect its strategy to be influenced by digitalization. They associate high expectations regarding improvements in resource efficiency and productivity with the application of digital technologies in production. The findings and results are summarized in Table 1 and 2.

Table 1 Results of Company Alfa

Benefits to Company Alfa	Benefits to their customers	Digital technologies
Company Alfa is paid by the National Grid for providing demand flexibility. National Grid's Power Responsive initiative stimulates interest and adoption of technologies to help balance electricity supply and demand through financial incentives.	*No disruption:* the technology functions almost invisibly, requiring minimal behaviour change. The installation process itself is not complex and does not require large input costs.	Business model innovation, Artificial Intelligence, Machine Learning, Big Data Analytics and IIoT
	Efficiency: through data-based insight into how the customers' processes and equipment are working, Company Alfa can identify problems and possible efficiency gains, thereby lowering their customers' production costs.	
	Carbon emissions: demand flexibility reduces the National Grid's reliance on fossil fuelled power stations for balancing the grid – thereby cutting carbon emissions in addition to creating a smarter, more resilient and more secure energy system.	
	High satisfaction: 78% of DSR users are satisfied with the outcome.	

The analysis of the case studies shows some impressive results concerning the sustainable implications of the digitalization of manufacturing processes. Increasing the efficiency of material and energy usage is a fundamental condition for both the two companies (Table 1 and 2), which correlate high expectations for more resource efficiency towards their digitalization. If the predicted benefits can be achieved through digital technologies, they could massively impact on sustainability. This becomes relevant regarding saving energy, as reported in Table 1. So, the digital transformation can create several opportunities for reduce material dependence, improve productivity, increase the usage of renewable energies and synergies between companies and improve the efficiency of industrial sustainability.

Table 2 Results of Company Beta

Benefits to Company Beta	Benefits to their customers	Digital technologies
Being a market leader allows them to gain a competitive first mover advantage and develop more global customers. Costs of IoT, data analytics, AI technology will decrease, further increasing their profits.	*Deployment* is realized with minimal disruption to existing operations.	IIoT, Machine Learning, Artificial Intelligence, Virtual sensors
	Improved business efficiency: optimization of production processes reduces energy consumption, water requirements, less unplanned downtime, resulting in higher yields.	
	Lower costs/ higher revenue generated from reduced unit costs, which can be reinvested or passed onto consumers in the form of lower output prices.	
	Extended equipment lifetime further reduces *production costs* and *waste*.	

6. Conclusions and Recommendations for future research

This analysis shows that companies are still targeting resource efficiency or resilience for their exploratory use of digital technologies. The benefits from the individual case studies are evidence for early realization of value and impact from the interaction between digital technologies and sustainable business. This work has attempted to set out the scale of the potential benefits if such ideas were adopted by the mass market, but the analysis needs strengthening to guide detailed action. It would be beneficial to analyze further case studies (may be from different countries), which can improve the evaluation of the conceptual framework and provide additional information about the impact and related benefits of digitalization. In addition, further research into the potential net impact of these emerging technologies for a low carbon economy can enable to minimize challenges and maximize opportunities, particularly in big data and predictive analytics where little research exists. A suggested possible framework could be split into private and social benefits, with various scenarios assuming no adoption of firms using new digital technology to improve sustainability, the current adoption rate trend and a higher adoption rate. Possible metrics could include:

Table 3 Sustainable metrics for manufacturing companies in the digital era

Sustainable metrics for the digitalization era	
Firm production costs	Number of employees in firms using digital technology to improve sustainability
Cost reductions	Amount of money reinvested in green technology
Number of defects, faults and breakdowns	Amount of tax revenue generated from creation of new companies
Energy consumption and rate of energy efficiency	Amount of investment in firms using digital technology to improve sustainability
CO_2 levels	Number of patents in sector
Amount of landfill waste	Trends around technology installation costs over time
Rate of IIoT device penetration	Qualitative data from user satisfaction surveys
Triple bottom line data, taking into account economic, environment and social impacts	Quantitative and qualitative data of knowledge and innovation from spill-overs from the new technology into other firms and sectors

This work concludes that, both industries and governments should analyze their own resource efficiency performance and identify the potential benefits from the use of digital technologies. This is crucial in encouraging i) digital technologies take-up, ii) government procurement to benefit from digital technologies in its suppliers and to encourage researchers. To achieve this, industry must work with government and other experts to develop, test, advertise and encourage the take up of methods to help industry calculate resource efficiency and resilience benefits. Industries and governments should pool their existing resources to build a cross-industry competence center that will build scalable and efficient processes and use these to actively help manufacturers use digital technologies effectively. Finally, entrepreneurial capacity has to be built to nurture the sub-sector of "sustainable digital technologies" start-ups. Learning from each other and working with support systems that understand the sub-sector will help to accelerate and grow these nascent successes.

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