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The Triple Bottom Line of Smart Manufacturing Technologies

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THE TRIPLE BOTTOM LINE OF SMART MANUFACTURING TECHNOLOGIES

An economic, environmental, and social perspective

Thorsten Wuest, David Romero, Muztoba Ahmad Khan and Sameer Mittal

Introduction

Smart technologies and digital transformation are impacting many realms of modern society, including but not limited to the economy and its different industrial sectors. Manufacturing is no exception, given its stature as one of the oldest and most critical industrial sectors for a majority of global economies. Smart manufacturing and the Industry 4.0 paradigm build upon the opportunities presented by the emerging digital, or smart, technologies, including but not limited to artificial intelligence (AI), the Industrial Internet of Things (IIoT), and Additive Manufacturing (AM) (Thoben et al. 2017).

The manufacturing sector has seen a rapid (digital) transformation and adoption of smart technologies across the board. Both companies and (local and federal) governments globally have invested heavily in new smart technologies, processes, and tools. However, many are still struggling with this digital transformation. Many ambitious projects aimed at the adoption and implementation of these new smart technologies are finding themselves stuck in a so-called prototype or pilot purgatory, never deploying on a large scale on the shop floor or in the supply chain. There are many reasons for this struggle, including the sheer complexity of the task at hand, undefined responsibilities, the novelty of these new smart technologies, and unclear business cases and value propositions. Small and medium-sized manufacturers are especially struggling with this transition, given their limited resources and other limiting factors (Mittal et al. 2018a).

When we look at smart technologies within the manufacturing domain, the majority are digital in nature and heavy on information and communication technologies (ICTs). This requires a different (digital) skill set compared to traditional manufacturing operations. While digital transformation continues to shape the industry, manufacturing operators have to be onboarded and have their voices heard when it comes to new technologies adoption and or the question of alignment with current and future (re-)designed processes. Overall, a top-down approach of forcing smart technologies only, without re-thinking current processes and workflows, has proved to be very problematic (Romero et al. 2019a; Sinha et al. 2020).
A question that has so far not been completely addressed is the impact of these new smart manufacturing technologies on the triple bottom line (TBL) of the sustainability of businesses and supply chains. Interestingly, the origin of “smart manufacturing” can be traced back to smart and sustainable manufacturing – with a strong emphasis on “energy-efficient manufacturing” and facilitation of more “efficient manufacturing processes”. However, when we look at sustainability more holistically – focusing on the triple bottom line – there has not been much work dedicated to exploring this phenomenon. Just recently, some attention has been put on the TBL perspective with regards to the smart manufacturing paradigm in professional and scientific literature, for example, in Forbes business magazine (Clemons 2019) and selected academic journals (Abubakr et al. 2020). However, these recent works focus not solely on smart technologies but more on the overall smart manufacturing paradigm.

This chapter aims to close this gap and opens the discussion by seeking to answer the aforementioned question: What is the impact of new smart manufacturing technologies on the triple bottom line of the sustainability of businesses and supply chains?

The chapter is structured as follows. We first provide an overview based on an explorative literature review of the key terminology, technological developments, and on-going paradigm evolution within the emerging smart manufacturing systems. In the following section, we discuss the impact of Industry 4.0 and smart manufacturing paradigms from a TBL perspective before honing in on the smart technologies that are commonly associated with smart manufacturing systems. After this, we review recent scientific and grey literature and identify 10 key smart manufacturing technology clusters and discuss each with an emphasis on use cases and their economic, social, and environmental impacts. The next section takes a step back and highlights the barriers and challenges faced by organisations when engaging in their smart manufacturing journey and the adoption of these key technologies. The penultimate section takes a bold look at future technological developments and provides an outlook as to how this diffusion of smart technologies will shape the manufacturing sector and our society overall. The final section concludes the chapter and addresses the limitations of this work.

**Literature review**

**Smart manufacturing and Industry 4.0 paradigms**

The manufacturing sector has always been at the forefront when it comes to technological innovations. Over the last centuries, there have been four distinctive events, commonly referred to as industrial revolutions. During the First Industrial Revolution, the manufacturing sector became industrialised, driven by the mechanisation of labour, exemplified by the introduction of the power loom. As a result, a myriad of machines, tools, and inventions blossomed and spurred tremendous economic growth. Then, the Second Industrial Revolution introduced mass production and the moving assembly line. Most notably, Henry Ford’s Model T production facilities are credited with initiating and exemplifying the Second Industrial Revolution. The Third Industrial Revolution came into the picture with the advent of numerical control and computer systems and their introduction to the shop floor. Finally, around 2011, the term “Industry 4.0”

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1 The *triple bottom line (TBL) framework*, in the manufacturing context, accounts for three forms of sustainability outcomes when producing a product: (a) environmental – e.g., emissions, hazardous waste, and (natural) resources usage; (b) economic – the flow of capital and infrastructure investment; and (c) social – e.g., safe working conditions and fair wages (Elkington 2018).
was born, indicating the start of the Fourth Industrial Revolution, centred around the introduction of Cyber-Physical Systems (CPS) in the manufacturing domain.

The term Industry 4.0 originates in politics, and therefore different terms have been coined globally to represent it. For instance, in the US it is often synonymously used with smart manufacturing, whereas in South Korea, it is referred to as smart factory (Thoben et al. 2017). However, unlike the three earlier industrial revolutions, “Industry 4.0” came popular prior to its full manifestation in the industrial landscape. Industry 4.0 is not a technology; rather, it denotes an umbrella of technologies that will lead to connected systems and data-driven decision-making environments (Mittal et al. 2018a). Although “data” has always been present, with the advances in and convergence of information and operational technologies (IT/OT) and the consistently decreasing associated cost of installing both, Industry 4.0 has become quite popular in the last few years.

Implementing Industry 4.0 or smart manufacturing technologies can have many advantages; these have motivated a number of organisations and the governments of many countries to act and engage in activities aimed at implementing them into their processes (Tao et al. 2018):

1. **Real-time awareness.** With the help of Industry 4.0 technologies, such as the Industrial Internet of Things (IIoT), all systems and subsystems, and their elements, within an organisation or across a supply chain can be connected. As a result, if there is an issue anywhere, the entire system can be notified and thus is enabled to make an informed decision or take action.

2. **Involvement of the customer during product design.** The involvement of the customer during the product design phase, also known as “co-design”, was previously difficult, as the customer was required to visit the plant more frequently. However, with the advent of Industry 4.0 technologies such as virtual and augmented reality (VR/AR) and digital twins, this is now possible to a much greater degree.

3. **Predictive maintenance.** The availability of big data thanks to smart sensors and networks, and the seamless transmission, storage, and processing of data in the cloud, or edge, enabled the emergence of new data analytics techniques supporting new, more foresight-oriented maintenance strategies.

4. **Employees and smart machines as co-workers.** The use of data also ensures that employees, who are now working in parallel with “smart” machines, and all stakeholders can learn from each other. As a result, the degree of employee productivity and employee satisfaction will increase, a paradigm known as “Operator 4.0” (Romero et al. 2016).

5. **Sustainable production.** Industry 4.0 technologies enable data-driven decision-making environments and, therefore, can make the best use of any production resource while reducing waste through the use of different optimisation techniques. As a result, the application of Industry 4.0 technologies also leads to more sustainable production systems such as Digital Lean Manufacturing Systems (Romero et al. 2019b).

**Economic, environmental, and social impact of Industry 4.0**

“Sustainability” and “Industry 4.0” are trending in the advanced manufacturing technologies literature. The technological state of the art includes AM applications (Ford and Despeisse 2016) and emerging production processes and systems based on flexible automation, collaborative and cognitive robotics, cloud computing, big data analytics, and CPS (Kiel et al. 2017; Bonilla et al. 2018; Jena et al. 2020). On the one hand, manufacturing businesses are expecting TBL-related benefits from Industry 4.0 technologies in terms of:
Economic gains, enabled by savings through more accurate and precise production planning and control systems, as well as shorter lead times thanks to the development of agile manufacturing capabilities on the shop floor.

Environmental gains, enabled by increased energy efficiency in manufacturing operations; real-time monitoring of production assets’ energy consumption helps to avoid spikes, reduce base loads, evaluate peak hours, and identify irregularities and thus optimise operational scheduling. Further, a decrease of manufacturing scrap waste is enabled by employing advanced total quality management systems in order to improve process efficiency and product quality while minimising and eliminating quality defects and process errors.

Social gains, enabled by wearable and collaborative technologies increase the safety, health, and welfare of workers on the shop floor (Ejsmont et al. 2020).

On the other hand, selected Industry 4.0 technologies adoption implies and raises several sustainability concerns about

Economic factors, due to their cost-intensive nature and difficulties in estimating their full financial benefits (ROI) and economic effectiveness.

Environmental factors, which are related to their energy consumption and electro-waste at their end-of-lifecycle.


Hence, both benefits and concerns should be clearly pictured in a TBL perspective and within a Sustainable Industry 4.0 Framework (Kamble et al. 2018).

Smart technologies in Industry 4.0

The past three industrial revolutions were supported by disruptive production technologies and power sources of the time that significantly altered manufacturing processes and systems. For example, the First Industrial Revolution was promoted by water- and steam-powered mechanical manufacturing facilities; the Second Industrial Revolution was supported by electrically powered mass-production lines; and the Third Industrial Revolution was led by the widespread usage of electronics and ICTs to further automate manufacturing systems (Liao et al. 2017). Today’s emerging “smart” manufacturing technologies are mainly fuelled by data. These data-fuelled smart technologies, such as the Industrial Internet of Things (IIoT), CPS, and big data analytics (BDA), are paving the way for the Fourth Industrial Revolution that sets the frame for the smart manufacturing paradigm.

Smart manufacturing is driven by data and data analytics. The successful operation of any smart manufacturing system depends on the generation, transmission, storage, processing, and application of data-driven decisions in operations management, which are greatly facilitated by various smart manufacturing technologies (Klingenberg et al. 2019). For instance, smart sensor systems, embedded systems, and RFID technologies are critical for data generation. For data transmission, some of the important technologies are IIoT, smart sensor networks, and cellular networks, such as 5G. In order to store and process the transmitted data, we can utilise various technologies such as cloud storage and -computing, blockchain, big data analytics, machine learning, artificial intelligence, virtual and augmented reality, and cybersecurity. Finally, relevant technologies that can facilitate data application may include robotics, connected factories, smart products, and, ultimately, smart manufacturing.
Relevant smart manufacturing technology clusters in literature

Several researchers have previously identified a wide variety of technologies related to smart manufacturing systems. Mittal et al. (2019) presented a comprehensive list of characteristics, technologies, and enabling factors frequently associated with smart manufacturing. Klingenberg et al. (2019) identified 111 Industry 4.0 technologies through a systematic literature review, while Frank et al. (2019) compiled a list of six technology clusters associated with smart manufacturing. Ghobakhloo (2019) provides a schematic presentation of the key information and digital technology trends that enable smart manufacturing. However, the smart technologies mentioned in the available scientific literature do not always match.

A refined list of smart manufacturing technology clusters built on previous work is presented in Table 16.1, which intentionally excludes some smart technologies illustrated in previous publications. Examples of the omitted technologies are (a) CAx technologies (Dalenogare et al. 2018; Mittal et al. 2019; Ghobakhloo 2019); (b) vertical and horizontal systems integration (BCG 2018; Dalenogare et al. 2018; Klingenberg et al. 2019); and (c) energy management (Mittal et al. 2019; Frank et al. 2019). While the reasons for exclusion vary, they are based on either the reviewing methodology of the original sources (e.g., energy management) or disagreement with their classification as a technology rather than as an enabling factor (e.g., vertical and horizontal systems integration). In the table, we mapped the alignment with previous work on the topic to ground our resulting list in the state of the art. We decided to add 5G networks (Table 16.1 – No. 10) despite this not being mentioned in previous work, as we believe this will have a significant impact on future developments in the smart manufacturing domain.

In the following section, we discuss each of the 10 key smart manufacturing technology clusters presented in Table 16.1 in more detail.

Smart manufacturing technology clusters:
a triple bottom line (TBL) discussion

The 10 key smart technology clusters associated with smart manufacturing and Industry 4.0 are diverse in nature and include manufacturing processing, data analytics, and information and communication technologies. We present each in the following subsections with an emphasis on their more significant use cases and economic, social, and environmental impacts to adequately reflect the TBL perspective.

Artificial intelligence (AI), machine learning (ML),
and advanced simulation

Artificial intelligence (AI) and other analytical and data-driven approaches are at the core of the smart manufacturing and Industry 4.0 paradigms (Kusiak 2017). Therefore, we consider AI, machine learning (ML), and advanced simulation technologies as the foundational pillars and thus the basic technologies in the smart manufacturing domain. Several other key technologies, listed later, aim to either feed data into analytical models or to build on actionable insights derived from data.

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2 The refined Smart Manufacturing Technology Clusters were created using established ontologies in relation to smart manufacturing vocabulary (e.g., glossaries) and the consideration of the semantic distance between the terms being classified (Harispe et al. 2015).
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<tbody>
<tr>
<td>1</td>
<td>Artificial intelligence, machine learning, &amp; advanced simulation</td>
<td>Artificial intelligence</td>
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<td>Big data analytics</td>
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<td>Machine learning</td>
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<td>Machine vision</td>
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<td>Advanced simulation</td>
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<td>2</td>
<td>Cloud, fog, &amp; edge computing</td>
<td>Cloud computing</td>
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<td>3</td>
<td>Additive manufacturing</td>
<td>Additive/Hybrid manufacturing</td>
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<td>4</td>
<td>Industrial Internet of Things &amp; Cyber-Physical Systems</td>
<td>Industrial Internet of Things (IIoT)</td>
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<td>Cyber-Physical Systems (CPS)</td>
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<td>5</td>
<td>AR, VR, &amp; DTs</td>
<td>Augmented, virtual, &amp; mixed reality</td>
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<td></td>
<td></td>
<td>Digital twins</td>
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<td>6</td>
<td>Automation &amp; robotics</td>
<td>Automated guided vehicles &amp; autonomous mobile robots</td>
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<td>Collaborative robots</td>
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<td>Drones</td>
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<td>7</td>
<td>Cybersecurity</td>
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<td>8</td>
<td>Blockchain</td>
<td>Blockchain</td>
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<td>9</td>
<td>Smart sensor systems</td>
<td>Industrial sensors, actuators, &amp; PLCs</td>
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<td></td>
<td></td>
<td>Smart products, machines, &amp; wearables</td>
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<td>10</td>
<td>5G networks</td>
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Key use cases. AI and data analytics are broadly applied across the various levels within a manufacturing environment. Use cases range from (a) predictive maintenance, where AI predicts the moment in the future when a machine tool will fail, through (b) continuous improvement of the production planning and scheduling with advanced simulation and optimisation techniques, to (c) in-situ real-time monitoring and prediction of process efficiency and product quality using machine learning. In the future, even personalised automated design will be AI-powered, and on a digital supply network level, the supply and demand risks will be predicted and managed by AI.

Economic impact. The economic impact of AI and other data-driven tools is significant. Recent studies suggest that AI can help make products lighter and stronger, as well as reduce demand forecast errors by 30% and demand planners’ workload by 50% (Columbus 2020). Overall, AI is expected to have a transformational impact on the manufacturing sector as a whole, and organisations failing to adopt this technology are predicted to fall behind their competitors (Bughin and Seong 2018).

Environmental impact. The environmental impacts of AI come down to the energy that computer systems use to train AI/ML models and supply the necessary training data for model creation. While running a classification model is comparably energy efficient, training a new, complex AI/ML prediction model can be five times the life-time emissions of an average car (284t CO2) (Lu 2019).

Social impact. The social impact of AI changes the workflow and how operators approach their different manufacturing tasks. Before the introduction of AIs on the shop floor, operators spent a significant amount of time on analysing and interpreting data. In the future, with AI-based analytics monitoring of manufacturing processes in real time, the operators will be alerted to any future issues. However, often the AI models are black-boxes that do not provide insight into how the predictions are derived – which can cause stress and anxiety for the human operators. Furthermore, human operators might struggle with accepting tasks from an artificial system. Despite the widespread fear that AI is eliminating many jobs in manufacturing, newer studies do not support this (Scott and Shaw 2020).

Cloud, fog, and edge computing

Cloud computing and industrial internet platforms have transformed the way we operate and approach storage, communication, and access to data, as well as its complex analysis (Menon et al. 2019). The ability to scale data storage and processing capabilities without having to add, manage, and maintain servers in-house is already a game-changer. However, the ability to rely on dedicated cybersecurity experts as well as the flexibility to adjust to peak computing demands makes cloud platforms a core smart manufacturing technology. While cloud computing is at the core, fog, edge, and hybrid variants and extensions are expanding the data management abilities for different shop floor applications that are driven by demanding requirements (e.g., low latency) or security measures (e.g., defines manufacturers). Hence, fog and edge computing enhance the cloud computing paradigm by adding data processing and analytics (physically) closer to the data origin (Sinha et al. 2020). While often mistakenly used interchangeably, fog computing describes the processing of data in the local network, and edge computing focuses on processing on or connected to the sensor system itself. Moreover, hybrid computing describes a combination of different layers, for instance, where some parts of the network are hosted locally, and other data is stored in a cloud environment. The reasons for a hybrid approach are manifold and may include cybersecurity concerns, economic considerations, and/or technical (computing) requirements.

Key use cases. Cloud, fog, edge, and hybrid computing in smart manufacturing range from process planning applications, to process data storage, to data exchange, to advanced analytics.
Quality monitoring and predictive maintenance are two applications that heavily rely on industrial internet platforms and extending data analytics across different nodes of the shop floor and supply chains, which are mostly made possible by leveraging cloud infrastructures.

**Economic impact.** The economic impact of cloud infrastructures and industrial internet platforms on the manufacturing sector are manifold. The main appeals of cloud computing for manufacturers include zero upfront cost, rapid scalability, reduced redundancy requirements (increasing resiliency), and dedicated cybersecurity. While these are all considered positive, and also lower the barriers for small and medium enterprises (SMEs) to engage in smart manufacturing applications, some economic aspects are less appealing. There are only a limited number of industrial internet platform providers, and as such, there might be some form of lock-in possible in the future (Menon et al. 2020).

**Environmental impact.** From an environmental perspective, utilising cloud services has a significant impact on energy consumption. On the one hand, centralised hosting can leverage economies of scale and scope and focus on renewable energy usage. A 2020 study by Microsoft (Microsoft 2020) found that cloud hosting is 20–93% more energy-efficient than local hosting. This is promising. On the other hand, however, the ease of use and ability to scale entices users to store more data and use the systems’ processing capabilities to a greater degree. However, Masanet et al. (2020) found that while demand for cloud services surged, the energy demand has grown at a significantly lower rate.

**Social impact.** The social impact of cloud technologies is largely considered positive. Cloud computing enables remote access and, as such, remote work and more flexible workplace models that benefit underdeveloped areas and underrepresented groups – for example, working parents in rural areas. On the other hand, decentralised storage and access from anywhere do not align with higher costs of living in some areas/countries and might lead to more competition in the labour market and lower wages. However, at this point, there is no evidence that this might materialise at scale. The other aspect at the intersection of social and economic impact is (digital) skills development and retention of critical knowledge within the organisation. When manufacturers outsource storage, processing, and analytics to external platforms, there is a risk of losing critical skill sets within their own workforce. Given that data analytics and data-driven decision-making are core skills that will define the future of competitive success, this might lead to significant problems sooner rather than later.

**Additive Manufacturing (AM)**

Traditional subtractive manufacturing processes such as milling, turning, and drilling remove material from a blank to create a product. Deformative processes such as forging or casting change the shape without adding or removing material. **Additive Manufacturing (AM)** deposits material layer by layer and creates a 3D-object with the help of a CAD model and is therefore also referred to as 3D printing. Subtractive and deformative manufacturing processes utilise digital technologies, such as Computer Numerical Control (CNC), but are not dependent on them. AM, on the other hand, is digital in nature and cannot be operated without digital input. Based on the strength requirement of a final product, various AM methods may be used, such as powder bed fusion, vat photopolymerisation, binder jetting, and direct metal deposition.

**Key use cases.** AM methods can be seen across various industries, such as automotive, aerospace, biomedical devices, and even construction, due to their unique capability to enable the manufacturing of complex geometries and rapid prototypes (Ngo et al. 2018).

**Economic impacts.** AM is still in its early adoption phase, and there are various barriers hampering its widespread adoption and implementation, such as a comparably slow speed of
printing, high cost of printers, materials, and maintenance, CAD software complexities, copyright infringement, and lack of expert designers (Shukla et al. 2018). As a result, only selected industries have started to use AM at scale. However, the rapid pace of innovation in the AM domain will likely help to overcome many of these barriers. In the future, more and more industries will find AM technologies to be an affordable option that provides easy access to customisation, personalisation, and rapid prototyping capabilities.

*Environment impact.* AM technologies, in general, are significantly more environmentally friendly compared to subtractive manufacturing technologies, as in an AM process there is no wasted (raw) material generated. Even the powders or resins used as raw materials during AM processes in most cases are recyclable. In consensus with earlier statements, an innovative strategy combining both additive and subtractive manufacturing processes, known as hybrid manufacturing, has suggested that such a strategy will demand low levels of energy and create less environmental impact compared to the impact created by using subtractive manufacturing processes alone (Thao Le et al. 2017). This environmental impact will be further reduced when AM is used by itself.

*Social impact.* When AM technologies become more common and are adopted on a mass scale, there is potential to revolutionise many apparel industries. For instance, the footwear industry providing customised footwear will share the design of the footwear with the customer, while the customers themselves can 3D-print their own shoes. Similar changes will be observed around customised clothes and automobile spare parts as well, thus affecting the entire business model and supply chain. For example, with lead time reduced significantly, products will not take too long to arrive.

### Industrial Internet of Things (IIoT) and Cyber-Physical Systems (CPS)

The *Industrial Internet of Things (IIoT)* is about connecting “things” used in an industrial environment such as the manufacturing shop floor or a warehouse. These things may be in the form of people, machines, materials, or products. Furthermore, there is now an extension that includes immaterial “things” such as service, sometimes referred to as the Industrial Internet of Things and Services (IIoTS). When these “things” are used in the consumer goods space, we refer to the widely known Internet of Things (IoT). When various systems are interconnected with the help of IoT devices and can-do computations and make complex decisions, we refer to them as *Cyber-Physical Systems (CPS)*. IoT devices lay the foundation for CPS and therefore are considered within the same technology cluster. By remaining connected, “things” are able to develop real-time awareness of each other and thus enable informed decision-making.

**Key use cases:** IIoT and CPS regularly shape our daily lives. With the help of IoT devices, the real-time location of an order can be monitored by the manufacturer without contacting the supplier. These connected smart devices also let us know what the weather will be in a region, and if needed, the route of the vehicle transporting the order from supplier to manufacturer may be changed to avoid delays due to inclement weather.

**Economic impact.** IIoT and CPS require less investment compared to other smart manufacturing technologies. The typical requirements are sensors, network, and cloud, which are available at affordable prices. The advantage of IIoT and CPS is that due to the availability of a wide variety of sensors, everything can be connected. As a result, organisations can become more efficient and utilise their production and logistics resources optimally. The literature also shows how traditional lathe and mill machines, omnipresent in most manufacturing workshops, can be upgraded and made smart without significant investments (Mittal et al. 2018b).
Environmental impact. IIoT and CPS can make the lives of shop floor managers easier and contribute to reducing machine tool energy consumption. However, cybersecurity becomes a potential threat. If a hacker gains access to a smart machine, they might be able to manipulate it remotely and cause significant harm to the production, machine, or even operators. Similarly, environmental hazards are created by batteries and other electronic waste, which will be produced in greater quantities than before, and disposal will become an issue that needs to be addressed. The signals emerging from the operation of these smart devices can affect populations of birds and insect pollinators, as their eggs may be damaged. Similarly, this overall development will also further increase screen time for humans, thus affecting their health, including their eyes.

Social impacts. IIoT and CPS will have a tremendous impact on smart factories and the future workplace (Autor 2015; Romero et al. 2020). On a smart shop floor enabled by IoT devices, for instance, a worker will be able to (remotely) operate production resources (viz., smart machines, robots, and computer systems) present at the manufacturing site by opening an app on a mobile phone. As a result, if a person forgot to shut off a machine, he/she would be able to do that from any remote location.

Augmented reality (AR), virtual reality (VR), and digital twins (DTs)

Augmented reality (AR) is a technology that overlays computer-generated virtual objects into the physical environment, whereas virtual reality (VR) replaces the physical environment with a computer-simulated one that uses sight and sound to produce an immersive experience for its user. Furthermore, digital twins (DTs) are virtual replicas of physical devices used to run advanced simulations before actual devices are built and deployed, and are able to mirror in real time the static and dynamic characteristics of its physical twin as a result of seamless data exchange with its virtual replica.

Key use cases. Among the main VR and AR industrial applications, virtual engineering, virtual training environments, and digital assistance systems stand out. Two of the biggest industrial use cases of AR technology are in the maintenance, repair, and overhaul of complex equipment and in the assembly of complex products. In both cases, AR technology enriches the real world with virtual objects and digital information that is overlaid in real time in the operator’s field of view for error-proofing the execution of different manual operations. Some VR technology industrial use cases include, but not limited to, virtual engineering and virtual training environments. The former supports the modelling, simulation, and visualisation of products and systems behaviour under real-world operating conditions. The latter facilitates the transfer and assessment of procedural knowledge and technical skills for performing assigned tasks. Both virtual environments provide a combination of interactive virtual reality and advanced simulations of realistic scenarios for optimised decision-making and action-taking. Furthermore, some DT use cases may include virtual simulations supporting the development of new or re-design of existing products and product variants; quality assurance by real-time monitoring of every part of a product, asset, or production process; and system planning and control by modelling and simulating different scenarios for a manufacturing system in order to optimally configure, update, and provide feedback for its production plan and schedule. In any of these three cases, DTs use advanced simulations and other prediction models to proactively identify and correct performance issues.

Economic impacts. According to PwC (2020), VR and AR technologies could bring net economic benefits of $1.5 trillion by 2030 thanks to their productivity uplifting capabilities.
On the one hand, AR technology can improve worker productivity, efficiency, and accuracy on the shop floor by means of digital assistance systems; on the other hand, VR environments can lessen the costs of product prototyping and testing as well as of expensive training scenarios. At the same time, they reduce the time to market for new product developments and offer a speed-up of the learning curves of the workforce. In relation to the economic impacts of DTs, GMInsights (2019) claims that their market size is expected to grow to $20 billion during the period from 2019 to 2025, driven by their potential to enhance operational efficiency, predictive maintenance, and dynamic simulations and to reduce overall design and engineering costs.

**Environmental impact.** VR and DT technologies have the potential to contribute towards more environmentally friendly design, engineering, and production operations. This is mainly based on making use of virtual environments and advanced simulations for prototyping and testing new product designs in a resource-efficient way and commissioning new production plans and schedules that have been optimised for the efficient consumption of commodities, resources, and additives, energy demand, waste accumulation, and emissions generations. Furthermore, AR technology can be seen as a path towards a paperless shop floor when it comes to the delivery of work instructions.

**Social impacts.** When it comes to occupational safety and health (Romero et al. 2018), VR technology has created safer (virtual) training environments in cases where new procedures for dangerous tasks should be learned and learning rules and regulations may not be enough to guarantee the safety of a worker in training. Moreover, on the job, AR technology can provide the worker with detailed, step-by-step breakdowns of the tasks at hand in his/her peripheral vision through a digital overlay in order to encourage follow-up of the safe work procedure and to be alert to potential dangers that could be digitally highlighted. Lastly, human DTs tracking health-related metrics of workers could allow the real-time monitoring of the workforce’s physical and cognitive workload during its work-shift and set alerts and warnings to manage proper levels of occupational effort and stress.

**Automation and robotics**

While automation refers to the process of using physical machines, software, and other technologies to perform tasks with no (or minimal) human intervention, robotics refers to the process of designing, creating, and using robots to perform a certain task or set of tasks on their own or collaboratively with humans or other robots. In both cases, these processes make use of control systems to reduce or eliminate the need for human work in the execution of a certain task. Their required degree of intervention varies based on the different levels of automation (from completely manual to fully automatic).

**Key use cases.** There is an endless number of use cases available to exemplify automation and robotics in a manufacturing setting, from autonomous robots aimed at taking over dangerous tasks that humans cannot or should not do, to collaborative robots (cobots) designed to work side by side with humans to increase their productivity. Both types of robotic system focus on allowing human workers to move into higher-value work. Some industrial use cases of robotic systems include welding, painting, assembly and disassembly, palletising, packaging and labelling, materials handling, pick and place, and load/unload as well as transport in the case of automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and drones.

**Economic impact.** Automation and robotics systems continue to improve with regard to their functionalities while at the same time, their costs decline. Their impact on shop floor productivity increases when they are applied to tasks that they perform more efficiently and to a higher and more consistent level of quality compared to human operators. This allows humans...
to transition from low-value tasks to middle- or higher-value tasks such as problem-solving, finding creative solutions, and developing new ideas (Acemoglu 2002; Autor et al. 2003; Autor 2015; Goos et al. 2014).

Environmental impact. Present and future automation and robotics systems are designed to become more energy-efficient and will continue to help minimise the need for larger, less-efficient machines and eliminate waste with fewer human errors.

Social impact. There may be a negative effect on some labour segments due to automation and robotic systems replacing low-skilled workers and automating the tasks that they previously performed. At the same time, these same systems create new, high-paying and desirable jobs. For example, autonomous, collaborative, or mobile robots are now performing menial tasks such as raw materials sorting, transporting, and stocking, while higher-skilled roles are focusing on quality-related tasks and designing the robotic systems and their applications themselves.

Cybersecurity

While advancements in AI, smart sensor systems, and cloud technologies are driving innovation in the manufacturing sector, the integration of IIoT, cloud databases, industrial robots, and wireless networks have made smart manufacturing systems more vulnerable to cyber-attacks (Wu et al. 2018). A compromised device, machine, robot, or computer system within a smart manufacturing system can lead to significant economic losses, environmental damage, and unsafe working conditions resulting in bodily injuries or even deaths (Leander et al. 2020). Therefore, cybersecurity has become a primary technology of smart manufacturing systems. Cybersecurity technologies help to prevent or mitigate the effect of cyber-attacks. Emerging cybersecurity technologies in smart manufacturing include AI for intrusion detection and handling, end-to-end encryption to prevent data being read or secretly modified, machine authentication for authorising automated human-to-machine (H2M) or machine-to-machine (M2M) communication, rule-based access control for restricting system access to only authorised users, and blockchain for security and traceability of sensitive manufacturing information (Wu et al. 2018; Leander et al. 2020).

Key use cases. Cybersecurity technologies are used to monitor smart manufacturing systems and to detect unusual activity in control systems to prevent loss of critical data such as source files or intellectual property, bodily injuries or other safety issues on the shop floor, spyware, ransomware, and negative environmental impacts (Huelsman et al. 2016; Tsoutsos et al. 2020). For example, companies implement automated audit policies to monitor and signal when a system is operating out of tolerance so that the associated risk can be avoided or mitigated (Huelsman et al. 2016).

Economic impacts. According to a report from the Center for Strategic and International Studies (CSIS) and McAfee, cyber-attacks cost the world almost $600 billion annually (Lewis 2018). The manufacturing sector, as a critical part of economic growth, is among one of the most frequently hacked industries, second only to healthcare (Wu et al. 2018), and is increasingly attracting more cyber-attacks (Huelsman et al. 2016). For example, in 2014 cyber-attackers infiltrated the network of a German steel mill and eventually took command of their industrial control system. As a result, the control system could not shut down the blast furnace, which led to significant property damage and economic loss to the company (Lee et al. 2014).

Environmental impact. The consequence of a cyber-attack can extend beyond economic loss and safety hazards to significant environmental damage. In absence of proper cybersecurity measures, hackers might be able to manipulate control systems and actuators of a smart manufacturing system to release toxic emissions into the environment. For example, in 2000, a hacker
caused a spill of 264,000 gallons of untreated sewage to flood local parks and waterways of Maroochy Shire in Australia (Sayfayn and Madnick 2017).

**Social impact.** The social impact of cybersecurity in smart manufacturing systems can be considered from the perspective of safety-related workplace issues (Romero et al. 2018; Romero et al. 2020). For example, the safety of assembly workers, machine operators, or maintenance staff who work close to autonomous robots and machines may be compromised when there is a lack of appropriate cybersecurity measures. From another viewpoint, different cybersecurity measures are impacting society positively. For example, manufacturing companies have started to provide workforce training programs related to cybersecurity, ultimately improving skills and awareness of operators and other employees.

**Blockchain**

**Blockchain** can be perceived as a chronologically ordered set of time-stamped blocks, where each block contains transaction data and is managed by a cluster of nodes in a peer-to-peer network instead of by a central authority (Nofer et al. 2017). Since chained blocks are time-stamped and the data within the blocks are stored on a peer-to-peer network, transaction records become traceable, verifiable, and nearly impossible to alter or delete illicitly. Based on these characteristics, **blockchain technology** provides a transparent, secure, and reliable mechanism to store, integrate, and communicate transactional data between stakeholders and authorised organisations without relying on a third-party trusted authority. **Blockchain technology** also enables self-executing contracts, known as smart contracts, that automatically execute when a set of previously agreed-upon terms and conditions are met.

**Key use cases.** As manufacturers move towards the usage of robotics processes automation (RPA), the potential impact of blockchain technology is becoming more prevalent. **Supply chain management (SCM)** plays a critical role in ensuring the effectiveness of a smart manufacturing system. The combination of blockchain and IIoT enables a transparent and immutable record of information, inventory, and monetary transactions that results in faster and cost-effective product delivery, better product traceability, streamlined value exchange, and enhanced coordination among the supply chain partners while maintaining respective confidentiality (Bai et al. 2019; Gaur and Gaiha 2020). Similarly, blockchain can be used for tracking manufacturing processes to quickly identify the fault source when a quality-related issue arises (Westerkamp et al. 2020). Furthermore, blockchain-based smart contracts between collaborative partners or among various devices within connected factories facilitate process automation in smart manufacturing systems (Assaqty et al. 2020).

**Economic impact.** According to Gartner, the global business value-added of blockchain technology is projected to grow more than $176 billion by 2025 and $3.1 trillion by 2030 (Lovelock et al. 2017). Blockchain technology allows manufacturers to build confident relationships with supply chain partners; as a result, they can eliminate the cost of trust, also known as “trust-tax”, and reduce verification costs (Ko et al. 2018; Zhang et al. 2019). Moreover, blockchain-based smart contracts may help manufacturers to automate value-adding processes, thereby reducing transaction costs, minimising paperwork, and accelerating turnaround time substantially (CIOL Bureau 2019).

**Environmental impact.** When integrated with IIoT, blockchain can trace product lifecycle and provide accurate and tamperproof data that can facilitate optimal end-of-life decisions and make long-term circular economy planning more effective (Kouhizadeh 2019). Accurate product usage information when retrieved from a blockchain can lead to increased adoption of remanufactured products by end customers (Tozanlı et al. 2020). However,
blockchain-based solutions in general consume more energy than centralised architectures (Sedlmeir et al. 2020).

**Social impacts.** Blockchain technology allows supply chain partners, including customers, to detect counterfeit items and unethical suppliers. It also assures that products and components are produced under safety standards, the fair use of labour, human rights, and work practices (Saberi et al. 2019).

### Smart sensors systems

**Smart sensors systems** are a collection of smart materials and products, smart wearables, industrial sensors, actuators, and PLCs (programmable logic controller). Smart materials and products have built-in decision-making capabilities on their own, and unlike IoT devices connected to a network, these do not necessarily require constant connectivity to make decisions. Industrial sensors, actuators, and PLCs are deployed to collect data, control manufacturing processes, and increasingly perform analytics and decision-making on the edge. With the help of smart sensor systems, small batches, down to batch-size-one, may be produced without compromising on the use of resources, and smart sensor systems therefore become a vital technology for future smart manufacturing systems.

**Key use cases.** Smart sensor systems are not limited to in-situ systems embedded in the smart manufacturing system but rather encompass a wide variety of applications, including wearables such as fit-bits, heart rate monitors, etc. These devices can help operators to monitor occupational health and safety. Another example of a smart sensor systems’ use case is smart materials used in building structures that change their configuration based on the season and the weather outside (Hu 2009).

**Economic impacts.** Smart sensor systems will need more investment compared to IIoT and CPS. However, their deployment will optimise the use of resources and lead to the desired results. Therefore, the requirement of quality inspections, repair, and maintenance will be eliminated, as smart sensor systems will be able to rectify the defects themselves.

**Environmental impact.** Smart sensor systems will help to optimise the input resources required and thus reducing the use of energy and reduction in the waste of raw materials. However, at times smart sensor systems consist of sensors and actuators made from rare earth minerals. These emit harmful radiation during their lifecycle, and there is no environmentally friendly method to decompose them.

**Social impact.** Smart wearable health monitoring devices can support workers independently. Therefore, these devices can be of great help to elderly workers or workers that operate in stressful or unsafe environments. Smart sensor systems can contribute to identifying and avoiding repetitive and monotonous tasks performed by humans. This will help to reduce labour injuries, for example, while lifting heavy objects in domains such as manufacturing and mining. However, it may also reduce opportunities for unskilled and semi-skilled labour. Another potentially harmful aspect is reduction in social interaction between humans.

### 5G networks

5G is the fifth-generation technology standard for broadband cellular networks and is emerging as a key enabling technology for future smart manufacturing systems. On the one hand, it supports complex autonomous, collaborative, or mobile automation and robotic systems where ultra-Reliable and Low Latency Communications (uRLLC) will enable fully automated systems and safe collaboration between humans and robots on the shop floor. On the other hand,
it enables massive Machine Type Communications (mMTC) that focus on leveraging the full potential of the Industrial Internet of Things (IIoT), where vast numbers of connected devices can communicate with each other (Burow et al. 2019). Moreover, according to Nokia (2020), 84% of manufacturing decision-makers at the global level are considering deployment of their own local, private 4G/5G networks.

**Key use cases.** 5G private cellular networks will be a fundamental part of the rise of smart factories, allowing the secure connection of all manufacturing equipment on the shop floor and enabling the deployment of autonomous mobile robots, remote machines and robot operation, manufacturing processes monitoring, predictive maintenance, and other IIoT applications.

**Economic impact.** 5G connectivity will be a catalyst for economic growth in the Fourth Industrial Revolution with an estimated $13.2 trillion of global economic value reached by 2035 (IHS 2019). Through utilising 5G network communication and data exchange capabilities, production and logistics operations at the factory floor and supply chain levels will be more easily coordinated and therefore will enhance manufacturers’ and suppliers’ productivity gains in terms of agility, flexibility, efficiency, safety, and security (Tech4i2 2019; WEF 2020).

**Environmental impact.** 5G networks will enable an energy-efficient Industrial Internet of Things by reducing the energy consumption of its connected devices. Moreover, such connected IIoT devices will track in real-time each production resource performance in terms of raw materials, energy, and water utilisation towards higher production efficiency levels (Tech4i2, 2019; WEF 2020).

**Social impact.** Smart workplaces (Autor 2015; Romero et al. 2020) powered by 5G capabilities will support workers to maximise their productivity and performance by optimising the efficiency and effectiveness of business processes, assets, and services in the emerging Internet of Things, Services, and People (IoTSP) (Tech4i2 2019; WEF 2020).

**Barriers and challenges to the adoption of smart manufacturing technologies**

The appeal for manufacturers to adopt smart manufacturing technologies is gradually changing from “nice-to-have” to a necessity to remain competitive. However, there are several challenges and barriers which prevent large-scale adoption across the board. First and foremost, smart manufacturing technologies are not a silver bullet that will automatically solve all shortcomings of a company’s processes. Smart manufacturing technologies are tools that have to be strategically selected based on the value they add and the problems they address or solve. Moreover, just implementing smart technologies without critically assessing and reimagining one’s own processes and priorities is doomed to fail (Romero et al. 2019a; Sinha et al. 2020).

Before illustrating specific barriers and challenges of individual technology clusters (see Table 16.2), we will discuss their general and typical adoption obstacles.

1. **Technology awareness.** Described as the lack of awareness and knowledge of smart manufacturing technologies, this is a major barrier for many manufacturers, especially SMEs. This directly impacts the ability to envision the value-adding use of the technology within their operations. For example, business managers and production planners are not aware of the importance, cost-benefits, and use cases of technologies such as blockchain and cybersecurity. Recently, discussion on smart manufacturing technologies and their productive use on the shop floor has somewhat been democratised – thus expanding the reach from predominantly R&D savvy organisations and research institutes to a broader audience.
To further overcome this barrier, use cases, and case studies from different industries, smart manufacturing technologies, and company sizes are necessary.

2 **Technology piloting and scaling.** The so-called prototype or pilot purgatory can be considered a major barrier to the adoption of smart manufacturing technologies. Many manufacturing companies have started testbeds and prototype projects to evaluate the adoption and value of smart manufacturing technologies. However, often these testbeds and prototypes, while successful demonstrating the principal value of smart manufacturing technologies, fail to scale and transition to regular operation. This can be attributed to several factors, including missing top-level support, lack of acceptance, unclear cost-centre/ownership, or lack of strategic and tactical planning.

3 **Technology investment.** Many of the smart manufacturing technologies require significant capital investment and other resources that represent a key barrier for many manufacturers, again SMEs in particular. Together with the at-times unclear economic benefits associated with adoption and the difficulty of calculating the ROI, this prevents many companies from investing.

4 **Technology acceptance.** This involves the leadership and workforce operators as perceiving the value of, and their attitudes towards, adoption of smart manufacturing technologies.

A different kind of sustainability challenge associated with adoption of smart manufacturing technologies is that the continuous increase in productivity and automation in developed, industrial economies through the productive use of smart manufacturing technologies may have adverse effects on developing economies. Smart manufacturing technologies reduce the amount of manual labour required in many cases and thus the incentive to outsource activities to developing economies with access to lower-cost labour.

In the following, we present a closer look at the 10 key smart manufacturing technology clusters. We structured the barriers and challenges around three general ones but have split some up to reflect more detail. For example, required resources investment is split into financial and IT resources in Table 16.2.

<table>
<thead>
<tr>
<th>Smart manufacturing technology cluster</th>
<th>Technology adoption barriers</th>
<th>Awareness</th>
<th>Piloting and scaling</th>
<th>Investment</th>
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<td>AI, ML, &amp; Advanced Simulation</td>
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<td>AR, VR, &amp; DTs</td>
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Future developments

*Industry 4.0 and digital transformation* are still in their infancy, especially considering the adoption of smart manufacturing technologies among SMEs. While there has been rapid progress and advances made across the board, the expectation is that this will accelerate even further. During the recent COVID-19 pandemic, we have already seen the potential of digital, smart manufacturing technologies in helping companies to become more resilient and agile (Wuest et al. 2020). The expectation today is that adopting smart manufacturing technologies such as AI is no longer optional but a matter of survival for manufacturers in the competitive marketplace (Taisch et al. 2020).

Necessity during the pandemic has led to an increased desire of employees to work from home. While for most office functions this “new work” is more of a cultural and organisational matter, for shop floor operators there are significant hurdles and challenges to overcome to even consider remote work. Smart manufacturing technologies such as AR, predictive maintenance, and connected systems (IIoT) are one way to facilitate machine operators, maintenance personnel, or production planners to work from home.

An additional aspect that needs to be considered, in the midst of rapid change brought forth by digital transformation with regards to the TBL perspective, is the ability to “replace” (or simplify) complex, multi-tier supply chains with new manufacturing technologies such as AM. AM can facilitate customised or even personalised production locally without needing to use a large number of sources from around the world. Additive or hybrid manufacturing furthermore has the ability to disrupt traditional industries, such as foundries (casting), that today are largely operated overseas (not in the US or EU) today. Given the emphasis on local production and more control over critical supply chains, smart manufacturing technologies not only enable the production of complex parts locally but also do so in a more environmentally friendly and socially responsible way. Local production follows the often more rigid policies and laws, and close proximity to consumers adds another layer of oversight. The abilities of smart manufacturing technologies to drive energy efficiency and automation allows for the running of production at competitive economics despite the higher wage levels. Furthermore, reduced logistics has a positive impact on the carbon footprint, and adding desirable career options to local communities has the potential to improve the social fabric further. Expectations that the introduction of AI, robotics, and automation will lead to large-scale reduction in the workforce are overstated; a shift in the tasks for human operators is more likely to happen. This shift is considered desirable, as mainly strenuous, dangerous, and repetitive tasks will be replaced with tasks more aligned with human requirements, such as creativity, problem-solving, and human ingenuity (Wuest 2020).

Another driver of future development in the manufacturing sector is the servitisation of products and industries. The ability to sensorise smart products and to collect large amounts of data during their operation enables advanced non-ownership business models that are considered as drivers of the circular economy and sharing economy. A positive side effect is that products designed for such non-ownership business models are not designed following the “planned obsolescence” paradigm but are rather built for lasting and efficient operations (Khan et al. 2018).

Overall, the manufacturing sector will continue to transform over the next decade, with smart manufacturing technologies as a driving force. With regard to the triple bottom line, smart manufacturing technologies have the potential to elevate the industrial sector to new heights, with more desirable career options and safer, more digital tasks. Furthermore, the option to locate manufacturing operations closer to consumer markets closes the loop of trade imbalance and adds tax income to the local economy for more sustainable investments. At the
same time, the application of smart manufacturing technologies allows us to optimise energy usage and operations to improve the environmental impact of manufacturing operations. Ability to automate, reduction of waste (of energy, materials, etc.), and transition to non-ownership business models provide a positive economic outlook for manufacturing that is largely based on smart manufacturing technologies.

Lastly, while the future seems bright due to the positive potential offered by smart manufacturing technologies for supporting and achieving the triple bottom line, we have to keep in mind that the three dimensions interact, overlap, and at times cause conflict. Hence, organisations face the challenge of acting holistically to pursue environmental, economic, and social bottom lines in all their operations since each dimension represents a necessary, but not sufficient, condition for achieving true sustainability.

**Conclusions and limitations**

*Smart manufacturing systems* are built on the foundation of emerging Industry 4.0 and smart manufacturing technologies. However, none of these technologies can solve the sustainable production challenge by themselves without integrating with others in a systems approach. Selected smart manufacturing technologies that are strategically aligned can create significant opportunities to develop a more sustainable industrial environment aimed at achieving the United Nations’ Sustainable Development Goal for 2030 of “Responsible Consumption and Production”. Nevertheless, even though the emergence of smart manufacturing technologies creates the opportunity to leverage greater production efficiency and other sustainability benefits, the full potential and impact of the smart manufacturing and Industry 4.0 paradigms on the TBL are still unknown. This chapter aims to offer a more comprehensive understanding of how smart technologies can contribute to the triple bottom line of manufacturing and facilitate a continuous discussion among academics and industrial leaders.

Even though this chapter is not based on a formal systematic literature review, but rather contains an explorative review, it builds on the authors’ previous work (Mittal et al. 2019), where we conducted a systematic review and an exhaustive characterisation of smart technologies. In this follow-up research work, we provide an update and a critical look at the results reflected in our previous work from a triple bottom line perspective.

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