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Svetan Ratchev *Editors*

Advances in Digital Manufacturing Systems

Technologies, Business Models, and Adoption

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Introduction

R. K. Amit, Kulwant S. Pawar, R. P. Sundarraj, and Svetan Ratchev

Ever since the industrial revolution, manufacturing has been one of the key drivers of economic growth. Despite the increasing role of services, the economic prosperity of several countries would significantly depend on the manufacturing sector that can produce *diverse* products *faster*, *cheaper*, and *better*. Figure 1 highlights the importance of manufacturing, by showing the share of manufacturing of a number of leading countries, as a percentage of the global manufacturing output.

To achieve the normative goals of faster, cheaper, and better, manufacturing requires enabling ecosystem that integrates technology and knowledge for designing, producing, distributing, and recycling products in a sustainable manner.

To keep pace with such requirements, manufacturing paradigms have significantly evolved over the centuries. Figure 2 illustrates the evolution of manufacturing paradigms, vis a vis their impacts on product quality, variety, and production architecture.

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Fig. 1 Global manufacturing share (2019). *Source* https://www.statista.com

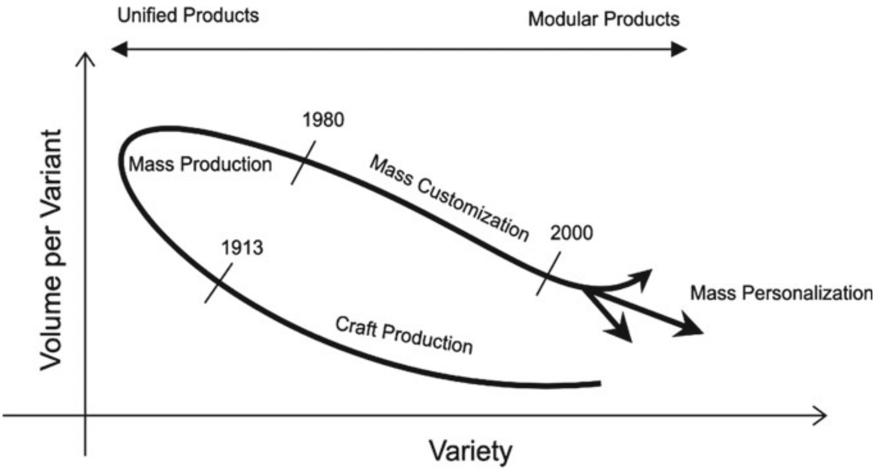

Fig. 2 Manufacturing paradigms. Adapted from Koren (2010)

In recent years, even the nature of technology has been changing. For instance, democratization of technologies has been a phenomenon that has been unfolding worldwide in the last two decades. Specifically, if were to focus on the power sector, for example, today, people can set up their own solar- or wind-based generation systems that go on to contribute to the grid, besides catering to personal power requirements. The other salient example may be witnessed in the computing industry, wherein Open Source and network technologies, coupled with an increased computing power as a manifestation of Moore's law, have enabled ordinary citizens to have access to cutting edge computing technologies, and contributing to the computing sector at large. This democratization phenomenon, in fact, has been affecting the manufacturing industry in recent times (Golightly et al., 2016). Importantly, the benefits of democratization were clearly apparent during the heights of the COVID-19 pandemic, when more and more firms sought to develop supply chains closer to 'home' (Sheffi, 2020). Focus began to shift toward 'contactless' digital technologies to minimize the virus spread. Notably, while some of the relevant core technologies have been around for some time, we are now witnessing a unique convergence of various elements, such as hardware, software, network, process standards, and manufacturing. To delineate the direction of this change, we interviewed industry experts who provided the following perspective.

The three broad shifts happening in manufacturing are in business models, in becoming environment conscious to become net-zero in carbon emission, and evolving towards a software-driven business.

The new trends within business models are a transformation to 'direct to customers' using digital channels for sales, reimagining distributor and service models, offering product-as-a-service, and new customer experience through marketplaces.

Environment conscious business are leading an energy transition towards renewables, a circular economy and a shift in mobility towards electricity. Battery and H2 powered transportation will become more mainstream and dominant. Factories, warehouses and logistics network will become autonomous using a confluence of technologies. As everything becomes software driven and connected, Real time observability will be feasible across the value chain and systems will learn to sense, process and respond becoming more autonomous and powering AI led assistants for human users.

Meaningful use cases will be discovered and deployed for Artificial Intelligence across the cloud continuum of central/edge cloud, edge and fog products, services.

Mohammed Rafee Tarafdar, Chief Technology Officer, Infosys

Since its foundation in 1886, the capability to industrialize and manufacture high volume products mainly for the automotive industry is one of the key strengths of Robert Bosch GmbH. Already in the 1990s, driven by the lean production movement in the Western World and inspired by the ideas of the Toyota Production System, Bosch started to implement the concepts of waste elimination and lead time reduction in its more than 250 plants around the globe. Later, these ideas were combined with business excellence models such as the European Foundation for Quality Management (EFQM) model.

More recently since around 2010, Bosch is deeply engaged in driving digital manufacturing systems assuming thereby a leading position in Industry 4.0 related activities. Here, Bosch has a dual role: On the one hand, Bosch is a mature user of I4.0 solution sets, on the other hand, Bosch is a leading provider of I4.0 standards to various industries. Bosch's I4.0 solution sets draw on key features such as open standards, virtual real-time representation, distributed intelligence, fast integration or flexible configuration and are thereby considered a powerful enabler for the implementation of lean principles through (a) creating transparency to foster problem solving and (b) enabling predictive and prescriptive activities strongly drawing on Artificial Intelligence thinking. The capability to quickly scale solution sets is thereby key for the rapid penetration and realization of potential improvements. Right now, I4.0 principles are applied throughout the entire product life cycle in many Bosch entities, including product development. As True North vision, Bosch aims for full-scale "Digital Twin" models of value streams.

To conclude, I4.0 enabled lean value streams can be considered a standard in the operations contexts at Bosch. Lean thinking in combination with I4.0 principles thereby enabled remarkable improvements in key performance indicators such as 30% inventory reduction or 10% output increase. Based on this foundation, Bosch will further expand its dual role through improving its own value streams and providing innovative solution sets to various other industries at the same time.

Norman Roth, Chief Technology Officer,
Electrical Drives Division, Robert Bosch GmbH

The automotive industry is at the cusp of major transformations. The popular CASE trend in the Indian context is slightly different-Connected, low cost ADAS instead of autonomous for driver assisted driving, Sustainability instead of shared, and eMaaS or electric mobility-as-a-service instead of just electrification. ADAS systems can become mandated by the government to improve road safety and avoid accidents by providing alerts for situations like driver drowsiness or a lane change.

The Ukraine war has shown the need to develop alternate fuels and reduce the crude oil dependency. CNG, LNG, EVs and hydrogen fuel cells are some options.

eMaaS is a business model change where customers pay vehicle makers on a per kilometer opex basis instead of procuring vehicles in a capex mode. Customers do not own the vehicle. It is already in operation. In order to cater to these changes, manufacturing should transform from product-centric to solution and a service centric business. That needs a huge mind set change starting from the CXO level.

Venkatesh Natarajan, Chief Digital Officer, Ashok Leyland

Manufacturing enterprises have recognized that data-driven innovation is the key to success in the wake of unprecedented market shifts brought about by the pandemic. This new world requires increasing personalization, being able to reach the long tail of users, adaptive cost management, and faster decision-making.

Cloud allows these enterprises to deploy smart analytics and business intelligence, providing a secure platform with a maintenance-free stack of data and AI services at an unmatched scale, speed, and availability.

By fostering an innovative and democratized data culture, the ability to accelerate development in an open, customer-friendly, and flexible environment becomes a reality.

The digital transformation journey focuses on three critical areas: customer experience, business outcomes, and operational efficiencies. Firstly, it helps bring the best experience to end customers. By uncovering ways to provide production visibility (that is, ‘track and trace’ of their product) and improving design and development to obtain user insights with a cloud data platform, organizations can improve their customer experience overall. Secondly, it enhances the internal business outcomes, including implementing efficiencies on the plant floor and production by lowering SCRAP rates, moving to a digitized platform, and removing ‘paper trails’ to build an integrated experience between business units, processes, and people. Thirdly, it develops operational efficiencies by implementing Artificial Intelligence/Machine Learning (AI/ML) technologies, predictive maintenance, visual inspection wherever possible, and removing manual efforts, ultimately decreasing costs, reducing SCRAP, and improving customer satisfaction.

Subram Natrajan, Head, Customer Engineering, Google India

Having worked in the World of Industrial Manufacturing for over 44 years, I've seen many technologies come and go without delivering true value to the economy, I believe Technology must have a purpose. The sceptic in me is seeing the likes of 5G being a Technology looking for an Industrial problem, my concern is technology being driven by marketing, I personally believe it critical that Technology must have a purpose and deliver real value.

If we take a step back and look at how Manufacturing processes have improved over recent years, the key benefits have usually been delivered through continuous Lean Design and Manufacturing. Lean Processes are and will continue to be essential, there is absolutely no point digitalising an inefficient process, it will simply become an inefficient digital process.

Addressing the increasingly merging Knowledge and Skills needed across sectors, historically IT specialists would spend the bulk of their time supporting the office environment, we now find those skills are more critically required on the factory floor. A secure and robust single source of the truth throughout the whole product lifecycle has brought together the need for IT and OT skills across the whole supply chain. Potential employees can no longer rely on their academic qualifications alone, they open the door to the interview room, after that attitude, enthusiasm, and the ability to self-adapt are absolutely essential, that culture of acceptance to change is now being driven throughout the Industrial community.

One of the hardest nuts to crack is supply chain, as large manufacturers are driving digitalisation hard to increase productivity, for most large manufacturers a highest % of their manufacturing is actually in the supply chain. This is where real value can be gained, by engaging with supply chains, secure machine to machine real-time connectivity throughout flexible supply chains will rapidly accelerate the introduction of customisation, increasing product value to meet customer demands, and thus productivity.

Siemens are collaborating with partner organisations such as NVIDIA to develop the Industrial Metaverse integrating Photorealistic Simulation with Industrially proven physics based models.

So where is the value of the Industrial Metaverse you may ask, well the utopia for Product Development and Manufacturing is to completely eliminate prototyping, in other words the first product you produce is your final production unit, the first time you switch your real manufacturing line on, it works first time without any hitches. This is where immersing product designers and production engineers into a common Industrial Photo Realistic environment will bring the factory to their fingertips without any fear of trying new things and making mistakes. Secondly, once the Industrial Metaverse is developed and proven, further process optimisation or product design features will be incorporated and proven at an accelerated rate. Furthermore, AI will be able to autonomously adapt the process to increase productivity and quality before pressing the button to seamlessly migrate changes to the Real World. All of this will allow the leaders in this space to bring products to the market quicker than their competitors with the highest quality.

Professor Alan Norbury, Chief Technologist, Siemens plc Digital Industries

If we look back 10 years, the amount of digitization at shop floor was quite minimal. Cyber Physical Systems was not a term that many people could relate to in 2012. Today things have really changed. Digital technologies are being used in manufacturing all over. Industry 4.0 has become a commonly used term and technologies like IOT, AI and ML, Robotics, 3D Printing and Cloud Computing are changing the Manufacturing at a pace never seen before.

As I see over next 10 years, role of digital in manufacturing will be huge, I see 3 distinct reasons for that:

(a) Evolution and maturity of Digital technologies
(b) Evolution of a digital savvy workforce
(c) Shortage of manpower

From a technology standpoint, as I see DARQ—Distributed Ledger Technologies (Technology behind Blockchain), Artificial Intelligence (AI), Extended Reality (XR) and Quantum Computing—and technologies like Metaverse, Wearables coupled with widespread adoption of 5 G (or 6 G, 7 G/8 G as the case may be) and Inexpensive data storage with increased computing power will completely change the look of manufacturing. To overcome shortage of manpower, Autonomous robots; Autonomous warehouse systems; Autonomous vehicles; Drones will become mainstream in manufacturing and these will leverage data using sensors (be it light sensors, audio sensors, temperature and other sensors) and using AI/ML algorithms and Cloud computing analyze real-time situations, adapt, and react without human intervention.

Digital twin—creating virtual replica of any assembly line, factory or particular equipment, or even supply chain—will be used extensively by organizations for optimizing production lines and layouts, quality and operational performance as simulating real world environment ahead of physical deployments for enhancing cost effectiveness and efficiency. I feel companies will be able to use Metaverse for Digital twins in next few years.

Supply chain, logistics and inventory management which is one if the major pain points of many organizations and this area will also see much more digitization using technologies like IOT, RPA, AI/ML to eliminate the need for human interference and increase visibility and reduce process errors and improve efficiency. Usage of technologies like Augmented and Virtual Reality (AR/VR) in manufacturing would become very prevalent with organizations using AR/VR/Metaverse for product design, helping workforce in warehouses, plant Maintenance, training etc. Last but not the least, manufacturing organizations would be focusing a lot on 2 other aspects where digital technology will play a big role—Sustainability and Cybersecurity.

Vijay Sethi, Digital Transformation and Sustainability Evangelist

In effect, this brings us to 'digital manufacturing,' it is an emerging ecosystem that encompasses an integrated array of technologies, processes, and models. It may also be termed as a synergistic culmination of different interdisciplinary areas, ranging from business strategy to mathematical and engineering models that provide the necessary theoretical and technological underpinnings.

A key premise of our book is that the scalability of new technologies requires the entire ecosystem to be economically viable; hence, after a broad overview of manufacturing, the initial part of the book focuses on technological details underpinning the advanced manufacturing systems (AMSs), including, for example, cyber-physical systems and digital twins.

Business models indicate how an organization would deliver value to its customers, and how it can make a customer perceive that value. A common business model paradigm is that of servitization; for instance, with companies, such as Rolls Royce, Airbus, and ABB delivering advanced services (Baines et al., 2017). Servitization essentially offers multiple advantages, including improved response to customer needs, increased barriers for competition, and new revenue streams that could potentially increase revenue and profit growth (Baines & Shi, 2015). Given the focus of our book, next, we explore the different ways in which advanced manufacturing systems can actually be implemented in businesses and the industry at large. Also, contained are how different tradeoffs can actually be evaluated mathematically (e.g., tradeoff arising in the level of servitization, in designing platforms, and in detailed shop-floor layout).

Given the various technologies and stakeholders involved, various contextual factors would determine the likelihood of an AMS adoption. For example, the cost, quality, and reliability offered by a particular AMS stakeholder would inform us whether they could fulfill the service levels that have been agreed to by the parties involved. Besides, such internal factors, external environmental issues, like human-resource and infrastructural (e.g., network) capabilities, along with legal and cultural aspects would also come into play. Hence, generally, the adoption of a technology is not a binary event. Rather, it is a process in terms of the number of adopters within an organization, industry, or country. Thus, the last part of the book brings out case-studies, cross-country comparisons, and a framework to evaluate readiness for advanced manufacturing.

We called for papers from leading experts around the world. Thus, we believe that this book includes a good mix of academics with practitioners to capture theory as well as practice. Notably, the contributions reflect current research and developments, as well as future trends and thinking. An overview of these contributions is given below.

Chapter 2: History and Future of Manufacturing

Technological innovations have consistently stimulated the industrial revolution, which provided various challenges and opportunities in the manufacturing sector. This chapter discerns the significant historical waves that helped in tracing the transformations seen in manufacturing. With this as a foundation, this chapter provides an understanding of the current trends and the possible future manufacturing scenarios with four primary areas of industrial systems.

Chapter 3: Development of Technological Systems

This chapter covers the development of digital technologies from Industry 3.0 to the Cyber-Physical Production System (CPPS), with a special focus on the various components of CPPS, its key enabling factors, and the role of humans in CPSS. This chapter also discusses the barriers, challenges, best practices, and the scope for future development in implementing smart manufacturing.

Chapter 4: Digital Manufacturing

Motivated by the need for digitalization, this chapter focuses on three key technologies underpinning digital manufacturing: Digital Twins, Additive Manufacturing, and the Internet of Things. The functionality of each technology and its combination are presented in detail. Additionally, the potential gap between R&D and implementation has also been identified.

Chapter 5: Business Models for Additive Manufacturing: A Consulting Services Perspective

Consulting firms are helping companies today in their endeavors for digital transformation, with the Implementation of Additive Manufacturing (AM), serving as one of the cornerstones in this process. This chapter provides an overview of an emerging business model for AM and illustrates the perspective of the consulting service, using the business model canvas framework. It also discusses the current AM Implementation challenges, as well the scope for future direction for consulting services.

Chapter 6: Servitization in the digital era

Holistically speaking, this chapter provides a strategic servitization framework, focusing on the transformation of the business model into an operating model. Specifically, it encompasses a break-even analysis for estimating the profitability in servitization with a real example. Additionally, it discusses the implications for organizational design, and technological requirements, and presents four practical recommendations for servitization.

Chapter 7: Manufacturer's Decisions for Sharing Products: Challenges, Opportunities, and Optimal Strategic Plan

Manufacturers' product-sharing platform policy must be competitive to stand with third-party product-sharing businesses. The policy needs to have an optimal decision for entering the product-sharing market. In line with this point, this chapter provides an analytical framework with a basic mathematical formulation to deal with various decision-making issues when a manufacturer establishes its product-sharing platform. Herein, a case study is solved, and the strategic implications and decisions arising therefrom are discussed.

Chapter 8: A Study on Mathematical Models for Transforming the Job-Shop Layout into Flow-Shop Layout

This chapter proposes a Mixed Integer Linear programming (MILP) model for solving the problem of transforming a job-shop layout into a flow shop layout; it has mainly been done through the introduction of additional machines. This transformation helps in automating the flowline, which is one of the cornerstones of digital manufacturing. This chapter also compares the developed MILP model with the existing model for the special case.

Chapter 9: Cross Country Comparative Analysis of Digital Manufacturing Systems

This chapter provides a cross-country analysis of six leading manufacturing countries' digital manufacturing strategies. An inductive digital-orientation framework is used for the analysis. The future manufacturing characteristics of these countries are compared and contrasted with one another. Moreover, this chapter also describes the important implementation of digital manufacturing in these countries with suggestions for future direction.

Chapter 10: Toward a Standard Framework for Organizational Readiness for Technology Adoption

This chapter presents the common patterns of readiness assessment from various industries through a systematic literature review. A General Readiness Assessment Framework for Technology Adoption (GRAFTA) has been constructed based on the theory of everything and multi-criteria decision-making (MCDM) techniques.

Chapter 11: Case studies of implementation approach to assessing and evaluating digitalization readiness

This chapter reveals both the benefits and challenges of manufacturing firms in digital implementation, by using multiple semi-structured case-study interviews on ten identified themes. The authors herein have created a digitalization-readiness indicator based on the understanding from case-studies and literature review. This chapter also highlights the impact of the COVID-19 pandemic on the digitalization of manufacturing firms today.

Chapter 12: Smart Factories and Indian MSME

This chapter addresses the challenges faced by the Micro, Small, and Medium Enterprises (MSME) in implementing smart manufacturing systems. Hereby, ten challenges are identified based on literature review and expert discussions. A ranking of these challenges and the inter-relationships among them are brought out by using the Fuzzy-ISM (Fuzzy Interpretive structural modeling) framework on data collected from experts.

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History and Future of Manufacturing

C. Sassanelli, M. Taisch, and S. Terzi

1 The Evolution of Manufacturing

Those over 30 remember well the crises faced in the last decade due to the great recession. It is still alive in the minds often in the skin of many of our fellow citizens when in a short time the financial crisis—the result of a development model dominated by a strong dose of greed by a few—dramatically transformed into a real industrial crisis, with multiple factories closed and innumerable jobs lost. The crisis-hit countries, across sectors and skills leaving scars that are still visible today.

The memory of the crises and the complications that followed remain very vivid to the reader, at least to those who remember and were affected, it is due to this traumatic event that today—in 2020—world manufacturing is alive, and still scuttling to rebound. Many of the phenomena (trends) that manufacturing companies are fighting to tackle now, actually began during this period, or at least were impacted at some level due to the economic downturn. Thus, it is necessary for us today to observe how—even after only a decade—the collective memory tends to decrease (just think of a typical university student of today, for whom the "crisis" is little more than an event they have heard about). So, it's always good to remember the past. Like all crises, difficult times can also bring about opportunities; if accepted, they give a sense of clarity to our actions, both individually and collectively. For our country, one point of clarity that we found from the crisis was to understand the enormous importance of the industrial manufacturing sector. Industrial "*manufacere*" is a fundamental part of the collective well-being for global economic value.

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Over 70% of world trade is directly linked to industrial activities, and over 60% of job positions are linked to the manufacturing sector. Data collected by the World Bank showed that the manufacturing sector alone contributed to the GDP growth by about 20–40% for global industrial powers (WMF, 2019).

Therefore, the great recession of 2008 (and subsequent years), immediately impacted manufacturing companies with a decline in performance and profitability, resulting—unfortunately—in the failure of many companies that had been prosperous for decades. This weakening of the sector was subsequently offset by a growing desire to innovate on the part of companies that survived to better compete in a new economic environment. In recent years, one could see how companies that were able to survive the crisis have actually aligned and adapted to change, increasing their competitive capacity in the European and global context. The archetype of "excellent medium-sized enterprises" (Serio, 2017) has gradually consolidated on the national scene. A recurring recipe of entrepreneurial drive, lean organizational models, digital transformation, along with a propensity toward foreign markets has allowed numerous companies to optimize their offerings and their penetration in international markets. Based on the latest statistical data (WMF, 2019) and taking alarmism with moderation, the current situation seems to enjoy an increase in confidence in companies (+0.6% in the last year), which in turn, has resulted in industrial production fluctuating slightly above zero, even if the prospects for the last half of 2019 does show a slowdown due to substantial contraction of German exports—with which, we share entire parts of the global industrial supply chains; add to that the ongoing tariff war between the US and China. In this ever-evolving scenario, it has been challenging for the manufacturing sector—with difficulty and not without a bit of collective suffering—to regain their global space, recovering points of productivity and shares of market, almost returning to pre-crisis levels. The manufacturing industry today represents—as in the past—a conspicuous part of the collective good and responds more quickly than other sectors of the economy at the national level. Without letting ourselves be taken by easy enthusiasm or—worse—dramatic anxieties of the daily trend of the global economy, we cannot refrain from supporting—loudly—the thesis that Italy is a manufacturing country for which to think about the future of manufacturing corresponds almost tautologically to thinking about the future of Italy itself. To imagine the future of manufacturing, it is thereby necessary to start from the understanding of the phenomena that currently impact (and will increasingly have an impact in the future) the global industry. These phenomena—many of which originated years ago—are usually identified as paradigmatic trends in the manufacturing sector ("manufacturing trend") (Garetti & Taisch, 2012).

2 Global Trends in Manufacturing

The world is experiencing an epochal period, with radical changes, global in scope and ever evolving, which impacts humankind and all economic actors, be they nations or companies. To understand what the future of the industry may be, we must learn to interpret and benefit from these "mega-trends" (Garetti & Taisch, 2012), including:

- Population growth, increasing urbanization, and displacement of entire masses in search of a better life have all been changing the structure of large portions of the planet. Above all, emerging countries have been the ones that have witnessed paradigm changes. China, India, and large portions of Africa, along with several South American countries, have witnessed a significant surge in populations, providing a younger workforce that is eager to free themselves from poverty and which promises to be an untapped consumer market. Urbanization redesigns are thereby necessary in order to contribute to the creation of sophisticated consumption (i.e., houses, cars, food, leisure, etc.). Countries that witnessed the first industrialization process grew old not only in words but also in deeds and infrastructure. Life expectancy, which has increased globally, is expected to cover almost 33% of the populous being 65 years of age or older by 2050. This phenomenon would characterize many countries and in particular developed countries. For example, according to studies developed by the United Nations' Industrial Development Organization, 50% of the European population would be over 50 years old. This would radically change society, lifestyles, needs, and consumption. For example, the demand for food resources is expected to increase by 35% by 2030.
- The indiscriminate exploitation of finite natural resources (e.g., fossil fuels, drinking water, rare earths, ferrous materials, etc.) predicated by the myopia of a model of cynical consumerism could generate dangerous social shortages, which in turn, would increase disparities amongst populations, fermenting social instability and creating unpredictable fluctuations in the cost of raw materials (The Ellen MacArthur Foundation, 2013). According to the United Nations' International Resource Panel (International Resource Panel, 2017), a dramatic future scenario is anticipated, whereby there would be a three-fold increase in terms of primary resource extraction, reaching a value of about 140 billion USD by 2050. Importantly, one has to bear in mind that greater the global consumption, the higher would be the demand for resources, cascading onto higher price rise across all commodities.
- Pollution produced by uncontrolled human activities has been showing its impact on climate change, creating thereby significant human and financial costs (European Commission, 2007, 2017a). Global CO_2 emissions are expected to rise by roughly 50% over the coming decades. Without being carried away by apocalyptic scenarios, one cannot fail to note how events, induced by unscrupulous environmental policies have become more relevant now, threatening thereby a possible blockage of entire economic cycles.

These phenomena, combined with a profound revision of the economic chessboard, whose control center has been increasingly moving from the West "to the East", along with other emerging countries, now these countries are eager to leverage their economic power, for obvious demographic reasons, to direct world development. With an increase in global wealth, even if poorly distributed, there has been a progressive satisfaction of basic needs, which have given way to more complex needs. In advanced, as well as emerging economies, the profiles of demand and consumption have now structurally changed, forcing thereby an adaptation of the forms of supply and production as outlined in the "market trends" presented below:

- Modern consumer demands have shifted from standardized mass-produced products to personalized and tailor-made products, capable of satisfying an intrinsic need at an individual level. This shift in consumer demands has become visible across different sectors of the industry, particularly in the automotive market, which offers multiple variants, as well as to manufacturers in the world of electronics and/or fashion (Piller & Kumar, 2006; Piller & Stotko, 2002).
- The market (both mass and target with high economic power) is constantly looking for novelty. Obsolescence is not just a technological issue, but rather a complex phenomenon, in which needs for self-esteem, presumed and real technical modernization are combined. Continuous innovation is an essential condition for maintaining and strengthening the competitive position of a company (Porter & Heppelmann, 2014).
- Possession is no longer the only possible formula for the use of an asset (Tukker, 2004). Consumption models are largely being based on pay-per-use, rental, leasing, and other usufruct-based models, which have appeared across sectors throughout the world. This phenomenon of growing servitization, simultaneously linked to a change in personal consumption, has been creating new propositions that are radically different from behaviors that were previously seen. It has been proven today, that the new urbanized generations have a lower propensity to acquire, and a greater focus on sharing, which effectively orients them toward "service" consumption profiles. Even in the more traditional sectors, servitization does transform spot revenues into recurring ones. For instance, from the machine tool in hourly leasing, to the photocopier paid for by number of photocopies, to "Software as a Service."
- The exploitation caused by a hyper-consumerist model has been a well-known topic, not only in the existent traditional industrialized countries, but also in new and emerging economies. Except that there are no simple solutions. Thus, it is necessary to observe how demand trends that favor sustainable and greener ways of producing and marketing are consolidating to meet new expectations and consumer behaviors. Importantly, both consumers and producers today, demand that products and services are more ecological, with less pollution. There has been more consideration for recycling and reuse; for example, ecological cars, organic food, sustainable fashion, and even green manufacturing, among others. Sustainable Development (WCED, 1987), coupled with green and Circular Economy (The Ellen MacArthur Foundation, 2013), Fair Trade, Social Responsibility are some of the common models today, that companies are adopting, both for marketing reasons and for social creed.

In parallel to these global and market trends, it is necessary to point out the enormous paradigm of continuous, fast, and unstoppable technological evolution.

After hundreds of years of evolutionary rhythms close to stagnation, in the last century, technological development has reached speeds never recorded in the history of humanity. This is true on all fronts, from production techniques to materials, from biosciences to information technology, all of which have drastically changed our lives.

3 The Historical Waves of Manufacturing

Technological innovation is considered one of the main headwaters of modern civilization and economic development (Nelson, 2002). The integration between inventions and innovations, i.e., between scientific progress and the applications of technological inventions to economic activity, represents a strategic way for humanity to cope with the population outburst (Coccia, 2014), along with the inevitable intertwined depletion of resources (Rosa et al., 2020). Indeed, the resources being limited, returns from lands and mines are naturally diverging to a slowdown, with the risk in the future to bring to the arrest and finally to the decline of productive growth (European Commission, 2011, 2020).

Since the beginning of the modern industrial development, at the half of the eighteenth century, periods of around half a century followed one another, each one marked by at least one great innovation (Xu et al., 2018). Four main industrial revolutions contributed to lead the entire world to an ever-growing level of wellness, thrust by improvements of production systems' effectiveness, efficiency, and productivity. In fact, each of them has been characterized in terms of energy source introduced, main technical achievement, developed industries, transport means, and challenges (Prisecaru, 2016). The first half of the eighteenth century saw first industrial revolution that took place in England, based on the use of coal as the main source of energy. Coal enabled the introduction of the steam engine, and thus, began the process of mechanization of production. This revolution triggered a switch from a feudal farming-based society to a capitalist industry-based one, changing in the process, the textile and steel industrial landscape in terms of employment, value of output, and capital invested (Xu et al., 2018). At the same time, it also contributed to trigger and gradually lighten employees' activities and efforts, converging the post-industrial society into the so-called service economy (Stahel & Reday-Mulvey, 1981). The Second Industrial Revolution was conventionally made starting from 1870 with the introduction of electricity and chemicals. Later, in 1900, it had an even stronger impact with the advent of the internal combustion engine, and the consequent increase of the use of oil as a new energy source. This resulted in rapid industrialization, using both oil and electricity as key energy sources (which appeared alongside coal) to power mass production. Notably, the automobile industry was one of the most dynamic in this context.

Subsequently, in the second half of the twentieth century, the Third Industrial Revolution took place starting from developed countries in the west. The birth of electronic systems and information technology (IT) brought about a series of transformation processes of the productive structure, and more generally, the socio-economic fabric, based on automation of production. The Third Revolution was characterized by a strong push toward technological innovation (closely linked to the birth of computers, robots, the first spacecraft, and satellites) and consequent economic development. Starting from the 1980s and 1990s, it also involved the rest of the world, in particular China and India.

It also has to be said that from the innovations coming with the Third Industrial Revolution (mainly programmable logical controllers), the digital age broke out. Indeed, even if initially automation was a big improvement (since making things involved screwing or welding lots of parts together), that was only the premise to the switch toward today's Fourth Industrial Revolution bringing with itself technologies, such as additive manufacturing (with three-dimensional (3D) printing) directly connected to computer-generated product design. Notably today, both in the production and organizational fields, digital technologies are progressively affecting the epochal turning point toward Industry 4.0.

The start date of the Fourth Industrial Revolution is still in progress and only afterward will it be possible to indicate which is the founding act. The term Industry 4.0 (I4.0) was first introduced in 2011 by Kagermann et al. (2011), and has been linked to some of the recent developments in production processes and their automation. I4.0 is a very broad domain that includes production processes, efficiency, data management, relationship with consumers, and competitiveness, among others (Piccarozzi et al., 2018). Indeed, the expression I4.0 indicates a phenomenon of global significance that has imposed itself in the sign of extensive and massive digitization. In fact, digitization has been affecting all the sectors of the economy, starting right from production to consumption, from transportation to telecommunications, including all areas of 'services'. The following technologies have primarily been responsible for serving as building blocks of I4.0; they include Big Data and Analytics, autonomous robots and vehicles, additive manufacturing and simulation, augmented and virtual reality, horizontal/vertical system integration, the Internet of Things, Cloud computing, fog, edge technologies, along with Blockchain and cyber-security (Rüßmann et al., 2015). Today, I4.0 represents a very important industrial paradigm related to the adoption of all these digital technologies (Ing et al., 2019) that have been playing a strategic role in the transition and key development of more intelligent manufacturing processes (including devices, machines, modules, and products). Shrinking the perspective on IT and straddling the last two industrial revolutions, three IT waves have been detected by Porter and Heppelmann (2014). They gradually transformed competition and strategy, reshaping the value chains and turning products from mechanical to digital.

If we were to look at the evolution of industrial revolution in detail, we note that the first wave (i.e., 1960s to 1970s) was linked to automation of individual operations (e.g., order processing and CAD) (Porter & Millar, 1985), which led to process standardization and productivity enhancement, driven by an increasing availability of data. The second wave (i.e., 1980s through 1990s) was directly connected to the advent of the internet, enabling organizations to globally coordinate and integrate activities with external suppliers and customers. Nevertheless, these two waves did not directly impact the products, being limited to mainly shape the value chains behind them. In the third and, so far, last wave, IT has been embedded and integrated onto the product. New components (e.g., sensors and processors), paired with a cloud, where product lifecycle data are gathered, enabling thereby new functionalities and performances. Again, the introduction of these products in the market has gone on to impact the value chain. They have begun to transform several dimensions and functions (e.g., product design, marketing, manufacturing, and after-sale service) of organizations, and have created a need for new activities, such as product data analytics and security. Lorenz et al. (2016) highlighted that the most required roles in the future would be related to data management, data security, software development, programming, data science, and analytics. Therefore, new IT waves would be triggered in the following years, ushering in greater innovation, productivity gains, and economic growth. Nevertheless, to fully exploit the benefits of I4.0, seven major categories of challenges (including data management and integration, knowledge-driven, process, security, capital, workforce, and education) need to be coped with (Ing et al., 2019).

Today we are experiencing the Fourth Industrial Revolution, dominated by electronics, air transport, and atomic energy. With this revolution, there is again an acceleration and diffusion of the innovation process, flanked by a growing scientific progress and applications of inventions to economic activity. In many developed countries, the growth of employment in services, for instance, has been accompanied by a decline, first relative and then also absolute, of employment in industry. This led to talk of servitization of manufacturing (Neely, 2008; Paschou et al., 2020; Vandermerwe & Rada, 1988) that allowed organizations in focusing on higher-margin services, integrated to products, creating superior competitive advantage (Bigdeli, 2016; Breidbach & Maglio, 2016). Many manufacturing companies today, have been facing commoditization of offering, and intense competition, which has been attracted by the possibility to differentiate themselves from competitors while introducing product-related services in their traditional portfolio (Ostrom et al., 2015). Notably, this change in their offering has been due to the modification of consumer behaviors, along with their increasing interest in companies' services (Baines et al., 2013; Rexfelt & Hiort af Ornäs, 2009).

As a result, manufacturers are changing their business models by delivering Product-Service System (PSS) by incorporating service-related activities in their value proposition (Goedkoop et al., 1999). Nowadays, this shift cannot be analyzed without considering the role of technological innovation in product, process, and service (Ardolino et al., 2017). New technologies, and in particular, the digitalization with services have changed the traditional paradigms characterizing services, such as perishability and inseparability (Holtbrügge et al., 2007). Furthermore, the introduction of technology in the product and service offering, while opening new business opportunities and creating new forms of customer integration, demands not only new capabilities and competencies (Lerch & Gotsch, 2015), but also new methods and tools to adequately integrate them since the development phase of their lifecycle (Pezzotta et al., 2018; Sassanelli et al., 2018, 2019a).