

Louvain School of Management

How Industry 4.0 drives sustainability in supply chains:

Analysis of the automotive industry

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Foreword

First of all, I would like to personally thank Professor Constantin Blome for his time and assistance in writing this paper.

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Abstract :

The ecological crisis faced by our society and the resulting concerns, such as global warming, have led to the emergence of the concept of sustainability. To overcome these concerns, we must urgently reconsider our behavior and the way we use our resources. At the same time, the new digital technologies that are being implemented in industry, leading to Industry 4.0, are reshaping the whole activity of companies, especially in their supply chain. The opportunities of these new technologies on the industrial activity are widely studied but the consideration of these applications to promote sustainability is very recent. This paper gathers the new studies that focus on the sustainable potential of Industry 4.0 within supply chains. The research paper focuses on the automotive industry, arguably considered as the largest and most dominant manufacturing sector in the world. Our analysis shows that new Industry 4.0 technologies can support the sustainability of automotive supply chains from an economic, social, and environmental perspective. By implementing it in their operations and by altering their internal processes to accommodate it, automotive companies can optimize resource and energy consumption, make significant cost savings, and improve traceability and transparency throughout the value chain. This paper also highlights the diverse risks and challenges associated with Industry 4.0 such as cybercrime, energy consumption, unemployment risk, expanded requirements for new skills, and investment necessities. We suggest solutions and leverage points to assist companies in overcoming these issues.

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1. Introduction

The most prominent challenge society is currently experiencing is environmental degradation and we are confronted with major complexities and challenges unprecedented in human history. Our way of life, industrialization, consumption habits, population growth and urbanization processes have generated and are still generating resource scarcity, pollution, biodiversity loss and global warming. All these issues bring themselves other major concerns such as the sustainability of our economic system, growing inequalities and social crisis and ultimately, a risk for our survival. Throughout most of human history, this environmental degradation has usually been so slow that it was hardly noticeable, but nowadays, these signals are so prominent that it becomes the priority matter for our generation. Effective and immediate solutions are needed to hope for a shift and not to find ourselves in an irreversible situation. In this context, the concept of sustainable development has recently emerged to address this issue and this new paradigm aims to limit these outcomes and mitigate their effects in the long term.

To address these challenges, society as a whole must acknowledge the critical nature of the situation, including people, government authorities and, most especially, businesses. The industry has been constantly evolving over time and its activity has unfortunately been very often harmful for the environment. Today, with the emergence of new digital technologies and their constant development, the industrial sector is bound to change drastically. The emergence of these new technologies has led to the evolution of the industry and the emergence of the concept of Industry 4.0. In addition to dealing with this drastic change in the way they produce and conduct their business, companies must now consider sustainable development and implement it in their strategy. Indeed, the increasing pressure from different stakeholders and authorities, consumers and employees' expectations, and the current macro-economic trends are now requiring companies to adopt a sustainable approach to carry on their activities in the long term.

A company's supply chain is the network of all the people, organizations, resources, and activities that are involved in the production and sale of a service or product. Considering the multiplicity of activities and resources that are involved, supply chains are usually the key element in the consumption of raw materials and energy. And therefore, it is also the element that generates the most emissions and potential negative effects on the environment. If sustainable development is to be further considered by companies, sustainable supply chain management is a crucial element to consider.

Over time, technology has often been recognized as a potential lever to address environmental and resource scarcity issues. As it is becoming more and more involved in the supply chain, the purpose of this work is to find out if the new technologies of Industry 4.0 can promote a sustainable approach within the supply chain. In order to address and explore the relationship between these new technologies and sustainable development, the automotive industry has been selected as a research sector. This industry is one of the most important in terms of size, production, and turnover. The dimension and complexity of its supply chain are efficient characteristics to address the research topic. Additionally, automotive companies have always been leaders when it comes to innovation and development

To figure out if Industry 4.0 could enhance sustainability within the supply chain, a literature review was first conducted to understand the evolution of the concepts of Industry 4.0 and sustainability. Then, this literature review aimed to identify the sustainable benefits that different technologies (Blockchain, RFID, Big Data Analytics, AI, additive manufacturing, AR/VR, and advanced robotics) could bring to the supply chain activities of automotive companies. It was especially challenging to gather the main ideas from the different literatures since, although there is a lot of research on the topic, the approach and the sustainable paradigm is very recent. Finally, following the main ideas found in the current scientific research, a critical and personal analysis will aim to answer the research question, develop an action plan for automotive companies and outline the potential sustainable benefits for all supply chain activities to finally identify potential risks and challenges.

2. Sustainability concept and evolution

2.1. Traditional wisdom

Even before the term sustainability was introduced and evolved over time, the first principles and the associated ideology could have already been identified in most indigenous beliefs and traditions (Mebratu, 1998). Before the dominant religions of the East and West, most communities, especially in the African tradition, already considered man as a beneficiary, a user of his environment. Historically, we have been forced to use nature to satisfy our various human needs, but this mindset has led these different communities to adapt their behavior to live in harmony with their environment and therefore to respect it. Although these spiritual insights had their origins in different contexts and geographical situations, the importance of living in harmony with nature was nevertheless the central element of these communities. Even if it would be unrealistic and probably very optimistic to seek the solutions to our current

challenges in its traditional teachings due to their significant dissimilarity with the current world, we can consider its first beliefs and traditions as « *one of the fundamental tenets of the concept of sustainability* » (Mebratu, 1998, p.498).

Thomas Robert Malthus (1766-1834), a famous 18th century British economist and philosopher, is considered as the first economist to consider and discuss the limits of growth due to resource scarcity. The Malthusian theory, also referred as the theory of "*environmental limits*" is considered by some experts to be the precursor of the concept of sustainable development (Mebratu, 1998, p.498). In 1798, Malthus published his work, "*An Essay on the Principle of Population*", in which his theory of population was introduced. This theory of population implies that the population will tend to grow faster than the resources available to satisfy its needs. This concept, although it differs from the modern debate on sustainable development considering certain phenomena, such as global warming, that Malthus could not anticipate at the time (Brander, 2007), still makes sense today in an overpopulated world where resources are exploited more than ever before. Based on this Malthusian analysis, sustainable development leads us to question the choices that can be made and the choices that must be made (Peura, 2012) to improve, or at least maintain, our standards of living in the future to avoid a major crisis that the economist already suggested two centuries ago.

If so far, we have outlined the main theories and the preliminary limits regarding the sustainability of human activity with its environment, the imperative of adapting our economic development has not yet strongly emerged. It is only at the end of the 20th century that the first alarmist studies on the impact of mankind and on a possible environmental crisis appeared. The first publication to receive credit as the first official study on environmental deterioration will be attributed to the Club of Rome, which with its report "*The Limits to Growth*" published in 1972, brought real public attention to this issue, introducing for the first time an ecological approach to industrialization. The Club of Rome was a think tank of individuals from various nationalities, and was composed of academics, diplomats, and members of industry. Their research advocated the idea that economic growth could not be sustained indefinitely due to the limited availability of resources over time and that industrial society as considered by that time would exceed its ecological limits in the coming decades. The authors warned that « *If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years* » (Meadows, 1972, p.23).

2.2. The Brundtland Commission

As strange as it may sound, the concept and term "sustainability" as we conceive it today is only about 30 years old. The concept of sustainable development first appeared in the Brundtland Report, also known as "Our Common Future", written and published in 1987 by the World Commission on Environment and Development (WCED), a commission that was initiated by the United Nations in 1982. The Commission included 21 members from different nationalities around the globe to form an independent group of experts and was chaired by Gro Harlem Brundtland, Prime Minister of Norway at the time. The Commission's mission was to formulate a « *global agenda for change* » and to « *propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond* » (World Commission on Environment Development, 1987, p.11). The Commission's "Our Common Future" report is still the most cited document in the literature on sustainable development (Quental, Lourenço, & Nunes da Silva, 2010). To address the challenge of improving human well-being while reconciling limited natural resources with the dangers of environmental degradation, the Brundtland Commission proposed sustainable development as a possible solution, which they defined for the first time:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- *the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and*
- *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*

(World Commission on Environment and Development, 1987, p.54)

For the very first time, a concept was introduced to associate the development of society with the need to manage its resources in the best possible way. This report gave it the wide recognition it still enjoys today (Kuhlman & Farrington, 2010) and is still the most widely used definition today (Du Pisani, 2006). This is effectively an important turning point for the concept of sustainable development as the awareness of the non-infinite nature of our world seems to be emerging in the international opinion.

The "Our Common Future" report, even if it approaches the ecological question, is nevertheless mainly focused on human needs and interests, and addresses primarily the notion

of global equity. For doing so, it discusses the necessity of redistributing wealth to poorer nations to encourage their growth, with the ultimate objective of meeting the needs of the entire population (Du Pisani, 2006). In fact, the Commission's goal is to satisfy current needs, but with the ambition of not compromising the ability of our future generations (Theis & Tomkin, 2012). According to the authors of the Bruntland report, economic growth is therefore essential, especially in developing countries, but we need to change the way we support this growth by developing "*sustainable development*" which should be integrated into national legislation and policies. (World Commission on Environment Development, 1987). They then recognize the damaging environmental impact that economic growth frequently brings. This environmental aspect was especially reinforced by the many ecological disasters that occurred when the report was published (Du Pisani, 2006). The Bruntland Report therefore defends the idea of a necessary economic efficiency, ecological protection and an essential well-being for all generations and proposes, to support its views, numerous solutions concerning biodiversity, energy choice, agriculture, and many other subjects.

Finally, in reading the "Our Common Future" report, we notice that the definition of sustainable development and the principles attached to it seem to be defined in a rather wide manner. Although it constitutes a major political turning point, it should not constitute the end of the development of the concept (Mebratu, 1998). Nevertheless, the Bruntland report represents « *a fundamental act for the introduction of the concept of sustainability in the legislative frameworks. Indeed, starting from this document a continuous process has been set up for the consideration of the sustainability as fundamental paradigm of action* » (Mondini, 2019, p.129).

2.3. The Three-Pillar conception

Following the emergence of the term sustainable development through the Brundtland Commission, the concept of sustainable development has evolved, while relying on the main ideas defended at the time. The report « *expressed the belief that social equity, economic growth and environmental maintenance are simultaneously possible, thus highlighting the three fundamental components of sustainable development, the environment, the economy, and society* » (Du Pisani, 2006, p.92). As a result, sustainability conception is today represented as the integration of three distinct dimensions: an economic dimension, a social dimension and an environmental dimension that must coexist in an integrated perspective (**Figure 1**).

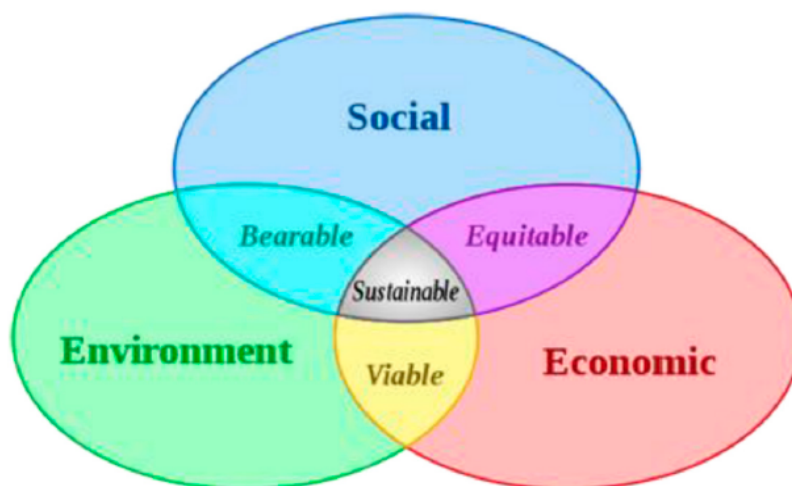


Figure 1. Barile et al., (2018), *Sustainability and the Viable Systems Approach: Opportunities and Issues for the Governance of the Territory*

This three-pillar conception is the dominant interpretation in the literature (Purvis, Mao, & Robinson, 2018). This tripartite division is based on the “Triple Bottom Line” principle, an expression first proposed by John Elkington in 1994 (Barile, Quattrocioni, Calabrese & Iandolo, 2018). In his book *Cannibals with Forks: the Triple Bottom Line of 21st Century Business* published in 1998, Elkington proposes a framework to measure the success of organizations to integrate the concept of sustainable development using three dimensions: economic, social and environmental. In his book, Elkington wrote that « *Sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality, and social equity* » (Elkington, 1998, p. 397). In his definition of the Triple Bottom Line, Elkington also uses the terms profit, people and planet to illustrate the integration of these three dimensions.

Economic sustainability « *implies a system of production that satisfies present consumption levels without compromising future needs. The ‘sustainability’ that ‘economic sustainability’ seeks is the ‘sustainability’ of the economic system itself* » (Basiago, 1999, p.150). The principle of sustainable economy implies that nations and companies must use their resources efficiently and responsibly to generate their operating profit consistently. Without using their resources responsibly, economic actors will not be able to maintain their activities in the long term. Ensuring profitability in the long term is logically their reason to exist, so it becomes crucial to see this principle as a necessity.

Environmental sustainability « *requires maintaining natural capital as both a provider of economic inputs called ‘sources’ and an absorber called sinks of economic outputs called ‘wastes’* » (Basiago, 1999, p.155). In other words, the concept of sustainable environment insists on the necessity to maintain the reproducibility of the natural resources we use, but also on the impact of the waste produced by humans that must be considered. Therefore, to respect this principle, it is necessary to consume the resources at our disposal at an acceptable level to keep their availability on the long term, but it is also necessary to pay attention to the negative externalities that this production and use generates.

Social sustainability « *calls for economic growth constrained by the requirements of social equity. In order to link these, an enabling environment must be created that optimizes resource use, prioritizes resource allocation, and fosters equitable resource distribution* » (Basiago, 1999, p.153). A socially responsible society must ensure the well-being of all individuals and generations by providing stability, social justice and guaranteeing similar conditions for everyone, such as health, education, and wealth. It must therefore ensure that human and political rights are accessible to all individuals.

In Figure 1 above, we can also see that partial sustainability can be achieved when at least two of the dimensions are considered. The social and economic dimensions enable equity, the social and environmental dimensions enable bearableness and finally, viability gathers the economic and environmental dimension. Nevertheless, to be called “sustainable”, « *a system has to achieve all of these objectives: economic welfare, social justice, and a healthy natural environment at the same time* » (Raith, 2014, p.7). For example, a system that enriches itself by degrading its environment cannot therefore be considered fully sustainable. Similarly, taking action to protect natural resources while violating human rights does not meet the definition either.

However, even though this three-pillar view has become the majority in the literature, it is not universal as many works consider other pillars necessary to be sustainable. (Purvis, et al., 2018). For example, Nurse (2006) explains that an institutional dimension is necessary to achieve sustainable development because institutions and authorities play a crucial role in supporting any approach. Furthermore, a cultural dimension seems equally relevant as the impact of production and consumption cultures must be altered and adapted now.

2.4. UN 2030 Sustainable Development Goals

The United Nations seems to have always given a particular attention to sustainable development and its application, as we have already mentioned earlier, with the Stockholm conference in 1972 and the establishment of the Brundtland Commission in 1982. Another summit of the Nations addressing the topic of sustainable development appears to be important to address: The Millennium Summit in September 2000. At this summit, the Member States unanimously adopted the implementation of eight Millennium Development Goals (MDGs), whose objective was to eliminate extreme poverty by 2015. In September 2015, the United Nations gathered again for the Sustainable Development Summit. Unfortunately, it was recognized that the goals set at that time had not yielded the intended results, but given the evolving situation, a new strategy was needed to intensify the efforts.

Consequently, the United Nations and its 193 Member States adopted the establishment of 17 Sustainable Development Goals (SDGs). Unlike the MDGs, the SDGs « *address the root causes of poverty, inequality, environmental degradation, and conflicts by addressing economic, social, and environmental issues in an integrated way* » (Carpentier & Braun, 2020). Indeed, these SDGs are not only broader than the MDGs originally developed, but they further connect the socio-economic context to the environmental context. These 17 SDGs have been categorized according to a more detailed approach of the 3Ps principle developed by Elkington (profit, people, planet) and are grouped into 5 major categories (people, planet, prosperity, peace, partnership) and aim to stimulate action for the next 15 years.

To ensure the effective implementation of these 17 Goals, the United Nations has established the Division for Sustainable Development Goals (DSDG). DSDG's role is to support the effective participation of all stakeholders in the policy process by sharing knowledge and skills (United Nations General Assembly, 2015). In addition, to ensure the follow-up, the Secretary General of the United Nations shall present an annual SDG Progress report, which will be based on data and statistics collected at the regional and national level. With this Agenda 2030 program, the United Nations hopes to free « *the human race from the tyranny of poverty and to heal and secure our planet* » and « *to complete what they did not achieve* » (United Nations General Assembly, 2015, p.3).

3. Corporations' commitment towards sustainability

3.1. Corporate social responsibility

As we have just discussed, the efforts required to ensure sustainable development are numerous and diversified. To achieve these objectives, it appears crucial that all economic agents feel concerned by this issue and adapt their behavior. Even if the commitment of individuals and institutions is required, the role of companies is probably the most determining factor, considering their status in the economic world. The fact that the notion of Elkington's Triple Bottom Line discussed above was originally developed to adopt the strategies and behaviors of companies is a concrete illustration. Today, the inclusion of sustainable principles within the business world is widely recognized as the principle of Corporate Social Responsibility (CSR). The concept of CSR can be considered as the willingness of a company to develop its activity by considering all the economic, social, and ecological concerns of its internal and external stakeholders, with the ultimate purpose of ensuring benefits towards society.

Moreover, since 2017, and the enforcement of the European Directive 2014/95/EU, companies employing more than 500 people over the fiscal year, must also present a “non-financial statement” (Directive 2014/95/EU, 2014, Article 19a). This report must, among other things, gather information on respect for human rights, the impact of their activity on the environment, employee matters and anti-corruption and bribery measures. Nevertheless, CSR should not be exclusive to large companies and the commitment of other companies and SMEs is equally vital to address current issues (Hutchisson, 2016). In addition, under the CSR principle, companies « *are not only supposed to respect the applicable legal regulations, but also take into account commitments which are not legally binding but result from universally recognized ethical principles and values* » (Swiatek, 2018, p.61).

Adopting a CSR approach in its corporate culture and activities may seem to request a lot of investments and efforts but, besides an altruistic approach defending ethical and moral reasons, the concept of CSR can nevertheless bring many benefits at different levels. First of all, it will reinforce the commitment of its employees and improve the company's image in the eyes of the workforce (Morais & Silvestre, 2018). CSR also helps to recruit, motivate its employees by increasing their efficiency and fostering their loyalty (Sprinkle & Maines, 2010). A study on employee motivation (Balakrishnan, Sprinkle, & Williamson, 2009) demonstrated that CSR may engender altruistic firm-contributions from employees and facilitate trust-based contracts.

Then, it helps to build a positive image of the company and will facilitate cooperation with all business partners. The reputation of a company can be considered as one of the most important non-financial assets to ensure profitability and reputation management is an essential practice for running a business. Building a positive brand image increases the commitment and interest of customers, public authorities, and investors. Firstly, today's consumers attach more value to trust in a company and are guiding their goods and services purchases more and more by sustainable principles. In fact, Sprinkle & Maines (2010) even consider CSR as “*free advertising*”. Secondly, it strengthens relationships with local and national authorities, who generally view CSR as a positive contribution to the environment and concerned citizens, and will be therefore more likely to suggest a strong long-term relationship (Swiatek, 2018). Thirdly, CSR tends to attract investors who see its socially and ethically responsible actions as a solid basis for financial development (Swiatek, 2018). Finally, a CSR strategy can also reduce some company costs by reducing resource consumption, improving energy consumption, or reducing operating costs by reducing polluting emissions. Swiatek (2018) also concludes that choosing to adopt a CSR strategy means improving its evaluation mechanisms, which subsequently leads to significant improvements in terms of management.

To implement a CSR strategy in its business and strategy, it is necessary, as discussed earlier, to consider the economic, social and environmental dimensions together. At the economic level, job creation, investment in local communities and organizations, partnerships with non-profit organizations and more reasonable dividends are some possibilities for companies. The intention is always to generate profit in order to maintain its activity but to operate in a more responsible way. From a social point of view, a company can aspire to fight discrimination and promote solidarity to minimize social inequalities. Besides remuneration, promoting training and development opportunities should be considered as incentives. Furthermore, in a CSR approach, it is essential to make the health and safety of its employees and partners a priority. From an environmental point of view, the principle is to protect the environment by reducing the risks of degradation through the measurement and monitoring of its activities. Ecological efforts include reducing greenhouse gas emissions, improving waste management, promoting zero packaging, encouraging the use of renewable energies and limiting travel as much as possible.

The popularity of Corporate Social Responsibility has also triggered the phenomenon of greenwashing. Tateishi (2017, p.3) sees greenwashing as a « *communication that misleads people regarding environmental performance/benefits by disclosing negative information and*

disseminating positive information about an organization, service, or product ». Given the growing importance of CSR, some companies do not hesitate to invent or accentuate their sustainable approach. Nevertheless, to prove the implementation of concrete actions, certifications such as B Corp or ISO 14001 help companies' actions to be recognized by an independent organization as true and well-founded. The adoption of a CSR approach to take advantage of its benefits without any real ethical motivation and managers' unwillingness to implement it effectively are two other limitations often attributed to the Corporate Social Responsibility approach (Swiatek, 2018).

In conclusion, the changing mindset of many stakeholders and the growing influence of information and communication technologies have given more importance to non-financial information, pushing companies to move away from traditional financial reporting. Thus, adopting a sustainable approach, in addition to being necessary for all the reasons already mentioned, seems today to give an undeniable competitive advantage to companies that include it in their corporate culture.

3.2. Sustainable supply chain

A supply chain is the network of all the individuals, organizations, resources, activities, and technologies involved in the production and sale of a product or service, from raw materials to end customers. It therefore encompasses all the successive stages of value creation, including raw material procurement, production, inventory management, sales, and distribution. This network of various organizations involved upstream and downstream of the manufacturing process is therefore generally a crucial function, if not the most determining function, in the activities of the main industry actors.

We can easily conceive, considering the numerous stakeholders and activities that the supply chain covers, that companies wishing to integrate a more sustainable strategy must gather their investments and efforts on this segment of their activities. According to a study conducted in 2016 by McKinsey, an international strategy consulting firm, 80% of the greenhouse gas emissions emitted by companies come from their supply chain, which is also responsible for 90% of the negative externalities on air, land, water, biodiversity, and natural resources. Moreover, according to Carbone Disclosure Project, an international nonprofit that promotes environmental disclosure, the impact of end-to-end supply chain on emissions is more than five times more important than companies' direct operations. The significant contribution of supply chain activities on global warming and non-renewable resources are increasingly leading

companies to consider the importance of sustainability in their supply chain operations (Narimissa, Kangarani-Farahani, & Zavardehi, 2019). Moreover, current pressures from government regulations and laws, consumers with their growing concerns, investors, and other stakeholders are pushing organizations to integrate sustainability concepts into their decision-making objectives (Jian, Guo, Jiang, An, & Su, 2019). This growing awareness and the need to address the issue of sustainability in their operations has led to the advent of the concept of Sustainable Supply Chain, which is defined as:

The management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements” (Seuring & Müller, 2008, p.16).

As we have argued several times before, the Sustainable Supply Chain principle logically emphasizes the need to address economic, social, and environmental dimensions. Typical social sustainability issues in supply chains include child and forced labor, discrimination, and poor health and safety conditions (Andersen & Skjoett-Larsen, 2009). In its guide to assisting Sustainable Supply Chain implementation published in 2010, the United Nations admits that working conditions « *in offices, in factories, on farms and at natural resource extraction sites such as mines, particularly in the developing world, often fall significantly below international standards and national regulatory requirements and can lead to serious human rights abuses* » (UN Global Compact, 2010, p. 8). Regarding the deterioration of the environment, companies must consider the impact of their supply chain regarding « *toxic waste, water pollution, loss of biodiversity, deforestation, long term damage to ecosystems, hazardous air emissions as well as high greenhouse gas emissions and energy use* » (United Nations Global Compact, 2010, p.9). Finally, from an economic point of view, companies must increase their monitoring of their entire value chain by eliminating the risks of fraud and corruption. Current trends, such as high media exposure and successive consumer boycotts, significantly increase the reputational risk of companies because of their suppliers (Schaltegger & Burritt 2014). Companies should therefore integrate Sustainable Supply Chain Management (SSCM) into their operations in order to develop and implement new management approaches and proactive strategies that combine social, economic and environmental issues throughout their supply chain.

The most critical point in the Sustainable Supply Chain principle is the challenge for companies to have an influence on their suppliers. For example, according to a survey of several large companies by the Carbon Disclosure Project in 2016, only 25% commit their suppliers to reducing their greenhouse emissions. The main reason why it is challenging to implement its ambitions on the suppliers' side is mainly because « *the upstream manufacturers and downstream retailers in the supply chain generally focus on maximizing their own interests* » (Jian & al., 2019, p.2). However, most primary suppliers themselves frequently subcontract part of their business to other firms. This globalization and fragmentation of the supply chain have raised concerns about the impact of second- and third-tier suppliers on sustainability (Miemczyk, Johnsen, & Macquet, 2012). Actually, « *the most serious environmental and social issues in the supply chain are often generated by suppliers located in the second tier or further upstream, also referred to as “lower-tier” suppliers* » (Tachizawa & Wong, 2014, p.643). First, lower-tier suppliers are generally the suppliers that firms have the most difficulty obtaining information about (Tachizawa & Wong, 2014). Second, firms generally do not have enough influence on these other organizations, which usually only act when large multinationals intervene directly (Villena & Gioia, 2020). Third, lower-tier suppliers generally attract less attention and are therefore less likely to be subject to pressure from the public and local regulations (Villena & Gioia, 2020). Fourth, Tachizawa & Wong (2014) argue that relationships are very unstable with these stakeholders because they are more likely to be replaced.

Several solutions are available to companies that wish to alleviate this problem and increase their control over first-tier and lower-tier suppliers. First, disseminating Codes of Conduct and asking them to fill out questionnaires allows to verify and implement the companies' own goals. Second, monitoring these organizations seems to be the most efficient solution. Corporations can set up sustainable goals and sustainability performance indicators that can support the supplier management process with incentives or sanctions (Harms, Hansen & Schaltegger, 2013). Ultimately, in extreme cases, a negative evaluation may lead to the termination of the relationship (Delmas & Montiel, 2009). Third, it is possible to ask all actors in the supply chain for labels or certifications that authenticate their compliance with economic, social, and environmental requirements. Fourth, it is important to increase collaboration with its actors to create mutual benefits because the « *cooperation between manufacturers and retailers will be a decisive component in enabling better performance* » (Jian & al., 2019, p.2).

The benefits of implementing a sustainable supply chain are numerous and for the most part, similar to those already mentioned above regarding Corporate Social Responsibility (reducing operating costs, organizational reputation, partnerships opportunities, employee and consumer engagement). However, other benefits specific to the supply chain can be achieved. For example, assessing your suppliers' strategies and reliability can ensure supply continuity and better risk mitigation. Then, it can also facilitate innovation by working more straightforwardly with all your suppliers.

4. Technology in sustainability

Since the notion of sustainability was first conceived and has evolved over time, through the various principles and ideals covered so far, technology has always been considered an enabler and a factor that can help to overcome the challenges we encounter today. Malthus' theory developed in the 20th century has finally experienced some limitations since the famines caused by resource scarcity predicted by the economist have not been as devastating as predicted due to capital investments but also due to numerous technological developments (Bretschger, 2020). Indeed, traditional economists and « *technological optimists believe that the concept is defunct. They argue that trade and technology have historically pushed back the “limits to growth” and will continue to do so indefinitely* » (Bell & Cheung, 2009, p.1). The Brundtland report, including in its definition, makes it clear that sustainable development is enabled by the viability of the economy and technology (Theis & Tomkin, 2012). Indeed, according to the findings of the Commission, « *technology and social organization can be both managed and improved to make way for a new era of economic growth* » (World Commission on Environment and Development, 1987, p.24), and « *the accumulation of knowledge and the development of technology can enhance the carrying capacity of the resource base* » (World Commission on Environment and Development, 1987, p.55).

Moreover, the Commission considers technological innovations as the main response required for developing countries to address the challenges of sustainable development, and that more attention should be paid to "appropriate technology". The concept of appropriate technology, defined as a technology that considers skills, population levels, and the availability of natural resources, is considered by some experts to be « *the immediate precursor to the concept of sustainable development* » (Mebratu, 1998, p.500). Then, as we have noted in the discussion of the three-pillar concept, some studies consider other pillars necessary for the concept of sustainable development. According to Joslyn Institute for Sustainable Communities, an American non-profit organization, two additional areas, a technological

dimension, and a policy dimension, must be considered in the model (Figure 2). Clune & Zehnder (2018) take a different approach and consider the three pillars of sustainable development as 1) technology and innovation; 2) laws and governance; and 3) economics and financial incentives (Figure 3).

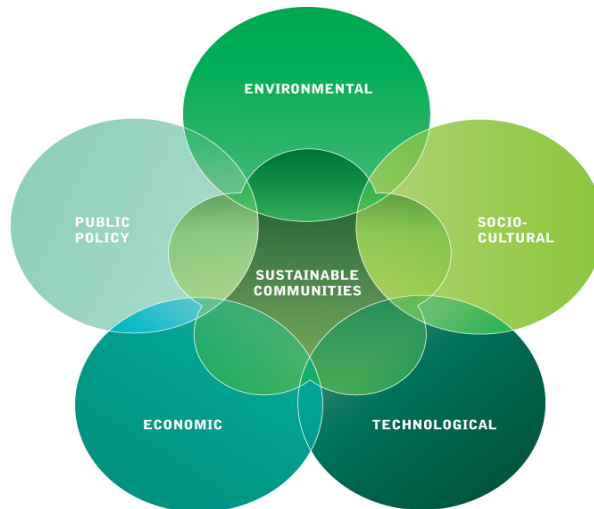


Figure 2. Joslyn Institute For Sustainable Communities (2016), *The Five Domains*



Figure 3. Clune & Zehnder (2018), *The Three Pillars of Sustainability Framework*

With regard to the United Nations 2030 Agenda, article 28 concludes that governments, organizations and individuals should contribute to building scientific, technological and innovative capacities to move towards more sustainable production and consumption. Furthermore, article 63 highlights the fact that « *processes to develop and facilitate the availability of appropriate knowledge and technologies globally are also critical* » (The 2030 Agenda for Sustainable Development, 2015, p.28). And finally, in its guide on the

implementation of Sustainable Supply Chain, the United Nations encourages « the development and diffusion of environmentally friendly technologies » (UN Global Compact, 2010, p.9).

To provide a mathematical approximation of the magnitude of technology's role in achieving our goals, we can use the IPAT equation, proposed by Ehrlich and Holden in 1971.

$$I = P \times A \times T$$

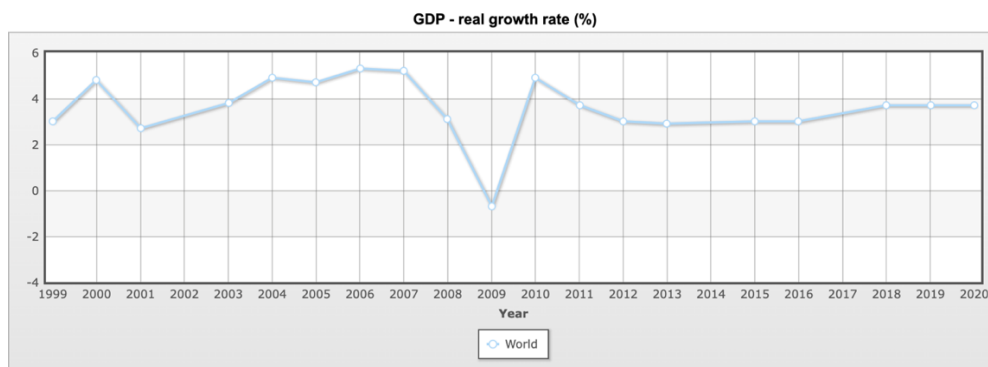
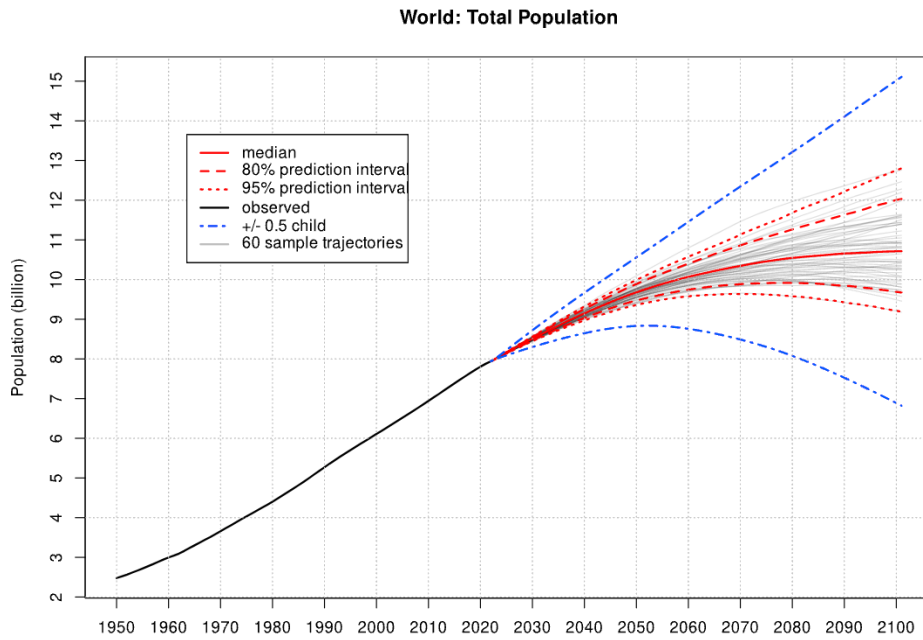
I represents the impact of a population or nation on environmental resources, **P** represents the population at a given moment in time, **A** corresponds to the level of consumption per person, and **T** corresponds to impact per unit of output, or technology « *interpreted in its broadest sense as any human-created invention, system, or organization that serves to either worsen or uncouple consumption from impact* » (Theis & Tomkin, 2012, p.8). According to Figure 4, the population in 2020 was 7.9 billion and projections estimate the population at 8.4 billion in 2030, representing a 5% increase. Based on Figure 5 on the annual growth rate, we can reasonably consider an average increase of 3% per year to project to 2030, considering the impact of the COVID-19 pandemic between 2020 and 2022. Therefore, it can be estimated that in 2030, the global economy will be 35% larger than in 2020.

Thus, if we want to maintain our environmental impact at the 2020 level, $I(2030) = I(2020)$, and consequently :

$$P(2020) \times A(2020) \times T(2020) = P(2030) \times A(2030) \times T(2030)$$

Or,

$$\left(\frac{T(2030)}{T(2020)} \right) = \left(\frac{P(2020)}{P(2030)} \right) \times \left(\frac{A(2020)}{A(2030)} \right) = \left(\frac{1}{1.05} \right) \times \left(\frac{1}{1.35} \right) = \left(\frac{1}{1.42} \right)$$



We can therefore conclude that, in order to maintain our environmental impact between 2020 and 2030, and assuming that the level of consumption remains the same, our technological decoupling will need to reduce impacts by approximately a factor of 1.5. Given that the objective of the 2030 agenda is to improve our environmental impact and not to maintain it, we can deduce that the technological role will necessarily be very significant. Goodland & Daly (1996) point out that the equation does not necessarily involve new technologies, but it is rather a matter of approaching and using existing technologies differently, which are too often considered only in terms of higher productivity and profitability. In the next sections of this work, we will explore how the emerging technologies of Industry 4.0 can help companies embrace a more sustainable strategy, and especially in their supply chain.

5. Industry 4.0 concept and evolution

5.1. Historical evolution of the industry

Industry has undergone a series of revolutions over time, each one increasing in complexity and productivity. The concept of Industrial Revolution « *is applicable to a situation where there is a development of productive technological capacity through creativity with a relevant impact on the economic, environmental, and social dimensions* » (Fonseca, 2018, p.1).

The First Industrial Revolution intervened in the 18th century with steam power and mechanization of production. It starts in Great Britain, which was the heart of technological innovations and at that time was the largest trading nation with its wide colonial empire. This First Industrial Revolution experienced an increase in the use of steam power, which was already known at the time, whose use for industrial purposes was a major breakthrough in increasing human productivity (Vinitha, Ambrose Prabhu, Bhaskar, & Hariharan, 2020). This Industrial Revolution is also recognized for the shift from hand production methods to machines, especially in the textile industry. The rise of business and the development of trade are also major causes. Overall, the First Industrial Revolution marked a turning point in the daily life of people by improving their quality of life, notably by a greater average income (Rojko, 2017). The development of steam-powered locomotive allowing the population to move faster giving way to urbanization is also a distinctive characteristic of this period (Groumpos, 2021).

The Second Industrial Revolution, also known as the Technological Revolution, began with the discovery of electricity but also with assembly line production using all the new technologies of the time. The focus of the Second Industrial Revolution is manufacturing mass production, enabled by the development of new machine tools. Henry Ford (1863 - 1947) applied all these new ideas in the vehicles manufacturing and significantly improved the process, making the production a succession of partial steps, increasing productivity and decreasing costs (Sharma & Singh, 2020). The different breakthroughs in manufacturing and production technology allowed the adoption of different technological systems such as gas and water supply, railroad networks and even the telegraph (Groumpos, 2021). Generally speaking, production and competition were intensified, and capital was at the center of this industrial transition (Sharma & Singh, 2020). The Second Industrial Revolution is dated between 1870 and 1914, with the beginning of World War I. Unfortunately, this event put an end to these radical approaches to manufacturing. Obviously, the war did not stop industrial production

completely, but the only developments made at the time were in this context and cannot be considered as industrial revolutions (Sharma & Singh, 2020).

The Third Industrial Revolution, also known as the Automation Revolution, began in the 1970s and is characterized by partial automation using computers and automation industries. With the introduction of these new technologies, the entire production process in the Third Industrial Revolution has been automated without any human assistance (Groumpos, 2021). The production assisted by programmable machines have allowed the industry to be more flexible, efficient, and safer in some processes (Rojko, 2017). The shift from analog electronic to pervasive digital technology has drastically changed the environment of the industries, especially the communication, energy, and engineering fields (Groumpos, 2021). The wider distribution of the manufacturing geography has also contributed to the development of the sharing economy and the emergence of supply chain management. In other words, the Third Industrial Evolution « *is the link between Henry Ford's drive for greater productivity and the smart processes we are seeing emerging under Industry 4.0.* » (Sharma & Sigh, 2020, p.67).

Today we are in the Fourth Industrial Revolution, also called Digital Revolution, which can be characterized as the application of information and communication technologies in industry, but also in other activities of society (Groumpos, 2021). Computer technology manufacturing processes are extended through a network connection, improving contact and communication with other facilities and bringing self-knowledge production (Sharma & Singh, 2020). This Fourth Industrial Revolution can drastically change the way of production where the digitalization of the manufacturing environment allows for greater efficiency and flexibility through access to real-time information (Groumpos, 2021). These developments and new processes are currently considerably altering the industry and these aspects will be discussed in the next sections.

5.2. Industry 4.0 concept

The current ever-changing market conditions create a tough global competition and force industrial production to adapt quickly to its environment. These requirements can only be met if companies adopt the radical advances in technology and move towards the fourth industrial revolution, nowadays also called Industry 4.0. The term Industry 4.0 was introduced by Germany in 2011 at the Hannover Fair, the world's largest trade fair for industrial technologies. The principle that was presented under this denomination was the support of the development of a new concept of German economic policy based on the emergence of new high-tech

strategies (Rojko, 2017). The fact that the concept of Industry 4.0 comes from Germany is not so surprising considering that the country has one of the most developed and competitive manufacturing industries in the world. Since its first mention, the concept of Industry 4.0 has been used by industrial and academic communities (Rojko, 2017). Industry 4.0 can be described as « *a collective term, referring to a set of connected digital technology solutions that support the development of automation, integration and real-time data exchange in manufacturing processes* » (Koleva, 2018, p.1). The principle of Industry 4.0 is to bring new digital technologies into the industry to deliver their capabilities and benefits in products and processes (Nicolae, Korodi, & Silea, 2019).

This new industrial revolution is characterized by smart factories including smart machines and smart products (Rojko, 2017). In Industry 4.0, smart production facilities are defined as Cyber-Physical Systems (CPS) that are connected to each other through the Internet Of Things (IoT). CPS consists of the interaction between the physical environment and the virtual environment that integrate, control and coordinate processes and operations using real-time data (Pereira & Romero, 2017). These smart machines are therefore connected to each other through IoT, which can be defined as the connection, via the Internet, of all physical objects present in a factory (Nicolae et al., 2019). In the concept of Industry 4.0, these smart factories therefore lead to the production of smart products. This new generation of products is able to generate and store data and interact in real time with its environment during its entire lifecycle without human intervention (Schmidt et al., 2015). These smart factories and products together enable an automatic exchange of information between all resources, all production processes and between all stakeholders including suppliers, manufacturers and final customers (Nicolae et al., 2019).

Relying on information and communication technology (ICT), Industry 4.0 emphasizes the future of the manufacturing trying to improve both the horizontal and the vertical interoperability of production systems (Nicolae et al., 2019). Horizontal integration is described as the principle that a corporation should both cooperate and compete with other corporations that have similar characteristics to improve its production process. Material, knowledge and finance can be connected more easily and create new business models (Tay, Chuan, Aziati, & Ahmad, 2018). This horizontal integration is seen as developing a new generation of global value-creation network (Koleva, 2018). Vertical integration is the integration of value elements such as equipment, employees, or products within a manufacturing factory, but also its entire operations. In Industry 4.0, smart factories can connect all activities in their value chain through

CPS and thus improve their efficiency and adaptability (Tung, 2018). In addition, the data collected and processed by these smart machines allows companies to have better visibility on all their operations (Tay et al., 2018).

Industry 4.0 will undoubtedly have an important influence on all industrial processes, manufacturing systems, and also in supply chains. It will bring greater visibility, better visibility and better resource allocation. The emergence of new technologies included in the scope of this fourth industrial revolution will definitely change the way products and services are produced and sold, challenging traditional business and bringing very new opportunities and business models (Pereira & Romero, 2017). It will also improve interactions with customers, allowing to face and respond to new market requirements. Companies that take the initiative to switch to Industry 4.0 will improve their competitive position, create more value, and minimize risks. Furthermore, Industry 4.0 and these technologies have a great potential to address current sustainability issues. In the next section, we will study and try to identify how their implementation and use can support companies to have a more sustainable supply chain, looking at applications in the automotive industry. Among the different technologies that are generally considered under the Industry 4.0 principle, we will go through the characteristics and assets of blockchain, radio frequency identification, big data analytics, artificial intelligence, additive manufacturing, augmented and virtual reality, advanced robotics and cloud computing.

6. Industry 4.0 technologies within automotive supply chains

6.1. Automotive industry

The automotive industry is arguably considered as the largest and most dominant manufacturing sector in the world and generally drives the entire economy of numerous nations (Ada et al., 2021). According to Globe Newswire (2021), the global automotive market accounted for over 85 million units sold in 2020 and is expected to reach over 120 million units by 2030. The automotive industry also has an important multiplier effect in the economy as it is decisive for other upstream industries such as steel, chemicals, and textiles but also for downstream industries such as ICT, repair and mobility services. In Europe, the industry employs about 13.8 million people and the turnover generated by the automotive industry represents more than 7% of the EU GDP (European Commission, 2022).

Automotive supply chains are characterized by complex networks, involving multiple organizational presences considering that a car has an average of about 20,000 parts, coming

from a multitude of suppliers around the world (Koricanac, 2021). The supply chains of automotive companies play a determining role in their successful functioning, implying the need for a timely and efficient evaluation of their supply chain (Kamble et al., 2021). Nevertheless, like other industries, automotive companies face many challenges arising from market trends and the need to respond effectively to this demand (Ada et al., 2021).

Moreover, from a sustainability point of view, automotive companies are also facing major environmental challenges such as adverse impact of climate change, air pollution, ineffective management of the end of life of vehicles and strict changes in rules and regulations (Guadge et al., 2022). In order to address this issue, the European Commission launched in 2017 the GEAR 2030 project, which aims to ensure that Europe has the most competitive, innovative and sustainable automotive industry by 2030 and beyond. This project is based on several principles and notably, the implementation of strict regulations and incentives, numerous investments, ensuring structural and technological changes, promoting international cooperation and trade and finally, changing the mind-set and culture of the community (European Commission, 2017).

Finally, considering the rising market expectations for innovation and the development of autonomous vehicles, automotive companies are forced to modernize their production process and supply chain to meet these expectations. As we will explore in this paper, investing in Industry 4.0 technologies can potentially help companies meet these efficiency, innovation, and sustainability concerns.

6.2. Industry 4.0 technologies applications

6.2.1. Blockchain

Blockchain technology has been promoted through its use in crypto-currencies and more specifically in Bitcoin, where its efficiency and security have built its reputation. Blockchain can be defined as a shared and immutable ledger whose purpose is to record transactions and track assets in a network (IBM, 2022). An asset can be tangible, such as a product or money, or intangible, such as intellectual property or copyright. We can consider the blockchain as a chain of "blocks" that contain a record of network activity such as a transaction, a file, or a data and that succeed each other once the previous one is verified and validated. Since these blockchains are created using cryptography, adding data to the blockchain is accessible by anyone performing transactions on the network, but no one can add, modify, or delete them without proper authorization (Yahiaoui, Fedouaki, & Mouchtachi, 2020). This technology is

therefore distinctive in how the administrative control is digitally maintained and regulated, which allows a better transparency and a limitation of the risk of deletion, thanks to its immutability (Esmailian, Sarkis, Lewis, & Behdad, 2020).

The massive use of this technology in finance and its efficiency has led to a further examination of blockchain in order to extend its assets and benefits to other applications. Although its adoption in other fields is still at a very early stage, blockchain technology is already considered as one of the leading disruptive technologies that will radically transform supply chains by incorporating sustainable activities especially on environment and social protection (Tsai et al., 2021). Indeed, its ability to integrate all resources and assets of the supply chain provides added value to several activities such as information sharing, product tracking and increased transparency in transactions. Blockchain therefore has the potential to support all areas of the supply chain including planning, procurement, manufacturing, and delivery (Kamble et al., 2021). Since the automotive supply chain encompasses several industries, is concentrated in different countries, and is governed by different regulations, this technology seems appropriate for increased efficiency. According to a study conducted by IBM in 2020, 62% of practitioners in the automotive industry consider that blockchain technology will be a major force from 2021. In 2018, recognizing the benefits of blockchain technology, BMW, General Motors, Ford, and Renault created the MOBI (Mobility Open Blockchain Initiative) consortium to promote the adoption of blockchain standards in the automotive industry to make their business more efficient, affordable and sustainable. Even if its adoption is still relatively new, as in other sectors, some features are already being implemented in their operations, as we will go through below.

As we have previously mentioned when discussing the concept of sustainable supply chain, one of the most critical challenges faced by supply chain is the lack of visibility. Supply chain visibility « *is the ability to track parts or products without any disruptions from manufacturers to the destination, including intermediary activities* » (Reddy, Gunasekaran, Kalpana, Sreedharan, & Kumar, 2021, p.7). However, the multi-tier network complexity of supply chains makes access to information challenging, especially when the firm wants to ensure the sustainability of its operations and resources. The main feature of blockchain technology is traceability, which allows organizations to facilitate the mapping of their supply chain by connecting tier-1 and tier-2 suppliers to consumers.

In the automotive industry, it is becoming imperative to be able to track components and semi-finished products used for a vehicle or a product line, but the lack of access to common information for all stakeholders makes this process difficult to execute in real-time. A recent study (Mubarik, Rasi, & Mubarak, 2020), found that the characteristics of blockchain allows a firm to visualize and track in real-time the upstream, midstream, and downstream supply chains. Through data obtained from trusted environments, end-to-end product tracking and multiparty authentication of the possession of goods, blockchain technology enhanced visibility, which promotes operational efficiencies. Indeed, this real-time tracking capability of blockchain allows companies to quickly identify the inventory level of their products and raw materials in order to undertake more integrated and well-informed decisions (Rejeb, A. & Rejeb, K., 2020). As a result, managers can simplify their business by simplifying tasks and eliminating multiple non-value-added activities along the supply chain. This can therefore, in addition to provide a real time-saving benefit, drastically help to manage optimal inventory levels, reduce costs, and increase efficiency (Khan et al., 2022). If a company cannot trace the entire supply chain process, it naturally becomes very challenging to ensure the sustainability of each of these processes. Blockchain technology, through this complete mapping, improves the ability of managers to trace the origin and spot unsustainability in their supply chain process, to fix them accordingly. A recent study (Khan et al., 2022) showed that blockchain traceability provides the ability for managers to zoom in on micro-processes, traditionally overlooked due to lack of means, to determine their compliance to sustainable practices.

For example, the BMW Group initiated the PartChain project, which uses blockchain technology « *to ensure the traceability of components and raw materials in multi-stage international supply chains* » (BMW Press, 2020). The pilot project was initiated in 2019 for the supply of front lights at two of the BMW Group's total 31 plants (Spartanburg/US and Dingolfing) and planned to expand the project over the next two years. According to the BMW Group, the long-term goal is to have complete traceability of all critical raw materials. Mercedes-Benz, by launching in 2019 a partnership with Icertis for the joint development of the implementation of blockchain technology in the supply chain, seems to give a special attention to traceability. The objective for Mercedes-Benz is to ensure that their subcontractors respect their contractual obligations and are compliant with the guidelines of the German group.

Blockchain's characteristics therefore increase transparency throughout the supply chain, and consequently enhance trust between the various stakeholders. While traceability is considered as the most valuable feature of blockchain, trust is identified as the most

significant benefit of this technology within the supply chain (Paliwal, Sharma, & Chandra, 2020). Blockchain technology has the potential to create an atmosphere of trust between the different stakeholders within the supply chain since « *the completeness and transparency of information and transactions on the blockchain constitute the necessary ingredients for establishing mutual trustful relationships* » (Rejeb, A. & Rejeb, K., 2020, p.5). In this regard, Lemieux (2016) concluded that trust assurance enhanced by this technology provides the critical underlying infrastructure necessary to achieve development objectives. In the automotive industry, considering the current challenging macroeconomic environment, it is crucial to increase transparency and trust between Original Equipment Manufacturer (OEM) and suppliers to develop a win-win partnership and long-term sourcing relationships (Reddy & al., 2021).

The trust and transparency brought by this technology allows specially to counteract corrupt individuals and consider any social wrongdoings such as human rights abuses, child labor, and corruption to achieve social sustainability (Munir et al., 2022). There are indeed many regulations and standards regarding these rights, but unfortunately it is very common to violate these rules and this issue is being taken extremely seriously by car manufacturers. For example, the Volkswagen Group is already using blockchain technology to monitor the provenance of the cobalt used for electric vehicle batteries (Volkswagen Group, 2019). The car manufacturer recognizes that cobalt can be extracted industrially or in an artisanal way, where child labor is a widespread problem in the sector. The position of the company communicated to its shareholders is that from now on, they will use the cobalt extracted in a "*clean*" way in order to maintain a sustainable approach for their electric vehicles. In addition, Polestar, the Swedish car manufacturer, has been working since 2021 with the company Circular, specialized in blockchain technology, to join the movement. For the company, the focus is currently on raw materials where social and environmental risks have been identified (Autoweek, 2021).

Blockchain technology can also play a role in strengthening the environmental dimension of sustainable development by significantly reducing the environmental logistic footprint. We have already discussed the ability to ensure the traceability of raw materials, but by leveraging blockchain, it is also possible to integrate other environmental protections, including the monitoring of the carbon footprint, energy consumption and waste management within the supply chain.

First, blockchain technology allows companies to trace the carbon footprint and thereby contribute to the reduction of carbon emissions and air pollution through accurate and treable greenhouse footprint analysis (Rejeb, A. & Rejeb, K., 2020). In addition, through these accurate analyses, it will be easier for companies to determine the accurate amount of carbon tax that each stakeholder should be charged, and it will also facilitate cooperation and exchange in the green-asset markets (Rejeb, A. & Rejeb, K., 2020). In the automotive industry, Reddy et al. (2021) note that car manufacturers are struggling to gather this emissions information and that the adoption of this technology will allow the development of region-specific business plans based on OEM footprint and industry analysis. For example, Porsche has partnered with CircularTree, a German blockchain startup, to create the CarbonBlock solution, which provides the carbon footprint of some parts and materials in the German brand's supply chain. The CarbonBlock solution, which won the Global Innovation Award by Plug and Play in September 2020, will incentivize suppliers to undertake a more carbon-neutral approach (Ledger Insights, 2020).

Second, from an energy perspective, according to Kouhizadeh, Sarkis & Zhu (2019), the technology has the potential to help firms identify materials that use non-renewable energies and allow them to either eliminate them from their supply chain or invest in renewable alternatives instead to benefit from the circularity of energy. The blockchain technology can actually « *simplify the participation of stakeholders in low-carbon energy initiatives, facilitate the implementation of environmental protection programs, and increase consumer access to clean energy* » (Rejeb, A. & Rejeb, K., 2020, p.368). The BMW Group is planning to use the capabilities of blockchain technology to source its aluminum only from plants that use solar power. The car manufacturer has even estimated that if it could promote green power throughout its aluminum supply chain, 2.5 million tons of greenhouse gas (GHG) emissions can be mitigated within a 10-year period (BMW Press, 2022).

Third, all supply chain partners will also be able to realize significant savings from the reduction of waste because the possibility for managers to zoom in on micro-processes as mentioned before, will also help identify waste. Effectively, blockchain technology « *facilitate recycling behavior by incentivizing individuals to participate in deposit-based recycling programs* » (Esmaeilian et al., 2020, p.8).

Another important feature of the blockchain is that, by storing numerous pieces of information, it can provide what is referred as a digital identity. This second virtual identity

will operate as a primary construct for all the stakeholders (Paliwal et al., 2020). This will allow manufacturers to monitor their products during their entire lifespan and thus promote better design, production, sale, and recovery of products. This increased visibility over the entire product lifecycle can further decrease waste generation and emissions, and further engage governments, stakeholders, and users (Esmailian et al., 2020). An important issue that automotive companies are facing is the effective disposal of parts after usage to promote environmental sustainability (Reddy et al., 2021). The blockchain technology allows to upload all information about a vehicle generated by users, authorities, insurance companies and all automotive eco-system stakeholders (Kamble et al., 2021). The MOBI consortium announced that they are currently working on the feasibility of a Vehicle Identity (VID), which for the time being is at the Proof of Concept (PoC) stage. The purpose is to give a "*birth certificate*" to each vehicle in order to share and collect information about the vehicle's lifecycle between the different stakeholders. The main objective is to be able to anticipate and improve vehicle maintenance, but the possibilities that this approach could offer are numerous. For example, Paliwal et al, (2020) noted that this "*digital twin*" of the physical vehicle could allow the implementation of a "car wallet" where the user would be the primary beneficiary. The authors imagine that users could receive credit in their car wallet for using green or clean fuel or taking an alternative route that would generate less emissions to benefit from these credits to pay for the various expenses related to the use of the vehicle.

The advantages of blockchain technology are numerous and companies are still exploring the benefits that this technology can offer them. We can deduce that this technology has the potential to address the challenges of sustainable supply chain and make the whole supply chain more responsive, efficient, and sustainable. Considering the volume of the components involved in the automotive industry, companies in the sector must take advantage of the critical parameters of traceability, transparency, and trust.

6.2.2. *Radio frequency identification*

Radio Frequency Identification (RFID) technology is an automatic identification technology that performs flow of unique information of a logistic (or product) item through electromagnetic signal waves at key points along the supply chain, without the need of manual operations. An RFID system uses an RFID reader that sends out a radio frequency wave to a transponder (also known as Tag), attached to or incorporated into objects. The data collected from the transponder is then sent back to a host computer or to a portable reader for data processing. The information flow efficiency increases the traceability and visibility of items, making this technology a key

element for the logistic supply chain optimization, as well as for promoting an environmental friendly approach (Jamaludin et al., 2018). This technology has been used for several years in the automotive industry and its uses are still evolving in the supply chain since RFID has the ability to provide more detailed information than bar-coding (Attaran, 2012).

Thanks to its enhanced traceability and its tracking capabilities, RFID technology can be used to promote reverse logistics. Reverse logistics can be considered as the set of steps and means by which goods produced, or some component « *return to the productive cycle (...), reacquiring value in secondary markets by reuse or the recycling of their constituent materials* » (Leite, 2003, p.4). This technology can actually help to promote product recalls and redistribute them faster and more efficiently, as well as facilitate final disposal if the return of these materials is not economically feasible. The concept of reverse logistics is increasingly being considered by automotive companies due to legislative pressures, rising raw material prices and the desire to adopt a more sustainable approach (Nunes, Schnatmeyer, Thoben, & Valle, 2006). Therefore, automotive manufacturers need to establish and operate a closed-loop supply chain that incorporates this reverse process, to maximize value creation over the entire lifecycle of a product. This closed-loop supply chain principle involves the collection, inspection, recycling and re-distribution of products or components during sourcing, production, and delivery (Kim, Chang & Park, 2017). On top of the sustainable nature of this approach, enhancement of the reverse logistics process will allow these companies to benefit from a sustained competitive advantage.

Nevertheless, to implement a closed-loop supply chain, it is essential to have an efficient Product Lifecycle Management, which aims to gather all the information generated throughout the product lifecycle. The nature and quality of the returned items differ according to usage environment, user behavior and all the events that occurred during the entire product lifetime. All these product characteristics will influence whether the product is recycled, reused, remanufactured, or destroyed and if these characteristics are not known or complete, they may cause a negative impact in terms of cost and resource circulation. It is therefore crucial to be able to provide the correct and necessary information to make the product recycling and reuse process efficient (Kim et al., 2017).

However, gathering and reporting all the information generated during the entire life cycle of a car component is very challenging. If the information flow is rather complete between the Beginning-Of-Life (BOL) and Middle-Of-Life (MOB) phases through Product Data Management and Knowledge Management systems, the information flow often becomes less

complete between the MOB and End-Of-Life (EOL) phases, until it usually gets stopped when the car is delivered to the end-user (Cao et al., 2007). According to Kim et al., (2017), this is mainly due to two factors. On the one hand, the exact timing and quantity of product returns is frequently unknown. On the other hand, manufacturers do not have a good visibility of the recovered resource « *because of a complex return network that consists of a number of return points and reprocessing facilities* » (Kim et al., 2017, p.2). Using a model developed by Cao et al. (2007) (Figure 6), applying an RFID system can solve this information gap by making product information accurate, complete, and available whenever it is required during its whole lifecycle. Nevertheless, it is apparent to carefully decide which data should be stored (Kim et al., 2017).

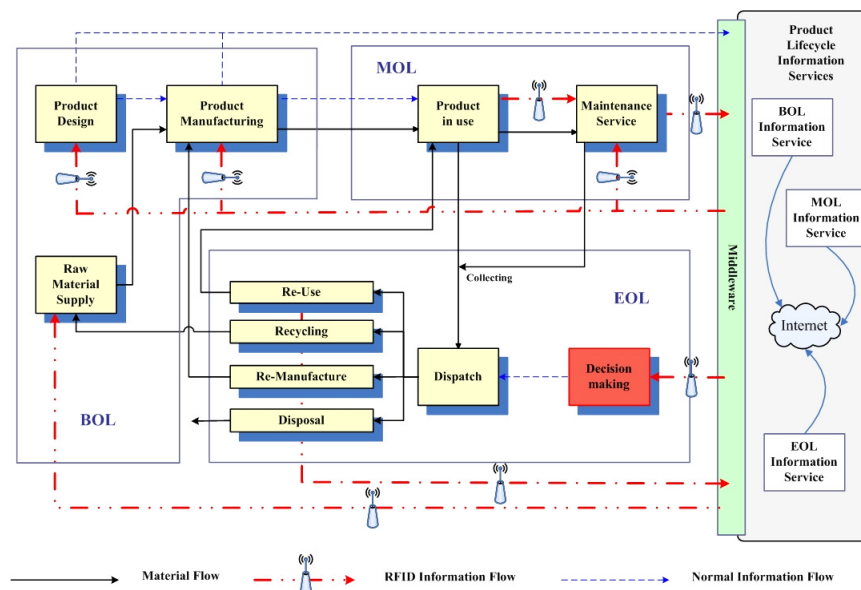


Figure 6. Cao et al., (2007), RFID-based Information Framework in product lifecycle

As described in Figure 6, the BOL phase starts with the raw materials at the manufacturer, the design of the product and its production. Once produced, it is distributed to the different customers where the product reaches its MOL phase. The use of RFID technology allows to capture and transmit selected information to an information management network, the Product Lifecycle Information Service, a framework that allows an automatic identification and sharing of information related to the life cycle of the item in consideration. Lastly, at the EOF phase of the product, the information needed to make recovery route decisions can be retrieved at any time from the Product Lifecycle Information Service. With the application of standards used between all stakeholders in the supply chain, this reverse logistic approach could become an economic reality and this closed product life cycle loop would save many resources and reduce waste generation (Nunes et al., 2006).

Plastics are largely used in the automotive industry because this material is light, cheap, and durable. According to the European Recycling Industries' Confederation (2020), there are on average 39 different types of plastics and polymers in a vehicle, representing between 150 and 200

kg per car. This makes it very difficult to identify plastics, but considering their high occurrence and environmental impact, their recycling is more than essential in the automotive industry. These heterogeneous plastic products are transported in a wide variety of containers and using RFID technology could facilitate the recycling process through the different system features mentioned above. Moreover, in addition to playing an active role in the sustainability strategy, the enhanced recycling rate through RFID implementation would reduce the logistics costs by approximately 30% (Nunes et al., 2006).

Even though recycling individual vehicle components improves environmental sustainability, reusing various car components, if economically sustainable, still involves less CO₂ emissions than the recycling alternative (Fujita, Nakamura, Matsuo, & Dodbiba, 2010). But for product recovery management, even more product information is required, and it is equally important to consider the life span of each part for its reuse. This product recovery is the responsibility of both OEMs and other third parties. To make the right product recovery decision, these agents need information such as material type, physical and functional conditions, disassembly instructions, reliability, or maintenance history (Fujita et al., 2010). In this reuse process, using a RFID system can enlarge the information availability and it could increase the number of reused or recovered car parts considerably. Indeed, the poor quality of remanufactured parts is often associated with premature testing and failure analysis techniques and « *the absence of these techniques causes an imprudent shredding of components that could have been restored to good-as-new condition* » (Kim et al., 2017, p.2).

To illustrate this concept of product recovery using this technology, we can look at the new tire tracking strategy being implemented by Michelin in 2021. The company has partnered with Murata Manufacturing to develop a new generation of RFID modules that are directly embedded into tires. These robust RFID tags, which do not require any external power supply, are measuring 1x1x6 mm, and are to be implemented in all the company's tires by 2024. This technology will facilitate the tire traceability throughout its entire lifespan, improving inventory management, aftermarket maintenance and recycling operations. This approach makes even more sense when it is estimated that each year 1.6 billion new tires are produced and 1 billion of waste tires are generated (Goldstein Market Intelligence, 2020). Incidentally, the tire industry came to an agreement on RFID technology at ISO level, where Four ISO standards were published in 2019.

Then, many automotive companies use RFID technology to improve their process and assembly operations. The RFID-assisted object tracking system can effectively help to localize an object in the assembly line and simplifies the decision making regarding where and when to process the working objects in the assembly lines (Wang, Luo, & Wong, 2009). Furthermore, an RFID-based monitoring system can reduce the inventory cost by constant monitoring (Jamaludin et al., 2018). The German car manufacturer Audi, which has been using RFID chips for some time, optimizes the location of its vehicles for dispatch at its Neckarsulm site. This location technique using RFID technology and a drone, is planned to be implemented in other production sites to facilitate the vehicles to dispatch to customers. Mercedes has also been using RFID technology in the assembly line of its vans since 2017. In addition to improved flexibility and better inventory management, this RFID process consequently « *relieves the employees of routine tasks and thanks to automatic checks gives them peace of mind knowing they installed the right parts* » (Mercedez-Benz, 2017).

Finally, in automotive industry, Returnable Transport Items (RTI) such as containers, trolleys or pallets are widely used to transport items between suppliers to the manufacturer, but also within different production lines (Jamaludin et al., 2018). However, due to human errors, loss of location or lack of information towards maintenance, this can lead to 15-20% losses and 20-25% excess purchased of RTI (Giubilato, Zhang, & Alfieri, 2019). A study from Jamaludin et al. (2018) to adopt this automated tracking system in an automotive manufacturing plant, demonstrated time savings in material handling process and a reduction in the number of trips.

6.2.3. *Big data analytics*

It seems that there is no globally accepted definition for the concept of Big Data, nevertheless a 6Vs framework is commonly used to describe it: Volume, for the large amount of data; Velocity, the data are generated and must be processed quickly; Variety, structured and unstructured data types are processed; Value, the purpose is to generate value for businesses; Veracity, reliability of the processed data and Variability; flexibility to adapt to new data formats (Chalmeta & deLeon, 2020). Big Data Analytics (BDA) can be defined as « *a set of tools, algorithms, simulations, and optimizations that can be applied to Big Data* » (Chalmeta & Barqueros-Muñoz, 2021, p.4). BDA implementation allows to gain knowledge and to reveal unknown, hidden, valid patterns and information to help businesses extract the maximum potential from the data available, to gain business insights and to guide decision making (Ahmed et al., 2018). In the automotive industry, effective and efficient use of BDA can

improve supply chain efficiency, enhance decision making, and improve sustainable performance (Zhu, Du, Shahzad & Wattoo, 2022). As such, the frequency of big data-related sentences in automotive company filings is 45% higher than in 2016 (GlobalData, 2021).

Big Data Analytics can be very useful in improving supply chain sustainability through its monitoring capabilities as it can be used to identify the sustainability impact of a company's supply chain in the past and help predicting and improving future sustainability impact (Chalmers & deLeon, 2020). In a recent survey (Beier, Kiefer, & Knopf, 2020) conducted among several professionals in the automotive industry, it was demonstrated that BDA could support environmental sustainability by using its multi-level analytical capability. First of all, it ensures a more accurate measurement of energy consumption within the supply chain. To achieve this purpose, all energy-relevant data are gathered in a common database to eliminate the data exchange via different individual systems. From this single source of data, a multi-site energy management system can be implemented, and BDA can then be used to analyze the information in real time and identify potential savings. Then, BDA can also be applied to enhance water consumption, which is needed in many processes such as cleaning, cooling, or painting. By tracking water consumption and using effective modeling, car manufacturers can better forecast expected consumption and some machines could be operated more resource efficiently. Finally, by tracking waste volumes and movements, BDA can be a means to detect trends and make predictions using current and historical data. Waste data management can also assist companies in drawing conclusions about the performance of the production line. In addition to the environmental benefits, these analyses can also generate savings and reduce specific production costs (Hofmann, Neukart, & Bäck, 2017).

Since automotive companies usually have a very large network of suppliers considering the numerous components and raw materials they need to source, BDA can assist them in optimizing their strategic sourcing. This helps organizations to improve their supplier relationship management by ensuring that their procurement processes are aligned to the organization's strategic goals and objectives (Scott, Ho, & Dey, 2013). BDA can offer companies the ability to improve their risk assessment by analyzing data related to quality, delivery guarantee or material availability. In addition, this technology is able to monitor all available data and news available on social media channels in connection with suppliers or the related market (Wang, Gunasekaran, Ngai, & Papadopoulos, 2015). All these methodologies therefore help to better assess the impact of sourcing on supply chain performance, thus assisting companies to make informed decisions. Besides supplier analyses that can be

performed in terms of costs and profitability, BDA also enables the monitoring of suppliers by focusing on the environmental and social aspects of sustainability. Due to low taxation, environmental regulations and cheap labor, automobile production has become an attractive option for some developing countries, but environmental degradation and non-respect of human rights can occur (Zhu et al., 2022). Nevertheless, advancement of information technology allows today to collect large amounts of data from each supply chain partners and BDA can facilitate management to take these issues into consideration. In terms of the social aspects, « *BDA can help with remote monitoring of labour issues, including compensation, likely use of forced or child labour and exploitation of communities where the supply chain facilities are located* » (Mageto, 2021, p.6). Moreover, Chen & Jia (2017) demonstrated that it was possible to select suppliers using a BDA model based on their environmental protection that aggregated data related to emissions and waste management.

Big Data Analytics is also considered as a crucial methodology to develop a sustainable product (Ali et al., 2020). In order to further consider the sustainability of a vehicle, the optimized calculation of life cycle assessments is often mentioned as a potential use case (Beier et al., 2022). However, the limited availability of environmental data across the entire life cycle of a car leads to the use of average data that do not allow to consider all these variables in an efficient way. However, with the different technologies mentioned so far, it is now more accessible to obtain information during the entire life cycle of a car. Automotive companies can use BDA methodologies to promote cooperation across departments, and especially regarding product development (Beier et al., 2022).

Another significant strength that Big Data Analytics can offer is the use of predictive analytics. This branch of advanced analytics can be defined as the use of current and historical data to make predictions about the future to anticipate trends or behavior based on the available data. In the automotive industry, this data-driven modeling can be a very efficient alternative for supplier network analysis, since a failure of a supplier to make a delivery on a critical component can stop the production line of car manufacturers. However, experience has shown that mapping all subprocesses and interactions between suppliers in detail is very challenging, especially when it comes to including lower-level suppliers. It is much more accessible to use BDA methodologies that gather data concerning suppliers, prices, delivery reliability and other variables to identify important supplier characteristics that are likely to affect the reliability of the entire production line. By using predictive analytics to simulate scenarios regarding its supplier network, automotive companies can identify and avoid critical paths in the logistics

chain (Hofmann et al., 2017). Vieira et al. (2019) demonstrated that the adoption of predictive analytics allows an automobile company to test disruption scenarios by considering the geographical situations of its suppliers and simulating the occurrence of events that may have direct and indirect impacts in the different plant. Furthermore, simulating the supplier network not only identifies potential bottlenecks, but also allows organizations to develop counteractive actions. For example, if a supplier regularly misses deliveries, organizations will often hold a higher quantity of products in inventory (Wang et al., 2016).

All the available technologies mentioned so far allow companies to collect a large amount of data. Using Big Data Analytics can be a great asset in order to exploit the maximum potential and to make strategic and development decisions with a more sustainable approach.

6.2.4. Artificial intelligence

Artificial intelligence (AI) is a term that appears more and more in our daily life and is used more frequently nowadays. Artificial intelligence can be defined as a branch of computer science that consists in developing a computer technology capable of acting or thinking like a human being (Kazancoglu et al., 2022). An AI can imitate, learn, and eventually replace human intelligence (Jarrahi, 2018). So far, this technology of advanced analysis relies mainly on optimization, in-depth learning, and machine learning. Machine learning (ML) is a subcategory of artificial intelligence that uses algorithms and a large amount of data to learn desired behaviors, recognize patterns but can also adapt to new situations. (Mayer, Gandhi & Hecht, 2019). AI is now considered as a technology likely to give a real competitive advantage as it can be used to optimize the supply chain through many applications that we will go through. Given its rapid advancements, particularly in machine learning, this technology is becoming one of the main players taking part in the car manufacturing processes. Its application can potentially bring many savings for automotive companies, but it can also help support sustainable development. According to a 2018 McKinsey survey, AI will reach a total accumulated value for automotive OEMs worldwide of USD 215 billion by 2025.

In the automotive industry, demand planning and production management are the most important factors to ensure the performance of sustainable supply chains (Nguyen, Li, Spiegler, Ieromonachou, & Lin, 2018). However, unexpected events and lack of information can lead to fluctuations in demand, and it becomes highly challenging for companies to maintain the resilience of their supply chains (Kazancoglu et al., 2022). As we have seen with COVID-19, automotive companies with complex supply chains have encountered difficulties in managing

their demand planning process and subsequently their production management. This information gap leads to a mismatch between supply and demand in SSCs and communication issues between the different partners (Queiroz, Ivanov, Dolgui & Wamba, 2020). As a result, traditional demand and supply planning approaches have become inadequate and automotive companies can no longer afford to plan on a periodic (quarterly or annual) basis without compromising the resilience of their supply chains (Koricanac, 2021). In this environment, AI technology « *which can be used to match demand and supply, will prevent an information gap since it will operate using real data* » (Kazancoglu et al., 2022, p.6). This AI support for demand forecasts, sales activity, and future market opportunity can provide a real advantage to automotive industry actors and can assist in better strategic decisions, especially since the consumer's demand is evolving at a very fast pace (Mayer et al., 2019).

Inventory Management is a crucial activity in the automotive industry and to mitigate the difficulties that may arise, it is essential to accurately predict the amount of stock and determine optimum stock levels (Kazancoglu et al., 2022). However, precisely predicting and accessing these inventory levels by traditional decision rules is not straightforward as it generally depends on the experience and judgment of inventory managers (Tirkolaei, Sadeghi, Mooseloo, Vandchali, & Aeini, 2021). Therefore, the support of technologies such as AI can optimize real-time inventory management and provide increased visibility of optimal inventory and production levels. On one hand, genetic algorithm, one of the sub-technologies of AI, by analyzing data such sales price, sales amount, and productions costs, can « *creates prediction models with the least error rate and provides improvement in inventory management in the automotive industry* » (Kazancoglu et al., 2022, p.14). On the other hand, machine learning can help companies to find hidden inventory patterns in order to realize significant savings (Tirkolaei et al., 2021).

Increasing competition in automotive industry requires companies to make efficient and cost-effective decisions and AI technology can help them to improve their purchasing processes. In the context of the COVID-19 period, the automotive industry has encountered many difficulties with the supply of raw materials, which have caused large disruptions in production and increased costs (Kazancoglu et al., 2022). In this context, machine learning, via data clustering algorithms using data and indicators in the planning stages of supply chains, can facilitate and ensure effective planning procurement (Dzalbs & Kalganova, 2020). In addition, the automotive industry used to rely on virtual agents to capture early payment discounts and detect errors in invoices or fraudulent activity. But with today's much more developed AI

technology, they can now perform other activities such as predicting future pricing patterns and conduct advanced risk assessments (Mayer et al., 2019). A recent survey (Schulze-Horn, Hueren, Scheffler, & Schiele, 2020), conducted with automotive industry professionals, also showed that AI can be a considerable asset in the negotiation process. Indeed, most automotive suppliers send quotes with a detailed cost breakdown, but this data is neither stored nor processed systematically because it requires a considerable amount of additional capacities. It has therefore been demonstrated that AI technologies is able to retrieve this data to facilitate negotiations with these different suppliers.

Implementation of digital technologies such as AI can also help companies to improve the traceability of their supply chain. Indeed, monitoring every stage in multi-layered global supply chain allows companies to respond more rapidly to unexpected problems and AI can help to expand and foster this traceability (Kazancoglu et al., 2022). Thus, for example, The Volkswagen Group's Porsche, Audi, and Volkswagen brands use artificial intelligence to identify sustainability risks such as human rights abuses and environmental pollution, among their direct partners, but also for lower-level suppliers. This monitoring is performed by an intelligent algorithm developed by the Austrian company Preware, which analyzes and identifies supplier-related news published on the Internet in 50 different languages and in more than 150 countries worldwide. If the AI identifies any sustainable risks, the automotive brand is immediately notified to investigate the situation and undertake the appropriate corrective actions. Since the launch of the project in October 2020, this intelligent algorithm has been able to monitor more than 4000 suppliers (Porsche, 2021).

Using AI technology can also provide a considerable advantage regarding predictive maintenance. On one hand, by analyzing data in real time, it can further predict machine maintenance and reduce interruptions in production lines. Machine Learning can indeed avoid unplanned maintenance and improve predictive maintenance schedules thus enhancing the efficiency of operations and reducing costs by avoiding unplanned downtime (Mayer et al., 2019). On the other hand, by leveraging AI solutions, automotive industries can also keep track of a vehicle's part health and act prematurely when it requires maintenance. These precautionary measures facilitated by the analysis of algorithms are a great asset to avoid a breakdown and thus, promote the lifetime of the vehicle.

Artificial intelligence is also recognized as having a great potential in the Research and Development and during the development stage of the product life cycle (Schulze-Horn et al., 2020). For example, AI can assist the automotive engineer to take cost parameters into account

and suggest alternative materials with similar characteristics. This can really deliver impressive results and support project decisions across all departments (Hofmann et al., 2017). Besides suggesting materials, AI can also help calculate complex models, using estimates and previous data sets (Mayer et al., 2017). For example, the BMW Group uses AI technologies to help employees process more carefully and quickly the 33,000 requirement specification documents, containing 30 million individuals' information about vehicles, components, and characteristics. A survey (Al-Alawi, Abdul-Wahab, & Bakheit, 2008) had already proven earlier the use of this technology in the design of car components. The authors used artificial neural networks (ANNs), a sub-field of artificial intelligence used for complex problem solving, to create an optimization model of an automotive component for maximizing its reusability, increasing its reliability, and minimizing its life cycle cost. Finally, we can also recall that AI is currently at the heart of the development of autonomous vehicles, which are expected to significantly increase mobility safety and reduce CO₂ emissions in the future (Williams, Das & Fisher, 2020).

Another area where AI can bring real added value is the optimization of the whole distribution network to make it more efficient (Mayer et al., 2019). Vehicle routing for distribution can turn out to be quite an important issue in the supply chain management of automotive companies (Tirkolaee et al., 2021). Machine learning is able to generate better delivery routes in a fast and objective way, making complicated computations much faster than the human brain. Indeed, this technology allows to consider simultaneously a multitude of data and parameters such as vehicles, infrastructures, fuel efficiency or even contractual agreements (Kumar et al., 2021) (Tirkolaee et al., 2021). For example, Ćirović, Pamucar and Božanić (2014) developed a model of light delivery vehicle routing using an adaptive neural network. This model demonstrated that artificial intelligence optimized the entire delivery process by making it more efficient, but more importantly, more environmentally friendly. In fact, this Ai-based system managed to establish the routing of vehicles while limiting harmful gas emissions, and an improvement in air quality since the system took care to avoid areas with high population concentrations.

It is also possible to use AI technology to increase sustainability through the intelligent utilization of energy consumption. AI has the ability to compress and analyze data coming from the whole production process in order to reduce polluting emissions and improve the environmental footprint of the company (Cioffi, Travaglioni, Piscitelli, Petrillo, & De Felice, 2020). A recent study (Sishi & Telukdarie, 2021) concluded that the use of AI technology could

optimize supply chain processes to decrease energy demand and CO2 emission. For the development of this model, the energy requirements of the different business functions were stored in a database. Then the AI, through complex algorithms, targeted energy consumption and identified the optimal level of energy needed for each operation. This allowed to monitor the influence of each of the resources on the energy demand in order to allow the organization « *to pinpoint and optimize business processes to achieve low energy demand* » (Sishi & Telukdarie, 2021, p.5). In 2020, Renault signed a partnership with Google to benefit from its expertise in machine learning to save between 10% and 30% of the energy consumption of its production lines, starting with the paint shops (Google Cloud, 2020). In another measure, BMW is conducting R&D work on AI-based software for in-vehicle energy management. The principle is that by taking the user's behavior and route information, the system can adjust energy consumption to reduce CO2 emissions (BMW, 2022).

Among other things, the last step of the production line in car manufacturing is the final check just before distribution. In this workshop, last repairs or modifications can still be done by the worker and this inspection is usually done visually by an operator. However, after several checks per day, the operator may be tired and may misqualify a component control. Today, there are AI technologies that can help in this process to support the workers and decrease the risk of product recall (Hachem, Perrot, Painvin, & Couturier, 2021). As an example, General Motors partnered in 2022 with UVtech to develop AI final inspections. This system uses high-definition camera and AI to quickly and accurately check all components of the car to detect any default, missing parts, or other safety-related issues (RDN, 2022).

The applications of artificial intelligence are therefore very numerous and can bring many benefits to car manufacturers in order to improve the efficiency and sustainability of their supply chain. According to Trikolae et al. (2021), this technology can help the circular economy. First of all, by designing circular materials by rapid ML-driven prototyping and testing. Then, by operating circular business models by improving product circulation through intelligent demand prediction, pricing, inventory management and predictive maintenance. Finally, in optimizing circular infrastructure by enhancing components remanufacturing, products sorting and disassembling, and materials recycling.

6.2.5. Additive manufacturing

Additive manufacturing (AM), also known as 3D printing, is a process to build parts and objects in three dimensions from a computer-aided design (CAD) model, by successively adding materials layer-by-layer (Zhang & Liou, 2021). This technology differs from conventional manufacturing processes such as machining or forging. Today, there are different techniques to build three-dimensional objects (Binder Jetting, Directed Energy Deposition, Powder Bed Fusion, Wire Arc Additive Manufacturing, Vat Polymerisation, Material Extrusion) and several materials can be used such as plastic, metal or composites. These different possible combinations of methods and materials provide many possibilities depending on the desired product attributes. (Zhang & Liou, 2021). With decades of development and due to the many applications this technology offers, its use is growing rapidly and is believed to have great potential to disrupt or revolutionize many different industries (Walachowicz et al., 2017). The advent of additive manufacturing and the expansion of its functionality is often attributed to its early adoption by the automotive industry, which was one of the first to employ AM processes and is further extended today (Charles, Hofer, Elkaseer, & Scholz, 2022). According to a 2013 McKinsey survey, the top four markets for AM are consumer products, aerospace manufacturing, medical components and tools, and the automotive industry. Together, they are expected to account for 86% of the total manufacturing market by 2025. Additive manufacturing can be applied in sustainable projects, processes, and products in the automotive industry, mainly because this integrated practice can be used in both new projects and in the maintenance of existing products (Dev, Shankar, & Qaiser, 2020).

One of the most appreciated benefits of additive manufacturing in the automotive industry is its ability to revolutionize the design of certain components. First of all, using 3D printing instead of traditional manufacturing reduces the weight of components, leading to a reduction in vehicle fuel consumption (Böckin & Tillman, 2019). The Volvo Group has estimated, based on an average of all test prints made, that 3D-printed components can reduce weight by 25% (Böckin & Tillman, 2019). Electric vehicles, which are now at the core of car manufacturers' strategies and an important factor for environmental sustainability, can also benefit from this weight decrease. Indeed, to improve the autonomy of electric cars, range extension can be achieved by reducing weight or by adopting more efficient management (Charles et al., 2022). Volkswagen Group, to explore this approach, partnered with Siemens in 2018 to reduce the weight of several components using the metal binder jet method. While reducing vehicle weight is usually one of the most targeted assets among car manufacturers, there are other benefits from adopting this technology in design as well. First, 3D printing facilitates assembly and

disassembly because it creates a whole item that does not need assembly, which can shorten the supply chain (Javaid, Haleem, Singh, Suman, & Rab, 2021). Moreover, Quinlan, Hasan, Jaddou and Hart (2017) noted that the more complex a product is, the more advantageous AM becomes, since the cost and energy are not dependent on component complexity. Second, the technical opportunities of AM can create cooling channels that could not have been obtained by traditional metal forming processes to "*create a better and stronger product and a further optimized process*" (Charles et al., 2022, p.343). Third, the techniques of this technology facilitate redesign because it is much easier and more accessible to adjust minor parts (Isasi-Sanchez, Morcillo-Bellido, Ortiz-Gonzalez, & Duran-Heras, 2020).

Another significant aspect of additive manufacturing is the reduced need for resources, implying less need for raw material and less waste. First of all, it permits the use of new structures, like the honeycomb, which are more stable compared to a fully dense component and require less raw material in its production process (Charles et al., 2022). Then, the fact that the printing components are generated by topology optimization and computer algorithms, resulting in controlled structure and volume, offers the opportunity to use exactly the required resource without any waste (Isasi-Sanchez et al., 2020). Finally, additive manufacturing can be adopted to speed prototyping and assist in reverse engineering (Javaid et al., 2021). Indeed, prototyping can be very costly for companies and the adoption of this technology for this purpose has become a cost-effective choice for corporations as it requires less raw materials and 3D-printed additives provide a real advantage. In this regard, since 2017, Ford has been using this technology in partnership with Stratasys to create some parts of their low-volume vehicles, but especially for some parts of their prototypes at the Ford Research and Innovation Center in Michigan.

Additive manufacturing can also have a considerable impact on spare parts for remanufacturing and repairing. This is mainly since « *the additive, rather than subtractive, nature of AM technology means that more of the input material ends up in the final component, thereby reducing material losses* » (Böckin & Tillman, 2019, p.978). A recent survey (Isasi-Sanchez et al., 2020), which studied the adoption of this technology in a Spanish mid-size car brand specialized in after-sales activities, showed that the adoption of 3D printed spare parts led to a 12.3% reduction in total material. In addition, printing spare parts on demand can reduce the need for manufacturers to maintain a complete spare part inventory. It is indeed more challenging to assess the demand for this type of products and the adoption of this process could decrease warehousing costs, as well as material savings from avoided loss of unused parts

eventually discarded (Holmstrom & Gutowski, 2017). In order to leverage this business opportunity, Nissan has been using HP's 3D printing technology since 2021 for some parts of the R32 Nissan Skyline GT-R model, for which the car manufacturer is still legally required to provide replacement parts (AutomationWorld, 2021). Nissan is taking advantage of this technology to supply its parts, which are more demanding in terms of raw materials than current parts, and to manage its inventory differently. 3D printing spare parts can also extend the life of vehicles through these repair opportunities. For example, Kellens et al. (2017) estimated, through their survey on printed spare parts, that environmental or energy improvements between 36% and 75% can be achieved. This may also encourage users to purchase only the spare part they need rather than buying the complete assembly. However, while this may have positive effects, we can suggest that this extended lifespan should not allow older vehicles, which would not benefit from the energy improvements, to remain on the road for too long.

While additive manufacturing can be very valuable for spare parts, this technology could have a broader impact and make the entire life cycle of vehicles and its components more sustainable. Colorado, Velasquez and Monteiro (2020) noted that remanufacturing of recycled waste is a key element to fostering the implementation of the circular economy using additive manufacturing technologies. Remanufacturing is the reuse of recycled materials to create new products. In a recent study, Nascimento et al. (2022) proposed a circular model that would use a sustainable 3D printing process for recycling metal components in the automotive industry (Figure 7). Metal has the ability to be recycled into powder, which can then be used as a raw material for 3D printing. The model aims to take advantage of this attribute to propose a circular economy initiative for metal parts in cars. This study and this model have been evaluated by experts from the automotive industry, which reinforces the consistency of this approach. The model can be summarized in 7 steps:

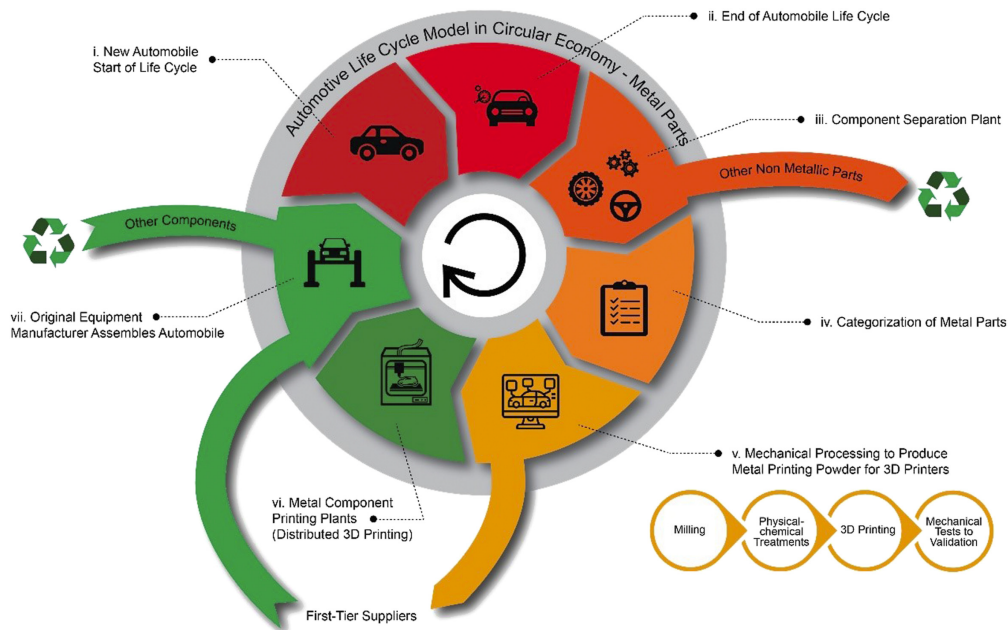


Figure 7. Nascimento et al., (2022), *Automotive life cycle model in a CE metal parts*

- (1) At the end of the vehicle's life, it is completely disassembled to get access to all the components.
- (2) In specialized plants, the components are separated into metal and non-metal elements and the non-metal elements are transferred to specialized recycling suppliers.
- (3) Since the goal is to remanufacture metal parts, it is important to gather components that have the same properties.
- (4) The various metals collected are then transformed into powder for the 3D printers.
- (5) This metal powder is distributed to plants as raw material to produce new vehicle parts.
- (6) The OEMs receive these new metal parts and combined with other recycled non-metal components provided by other suppliers, a new car can be produced.
- (7) The new vehicle is released on the market until the end of its life cycle.

This circular economy model represents an emerging opportunity for the automotive sector to better manage the life cycle of its products. Although this circular economy approach using additive manufacturing is still theoretical, Ford nevertheless seems to have identified the possibilities of this process. Indeed, by partnering with HP in 2021, the car manufacturer is already using this metal powder as a raw material for 3D printing certain injection components for its Super Duty F-250 trucks. The brand estimates that 90% of its vehicle components are recyclable and has a long-term goal of using this technology for the remaining components of its vehicles (AutomationWorld, 2021).

Another result of this technology is the reduction of the complexity of the global chain. Indeed, to assemble a component, it usually implies a large supply chain composed of different raw materials and subparts that must transit between several suppliers, and sometimes between different countries. This production process usually involves « *a large material and energy build-up along the supply chain, which can be largely avoided by on-site AM manufacturing* » (Charles et al., 2022, p.343). This multiplicity of stakeholders and production steps has a considerable impact on the carbon footprint of companies. In addition, raw material for the printers can be packed more densely than components or finished products, implying less shipping units required for the same amount of resources or products. At the same time, the reduction in weight that needs to be processed or moved during the process decreases the energy consumption (Charles et al., 2022). Even if these changes seem insignificant and having limited impact, if considered on a large scale, all these successive actions can definitely decrease CO2 emissions and promote environmental sustainability. In this regard, in their study on the use of 3D printing in the Spanish automotive company, Isasi-Sanchez et al. (2020) also addressed a new conception of the supply chain. In the traditional business model, the consumer is supplied directly from the dealers because they have no other alternative to order the original parts. But with additive manufacturing, he can be directly supplied by nearly all the stakeholders using 3D printers, the "*Additive Manufacturing Hub*". According to their estimation, the energy saving by this model could reach up to 9,2%, considering the important decrease in transportation.

This printing method can significantly reduce the number of ties in the supply chain by enabling local, on-demand manufacturing of a wide range of products and components and in the coming years, additive manufacturing could likely eliminate millions of shipping trips (Javaid et al., 2021).

Finally, on-site additive manufacturing also allows companies to have a "*digital warehouse*" where all 3D models can be stored online and used when needed (Nascimento et al., 2022). Besides being more cost effective in terms of inventory, this results in reduced energy consumption since « *AM equipment has the potential to be stackable, making space-saving vertical multi-level production structures with printer farms a real possibility* » (Charles et al., 2022, p.343)

In conclusion, it is worth highlighting that while many studies are emerging on the economic and environmental sustainability, research on the social benefits of this technology is very limited. Nevertheless, research and development for this technology towards new printing methods and new materials is constantly growing (Isasi-Sanchez et al., 2020). Therefore, additive manufacturing is likely to be more and more incorporated in the industrial processes in the future and this could only promote the circular economy and the sustainability of manufacturing resources (Godina et al., 2020). In the automotive industry, additive manufacturing could play an important role in reducing the life-cycle environmental impact of vehicles. However, before any industrial application, Isasi-Sanchez et al. (2020) noted that car manufacturers wishing to incorporate this technology into their supply chain should not overlook the liability and intellectual property risks. Additionally, the Covid-19 pandemic has demonstrated some weaknesses in the automotive industry's supply chain in terms of component sourcing. Even if 3D printing cannot replace all traditional manufacturing methods, automotive companies could still rely on this technology to limit the sourcing of raw materials, parts, and tools.

6.2.6. Augmented/Virtual reality

Augmented reality (AR) and virtual reality (VR) are two technologies known for their enriched experience that combine a virtual world with the real world using three-dimensional visuals. Nevertheless, even if these two digital technologies offer another perception of the environment to its user, they are slightly different. Augmented reality consists in integrating virtual components into the real world, thus enabling an enriched reality (Boboc, Florin, & Butila, 2020). In the supply chain, AR applications integrate graphics and elements into the current surroundings of the worker and allow him to access and interact with the information integrated in his work environment (Demir, Yilmaz, & Paksoy, 2020). Regarding virtual reality, Berg and Vance (2017) define this technology as an advanced interface that allows the user to have an immersive experience of the world beyond reality and to interact with it. In other words, while VR replaces the real world with an artificial environment, AR enhances that real environment rather than replacing it. These two technologies are used in automotive supply chains for their multiple applications, and it is estimated that today, 65% of automotives manufacturers use these digital simulations to operate products and assets within their supply chain (Accenture, 2021).

Logistics processes in the automotive industry are generally highly sophisticated and the application of AR and VR technologies can both improve efficiency and make them easier and safer for the workforce. Firstly, augmented reality can be used in the form of ultra-high-resolution projections that allow to map the working environment and to project graphic elements. This AR application, in the form of text, numbers, and geographic figures, can determine optimal positioning, fixing points, protective measures for certain components, or specific instructions projected on a specific part, on the part carrier, or on the floor. This type of augmented reality is generally used for informational purposes to improve handling operations and to minimize the errors that may result (Čujan, Fedorko, & Mikušová, 2019). The use of VR on the other hand contributes to the circular economy «*through the digital optimization of disassembly processes, thus increasing manufacturers' capacity of recovering valuable components and improving material restoration*» (Chen, Gong, Berce, Johansson, & Despeisse, 2021, p. 465). Secondly, if the application of augmented reality makes the processes more efficient and faster, it also supports the operators in their daily tasks. This assistance by augmented reality that provides information on the steps to follow, the tools to use, and the critical points improves safety and reduces the learning time and mental effort (Boboc et al., 2020). Audi is currently using the next generation of Microsoft's HoloLens to represent holograms that help planners to better assess the future situation. Thanks to this, the brand explains that prototypes of containers or equipment, which are complicated to produce, are no longer necessary. In addition to displaying checklists and operating instructions, these glasses allow operators to have their hands free to focus solely on their tasks.

Virtual reality can revolutionize the design and prototyping of vehicles. Car design is a process that requires continuous reviews and modifications before the car reaches the production stage. This process is generally the most time consuming, but also the most expensive since the early design phases can impact up to the 70% of the total cost of a vehicle (Lawson, Salanitri & Waterfield, 2015). Indeed, car manufacturers use many test vehicles per model, depending on whether the design changes are major or minor. Nevertheless, thanks to the progress in the capabilities of software and hardware, VR can now provide the ability to replicate these physical models in a digital way. This technology helps to determine the input requirements, to give recommendations for improving the process or the product but also to evaluate whether it will be possible to mount parts and components or not. This streamlined review process therefore improves decision making and early design fault recognition (Aromaa, Viitaniemi, & Leino, 2014). Furthermore, another strength of virtual reality is the virtual simulation of physical phenomena and crash tests (Čujan et al., 2019).

The use of virtual reality in the design and prototyping of vehicles has many benefits and helps to achieve economic, environmental, and social sustainability. Firstly, it really makes work faster and easier since it is possible to consider different life cycle phases in the early product design phase such as modifications and operator assembly and maintenance tasks (Aromaa et al., 2014). VR technology also accelerates the development of autonomous electric vehicles, thereby reducing carbon footprint through simulation testing. Second, by replacing physical materials, the need for resources and energy, is significantly reduced. Third, by saving resources and energy, it makes VR technology very cost-effective in the long term as it reduces the costs of the entire process. Fourth, using VR different processes of product development can increase the quality of the final products and consumer satisfaction (Lawson et al., 2015). Fifth, virtual reality is safer because it is a secure environment to test critical tasks (Aromaa et al., 2014). Since 2017, Hyundai has been using VR technology to enable the company's engineers to mill full-scale models, and 80% of Hyundai's design development is entirely digital. This allows the company to create models and immersive environments and to test unlimited color options and material applications. According to the automotive brand, this process saves time, reduces shipping and travel costs, and produces less waste, resulting in a dramatic reduction in CO2 emissions (Hyundai Press, 2019).

Another useful feature of AR and VR technologies is the ability to communicate and work on the same prototype, between different teams, and in different locations around the world (Lawson et al., 2015). A recent survey (Chen et al., 2021) demonstrated that the application of VR could improve communication efficiency and technical discussions, thus reducing travel trips, with the potential of reducing CO2 emissions. For this research, the Chinese manufacturing site of an automotive company was virtually reproduced using 3D laser scanning technology to immerse other operators located in the development center in Sweden. Almost all operators estimated that this could reduce travel frequency by 20% and half of them estimated that it could go up to 60%. Hyundai is currently using this functionality to enable real-time virtual collaboration between its different design centers (Hyundai Press, 2019). Another example is the use of HoloLens glasses by Skoda, which uses this technology to enable technicians to share their work environment with off-site colleagues (Skoda, 2021). Given the current health crisis and the various lockdowns, these features can provide real solutions for automotive companies.

The application of VR and AR can also provide a considerable added value to improve the operators training in the automotive industry. Trainings for assembly and maintenance can be largely facilitated by AR as it can be highly personalized depending on the level of expertise of the operator. In addition, the training process is made more intuitive by in real-time instructions that are displayed by the AR (Boboc et al., 2020). Regarding virtual reality, it can be used to recreate a virtual environment to first train operators to perform operations on the entire production line, or on isolated vehicle parts, to improve their efficiency in the real environment (Quevedo et al., 2017). Borsci, Lawson, Salanitri and Jha (2016) demonstrated that virtual reality training accelerates and improves learning. They showed that participants who were trained by VR on two car service procedures performed better on the physical equipment than participants who received traditional training through video instructions.

6.2.7. Advanced robotics

The automotive industry pioneered the use of robots, first by including collaborative robots, also called cobots, whose mission is to assist humans along the production line. Nevertheless, robotics is evolving very quickly and there are now many different varieties of robots. Most robots present today in the automotive industry are automated robots but recently, with the emergence of new technologies of Industry 4.0, we are seeing the emergence of intelligent and autonomous robots (Sun, Yu, Solvang, Y.Wang, & K.Wang, 2021). The automotive industry is now the largest user of robots among manufacturing industries, accounting for about 30% of total installations (International Labour Organization, 2021).

Autonomous robots can be defined as highly intelligent machines, capable of self-assessment and self-organization, and able to make decisions to perform certain tasks without human instructions (Sun et al., 2021). These robots can be of different sizes and have different levels of intelligence, mobility, and autonomy. The presence of autonomous robots in the manufacturing process will certainly increase over the next few years, especially within supply chain operations that include lower-value as final assembly and warehousing for example. They can be used to improve the speed and accuracy of routine operations, reduce inventory checks, and minimize the risk of error (Görçün, 2022).

These autonomous robots, in addition to being able to improve the efficiency of certain operations within the value chain, have the potential to significantly improve the working conditions of operators. First of all, using autonomous robots to perform repetitive tasks

improves the well-being and satisfaction of employees because it allows them to shift to more strategic work that is more stimulating (Kousi, Koukas, Michalos, Makris, & Chryssolouris, 2016). Then, in the future, more hazardous tasks will be able to be carried out by robots, thus moving workers away from dangerous environments. Moreover, working in collaboration with robots allows employees to improve their efficiency and thus reduce stress and anxiety. Finally, autonomous robots can carry and move heavy loads in a repetitive manner, thus limiting the physical effort of operators and reducing the risk of injury (Shamout et al., 2022).

Today, most automotive companies use automated logistics systems based on Automated Guided Vehicle (AGV). These static path vehicles use pre-determined paths between a starting point and a destination point for moving unit loads of materials between different locations on the production line (Gul & Rahiman, 2019). Although once programmed, these vehicles can navigate without human interference, their capabilities remain limited. Nevertheless, with the advancement of other technologies, AGVs are now undergoing rapid technological development to become more autonomous and flexible. Today, the highest AGV level are Autonomous Mobile Robots (AMRs). By combining technologies such as big data, internet of things and artificial intelligence, their degree of autonomy is significantly increased, and they no longer require the creation of pre-defined paths (Cech et al., 2020). The BMW group, by partnering with Nvidia in 2021, is currently testing this technology to facilitate the movement of products and vehicle parts without human intervention to allow operators to handle more critical tasks (BMW Press, 2021). Another example is the partnership between Toyota and Bastian Solutions, which aims to develop a new generation of AGVs, expected to be fully autonomous (Robotics & Automation, 2020).

Another technology that is expected to be talked about more and more these days is Robotics Process Automation (RPA). RPA is a new technology that aims to create software robots (bots) that can mimic human behavior across various applications (Doguc, 2020). Jain (2019) has shown that this technology can improve the efficiency of operations in the automotive industry. Like the adoption of autonomous robots, it frees human execution of repetitive tasks. But the adoption of this technology can also drastically improve the delivery of useful reports and data to increase the efficiency of processes. For instance, it can automatically generate revenue forecasting, inventory levels, defects, quality assurance or compliance and auditing outputs.

6.2.8. *Cloud computing*

Cloud computing can be defined as « *a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction* » (NIST, 2011). In other words, this on-demand technology offers computing services such as servers, storage, applications or even licenses as a service, requiring no substantial management. Even if all the technologies discussed so far can indeed significantly improve the efficiency and sustainability of automotive supply chains, the infrastructure and resources required can be a major constraint. Cloud computing therefore seems to be a potential solution for automotive companies that would like to benefit from the advantages of other technologies without considerable investments in their IT infrastructure and in the hiring of qualified personnel.

Adopting a cloud computing service has many benefits for businesses. First of all, organizations can choose the services that are most advantageous and strategic for them. This aspect is significant because automotive companies that would like to adopt this service can analyze in which functions they perform best and thus choose only the services for the functions in which they have shortcomings (Wang, Hou, Zhang, & Fang, 2021). Next, this technology can reduce the costs of organizations since it is no longer necessary to invest in complex IT infrastructures and make investments that can be profitable only in the long run (Pankowska, Pyszny, & Strzelecki, 2020). Moreover, it is a time saving alternative. Besides saving time by avoiding long-term investments, companies can focus on their own business and do not have to spend a lot of time and effort in unfamiliar fields (Wang et al., 2021).

The most noticeable feature of cloud computing is that it enables efficient storage and management of a very large amount of data (Schniederjans & Hales, 2016). The other Industry 4.0 technologies discussed so far can generate a very large amount of data of different types and from different sources. Nevertheless, not all automotive companies have the means to store all this data. Moreover, access to this data stored in the cloud is immediate and can be done anytime, from any device (Pankowska et al., 2020). In the automotive industry, cloud computing can be an effective solution as the companies' partners and suppliers are numerous and are frequently in different countries. This would allow, under a confidentiality principle that will depend on the type of data, the sharing of this data instantly and foster collaboration through one common platform. Thus, the BMW group announced in 2020 a collaboration with

Amazon Web Services on cloud-based data management. For the automotive group, this will increase sustainability across all aspects of the automotive life cycle, from design to after-sales services, by improving data management. (BMW Press, 2020)

Regarding energy consumption, Cloud Computing can also support companies in an environmental sustainability perspective. Traditional data hardware systems require a very large and continuous supply of electricity. If companies could move most of their IT needs to the cloud, this old equipment would no longer be available, resulting in savings in maintenance and energy consumption (Kumar & Vidhyalakshmi, 2012). However, in order to be sustainable on a global scale, this requires other implications that will be discussed later in the risk section.

Finally, automotive companies are likely to turn to cloud computing for its potential strengths in the development of autonomous vehicles (Kong, Khan, Wu, Chen, & Zeng, 2017). These future autonomous vehicles, which can play a key role in the environmental sustainability of mobility, will be equipped with sensors, radars, and cameras. Cloud solutions can support this continuous flow of data and provide a continuous service to ensure their use and security.

7. Sustainable supply chain framework

After reviewing the different Industry 4.0 technologies and their potential to enhance economic, social, and environmental sustainability, we can propose a framework that automotive companies should follow in order to achieve a sustainable supply chain (Figure 8).

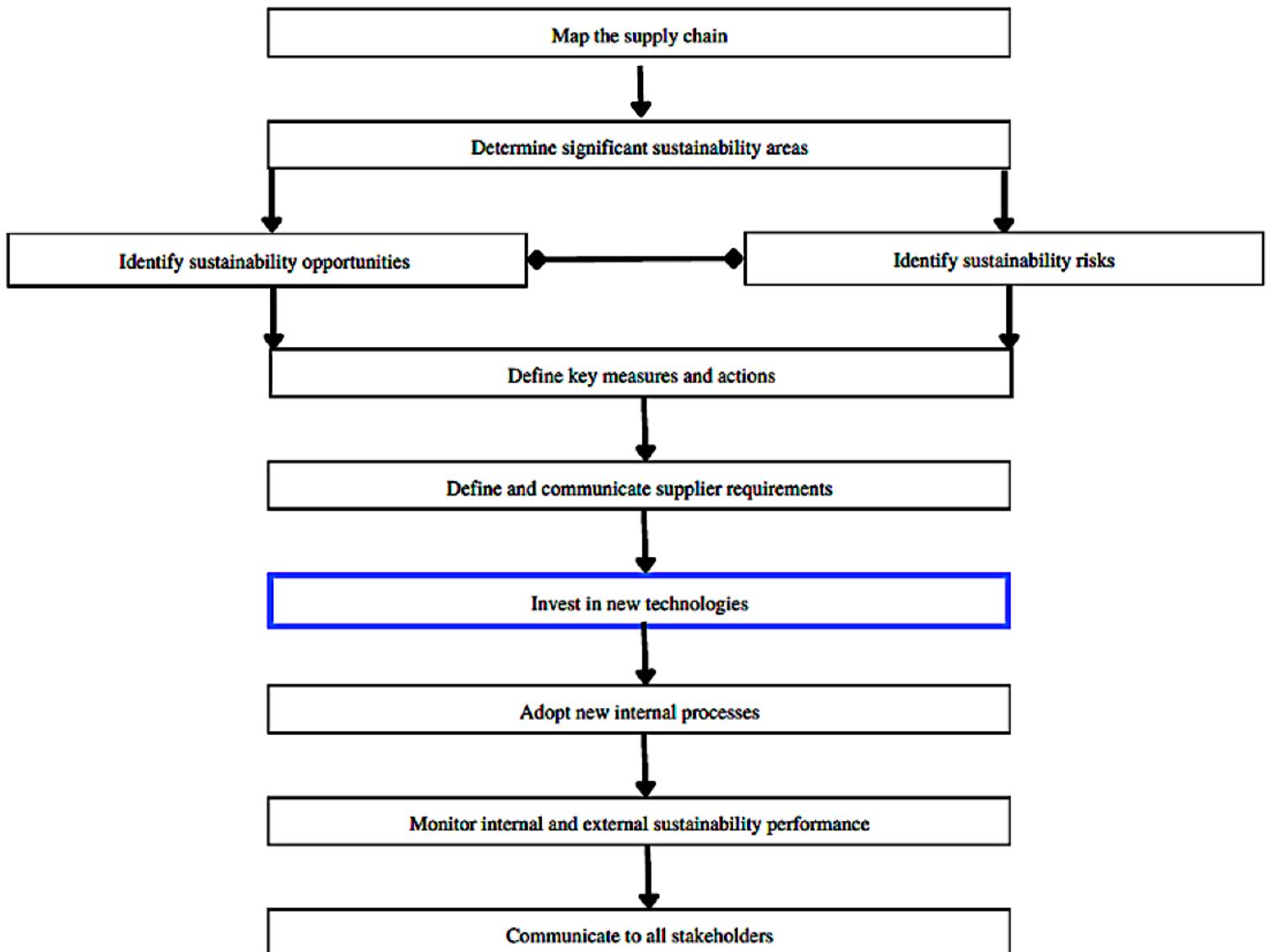


Figure 8. Proposed framework for SSC in automotive industry

The first crucial step before undertaking any reflections is to make sure you map your supply chain to get an overview of the value creation process. If you want to adopt a sustainable approach, it will be necessary to also identify the lower-level suppliers as the sustainable risks are more likely to come from them. Then, after gathering this information and increasing visibility, it will be necessary to identify the main social and environmental sustainability risks. This can, for example, identify raw materials for which the risk of human abuse is high and where the extraction process generates a lot of greenhouse gas emissions. Then, the automotive company can make the choice to reduce the identified risks or to take advantage of any sustainable opportunities that have been identified. Obviously, it is not excluded that a company may decide to include both options in their strategy. Then, after identifying the areas of improvement, the automotive company must define the actions to be taken in order to achieve the envisaged objectives. This step also involves evaluating which resources and stakeholders should be involved in these objectives. The next step, which consists in defining the expectations towards the suppliers, is crucial for the efficiency of the model. It is of course essential to inform them of the strategy the company wants to pursue and the efforts and processes they expect from them.

Given the many benefits that Industry 4.0 technologies can offer, automotive companies should consider integrating them into their supply chain. Even if these investments can be high, in the long run, economic and environmental benefits will result from their implementation. Nevertheless, the adoption of these new technologies will require new internal processes to get the maximum potential from the investments made. While the acquisition of these technologies can improve supply chain efficiency, it will require a rethinking of how vehicles are designed, sourced, manufactured and distributed. Monitoring will be a crucial function for the model to be bearable. It is only by analyzing and interpreting the impacts that the automotive company can afford to extend, improve or stop certain processes. The monitoring of suppliers will be a function apart to ensure that their commitments are met and if not, to support them with investments or incentives and in extreme cases, to exclude them from the supply chain. Finally, communicating the results to all stakeholders will make them aware of the efforts made and the results obtained, in order to promote the sustainable approach and increase the commitment of the various internal and external partners.

8. Supply chain processes optimization

Adopting the various technologies of Industry 4.0 can enable automotive companies to optimize and make their supply chain more sustainable, with benefits across their activities (Figure 9). We will discuss and present the potential benefits and internal process changes involved.

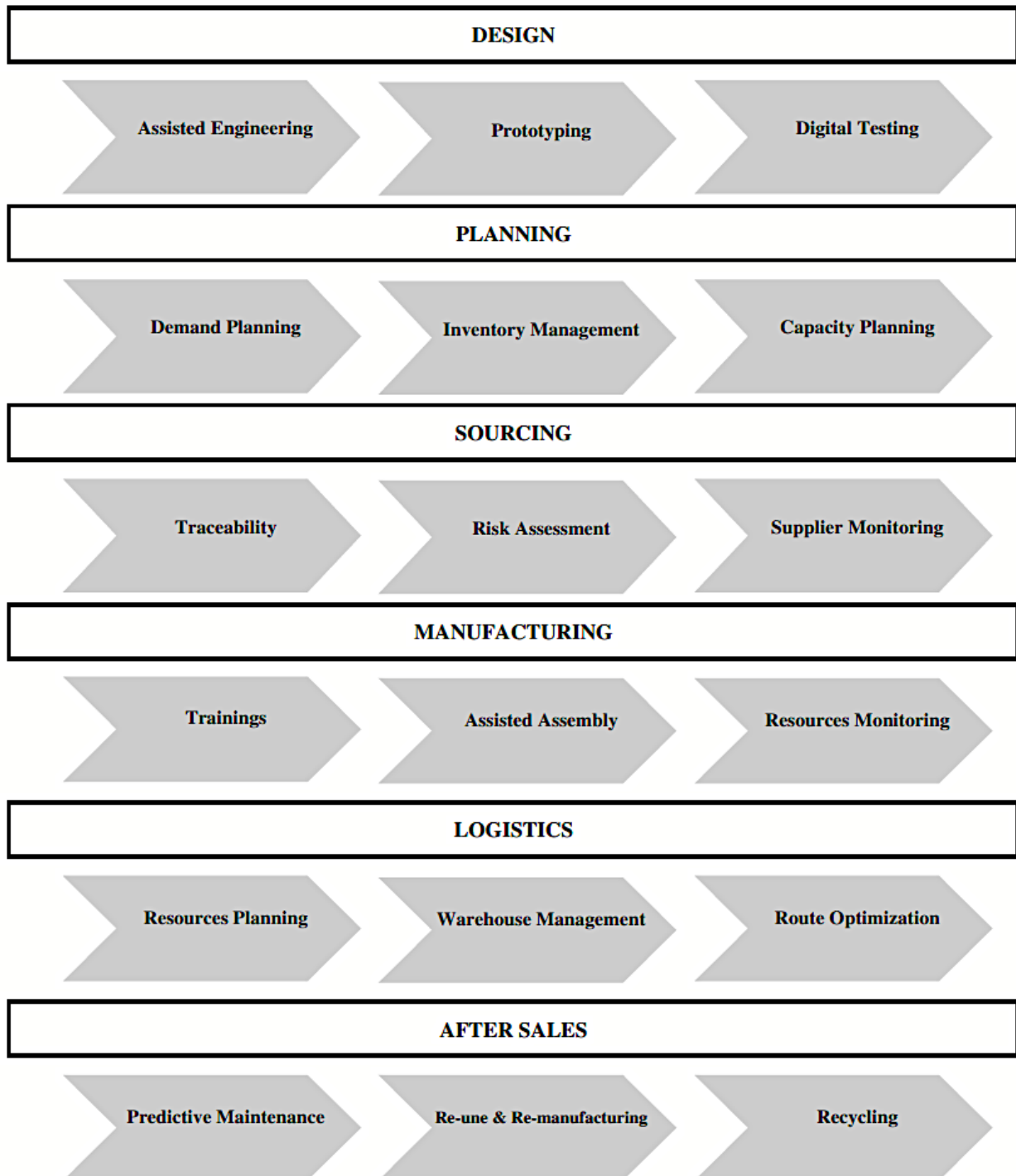


Figure 9. Automotive supply chain processes optimization using Industry 4.0 technologies

The design of future vehicles can be improved, first of all by an engineering that can be described as assisted. Big Data Analytics can help engineers to develop a more sustainable product through optimized calculation of life cycle assessments. Engineers can also rely on the help of artificial intelligence for the development phase. By suggesting alternative materials and taking into consideration several criteria simultaneously, AI offers real possibilities to make this crucial step more efficient for manufacturers as it will influence the entire following operations. The use of these powerful tools can dramatically speed up the design process and provide alternative solutions that combine the interests of cost effectiveness and sustainable design. Once the vehicle design is optimal, engineers have two alternatives for the prototyping stage. The first option is entirely digital with VR, allowing them to try out an infinite number of possibilities and tests. Then, if engineers want to see the outcome of their efforts, they also have the option of printing these prototypes in 3D. In general, prototyping in Industry 4.0 requires no, or very few, resources and also reduces the costs associated with these processes. Finally, VR can still be used to test the prototype. The advantage of VR is that the operation can be performed infinitely in a digital environment able to produce real-world conditions. The use of this technology for testing enables the detection of design defects more quickly and in the context of crash tests, it allows companies to preserve considerable quantities of material.

Then, before starting to manufacture the new vehicles, automotive companies can benefit from new technologies to improve their planning process. It is now possible, using artificial intelligence, to make more advanced demand forecasts because it uses real-time data and takes multiple factors into account simultaneously. Advanced demand planning would allow automotive companies to reduce the risk of overproduction, and thus to reduce storage costs at the same time. Inventory management is also a crucial activity in the automotive sector. Nevertheless, through the application of blockchain or RFID, companies will be able to track in real time their products, whether in the assembly line or in their inventory. If these data are transmitted and processed by artificial intelligence, this visibility can be more quickly accessible and the information on the inventory could not be more optimal. Capacity planning is the ability for organizations to determine their production capacity to accommodate changing demand. If automotive companies have an optimal view on their inventory level and demand trends, it makes capacity planning more efficient.

Sourcing is probably the stage where car manufacturers have the most difficulty in implementing a sustainable development strategy. However, thanks to the advantages of

Industry 4.0, they can put in place processes to ensure the sustainable objectives that have been identified and targeted. Blockchain technology is emerging as a technology that can revolutionize the traceability of raw materials and purchased components. Since the information stored using this technology is very secure, it will soon be very complicated to hide negative externalities. Thus, automotive companies can have direct visibility on micro-processes and lower-level suppliers. It will be much easier to consider carbon footprint, non-renewable energy use and waste generation in its procurement policies. Then, when its supply chain is considered safe, Bid Data Analytics can help companies implement or improve risk assessment. Using BDA to identify the risk of supply breakdowns and simulate alternatives can be a real advantage for automotive companies. The COVID-19 crisis highlighted the significance of adopting this type of analysis and prediction to avoid production downtime. Finally, BDA and AI are two possibilities to continuously monitor suppliers without the need for significant resources and means. In addition to financial analysis, these technologies allow the detection of any sustainability risk such as pollution, human rights abuses or any other risk that could affect the reputation and supply of automotive companies.

The manufacturing process of vehicles and all production operations can also be made more efficient, cost-effective, safe, and sustainable through the adoption of various technologies. Before starting any production and assembly stage, operators can take advantage of VR training to familiarize themselves with future assembly and maintenance operations, thus increasing their skills, efficiency, and familiarity with the machines before working on the production lines. Next, assembly operations and other production lines can also be made more efficient. As we have discussed, RFID can track in real time the different components and help locate them directly in the assembly line, which simplifies the visibility of operators. Augmented reality can also assist operators during their daily tasks. Whether it is through instructions via smart glasses or projections in the real environment, this AR application can improve handling operations and minimize the risk of error and injury. In the future, the most demanding and dangerous tasks can be assigned to the robots, which promotes employee safety and enables them to concentrate on other tasks. Finally, during the entire manufacturing process, the use of artificial intelligence provides increased visibility of resource and energy consumption. Thus, automotive companies will be able to monitor their water and electricity consumption throughout the production line but will also be able to use AI to optimize this consumption.

Then, when it comes to logistics, all of these technologies increase the insight into all employees, equipment and assets. Automotive companies could therefore use the various technologies of Industry 4.0 to optimize the allocation of its resources for product distribution. In terms of warehouse management, the development of Autonomous Mobile Robots in production lines can facilitate the movement of resources or components from one workshop to another. The deployment of other technologies such as Big Data Analytics, AI or RPA can also significantly improve the daily warehouse management of automotive companies by analyzing and interpreting the available data. Artificial intelligence can also revolutionize the distribution of final products through route optimization. The technology is indeed able to choose delivery routes that are economically more interesting but above all more environmentally friendly by analyzing several aspects such as fuel consumption, available vehicles and routes.

Finally, Industry 4.0 can improve after-sales tracking for car manufacturers and support the circular economy. The use of technologies such as blockchain and AI can support predictive maintenance of vehicles and machines. Blockchain is indeed capable of gathering information about the health of different components while artificial intelligence can warn of the need for early maintenance through the analysis of this information. One of the biggest advantages of these technologies is that they can significantly support a better management of the entire lifecycle of vehicles and their components. RFID and Blockchain allow tracking of vehicle components or parts. But more than that, these technologies can store information about the characteristics of these objects and their usage history. This ability to know where these resources are and in what condition they are in, favors either their re-use or their re-manufacturing. However, if the quality of its components is too degraded, it can still increase the recycling rate. The increased use of additive manufacturing in the automotive industry to replace non-recyclable parts would represent a major step forward for environmental sustainability and the circular economy.

9. Industry 4.0 risks and challenges

9.1. Industry 4.0 risks

9.1.1. *Cyber-criminality*

Nowadays, cybercrime is unfortunately a real threat, and such attacks make almost daily headlines in the press. Of course, even though it has been highlighted that the adoption of Industry 4.0 technologies can bring many significant benefits, it also increases the vulnerability of businesses towards this threat. In the automotive industry, an attack against a car manufacturer or one of its suppliers could potentially result in production disruptions, with substantial economic consequences. In addition, all sensitive data, such as demand forecasts, financial statements, customer information, which are monitored and stored can be leaked, resulting in a reputational risk. We can also assume that not all individuals involved in the deployment of these technologies have enhanced cybersecurity skills. This potential lack of expertise concerns even more the employees and regular users of these digital technologies. This risk is even more important as in the automotive industry, this includes some lower-level suppliers, in several regions of the world, where technical means are not always similar. Finally, it seems already very challenging to ensure continuous trainings on the adoption of these new technologies that evolve very quickly that companies risk to underestimate this aspect yet essential.

In order to mitigate this threat, investments in cybersecurity should not be seen as a cost but as a real competitive advantage. Indeed, on the one hand, it will reassure all stakeholders (employees, investors, customers) and on the other hand, it can avoid huge damages. It is therefore important to provide a minimum of instructions to the people involved and more advanced training for decisive positions. Considering the fast development of these technologies, it will also be important to make a regular follow-up and to bring updates. Then, companies in the automotive industry should carefully analyze their entire supply chain to determine the level of trust that is legitimate to grant to each partner and share knowledge and common guidelines for some of them. Finally, national and international authorities will have a decisive role to give guidelines, to support these initiatives, and to protect the different actors by regulations and laws.

9.1.2. Unemployment

Although we have discussed the extent to which the new technologies of Industry 4.0 can support social sustainability, it seems appropriate to put a limit on this approach. Indeed, due to the automation, independence, and efficiency of some of these technologies, there seems to be a real risk on employment. Given the growing complexity of these new digital technologies, we can predict that this potential unemployment will mainly impact unskilled workers. In addition to a considerable risk of unemployment, it may also decrease the wages of unskilled people. Moreover, given the speed at which these technologies are evolving, it is also likely that not all skilled workers will be able to meet employers' expectations in terms of skills and knowledge either.

Just like the automotive industry, the professions in this sector are likely to evolve and there will be an increased need for technological knowledge. Thus, the industry will see more and more new positions related to Cloud, Data, AI, or programming. While new professions will emerge, others will tend to disappear. It will be crucial for the next generation to find solutions to face and adapt to these new trends. For automotive companies, managing human resources will be a considerable challenge, and they must be careful to respect the well-being of their workers and their inclusion to comply with the social sustainability approach. With the emergence of artificial intelligence and robotization, automotive companies will have to use these technological developments with the sole purpose of helping their employees. This is because these new machines and technologies must be developed and used to help human beings and not to replace them, except for risky and unpleasant tasks.

Nevertheless, when we witness the quite impressive efficiency of machines, which do not have to rest, do not have to be motivated, can work in complete darkness and in most cases, perform better than humans, we can nevertheless raise concerns for the future. Unfortunately, given the newness of the subject, it is difficult to draw objective conclusions with appropriate distance.

9.1.3. Energy consumption

We have been able to highlight during this work that some of the new technologies of Industry 4.0 could be used to optimize and reduce energy consumption within the automotive supply chain. For instance, Blockchain allows to ensure that the materials used are non-renewable energies. Then, using Big Data Analytics, all energy-relevant data are gathered in a common database to ensure a more accurate measurement of energy consumption and to analyze the information in real time. Additionally, while artificial intelligence can optimize energy consumption and analyze the amount of energy needed for each component, additive manufacturing can reduce the weight of some components to ensure lower consumption.

Nevertheless, it is important to point out that all these technologies consume a lot of energy, especially Blockchain, Big Data Analytics and cloud computing. This increased energy consumption can also negatively impact the environmental sustainability and contribute to climate change. These technologies do need a regular supply of energy as they are continuously in operation. Furthermore, as automotive companies will be looking to digitalize most of their business partners within their supply chain to facilitate the adoption of these technologies, the use of these technologies will continuously grow. Another risk is obviously the increasing amount of data generation, which is growing exponentially every year. It is therefore essential for the respective users to store only essential information in these systems for an effective and energy-efficient system. Car manufacturers, besides monitoring the energy consumption of their products throughout their life cycle, will have to put the same rigor and effort into monitoring their own consumption. We can also suggest that it is essential for companies to switch as much as possible to renewable energy sources. All such efforts will reduce the environmental impact of the activities, but above all, it will lead to considerable savings on energy-related expenses. It is therefore important to see and consider this monitoring not as a cost, but as a long-term benefit. The role of national and international authorities in supporting the investment of future sustainable energy sources will be crucial to enable market players to access sustainable energy at lower cost. Claiming that the increasing presence of IT and digital technologies will lead to a proportional increase in energy consumption is not entirely truthful, but the subject must nevertheless be addressed. It is by jointly considering the use of clean power sources and the use of new technologies for higher efficiency, that we will be able to address the challenges related to energy consumption.

9.2. Industry 4.0 challenges

9.2.1. Investments

To leverage the technologies of Industry 4.0 and use their potential for enhancing efficiency and sustainability across the supply chain, investments will be required in terms of equipment, knowledge, and infrastructure. Obviously, the size of these investments will depend on the degree of maturity of the organizations, but also of their partners. However, in the current economic context, investments are strongly questioned by companies in terms of ROI. In this environment, automotive companies must not only respond to the changing needs of the business, but also address the return on investment. Thus, a clear cost-benefits analysis as well as reliable return on investment's forecasts is necessary. As we have covered, adopting these technologies will help companies in saving resources, but also in increasing consumer and investor engagement. In this way, it will constitute a strong competitive advantage for increasing the company's profitability. However, it is not only about investing in new technologies, but also about investing in the right ones to make it sustainable. We can advise automotive companies to incorporate supply chain managers in the decision-making process to ensure the right development strategies.

National and international authorities also play a critical role by raising the awareness of the subject, promoting investments, and facilitating financing. Governments are generally large funders of R&D and they need to collaborate now with private firms, for example through private-public partnerships, but also with private not-for-profit institutions like universities to support specific R&D projects. Just like companies, authorities cannot afford to wait for this evolution of the industrial world and have to take action now. In order not to risk employment and inequalities, they must also introduce policy measures to attract technology-oriented investment to keep up with the digital development of the industry.

9.2.2. Skilled workforce

The lack of technical expertise and hard skills related to these new technologies and the new work processes they generate may be seen as a significant challenge. Successful application of new technology requires a specialized workforce. First of all, the majority of employees working in the future intelligent automotive factories will have to develop solid IT skills. All activities related to the planning, supervision and monitoring of new processes and facilities will require increased knowledge. Then, besides acquiring skills in state-of-the art modeling and programming techniques, future automotive managers and engineers will need strong

analytical skills to leverage the increased amount of data being generated. Techniques and experience with new production processes, such as the use of 3D printing will also be required. Finally, in terms of soft skills, managers will have the major responsibility of transferring the newly acquired knowledge to the operators to make the new digitalization strategy effective within the factory. Resistance to change will also be another challenge for automotive companies, especially for the most senior operators. There is a potential risk that employees will not be receptive to the new systems.

The fact that the technological development is faster than the adaptation of the workforce requires a regular need for training and education. On the one hand, companies will have to offer training to their employees in order to acquire specific skills regarding these new technologies. On the other hand, schools and universities will have to continuously adapt and update themselves to support education opportunities to get the skilled and qualified workforce ready for the evolution of the industry. Furthermore, we can also assume that internal collaboration, effective communication, and teamwork will also be decisive elements within the workplace.

Lastly, employee commitment to sustainability cannot be underestimated. On the one hand, from a technical perspective, it is important that employees understand and interpret the implications of new designs, materials and resource savings and their impact on the environment. On the other hand, from a cultural perspective, it is important that employees are aware of and engaged in the sustainable strategies of automotive companies. If sustainable ambitions are perceived and shared within the company and by employees, they will be more willing to implement these aspects in their daily work.

9.2.3. IT Infrastructure

A high quality, efficient and reliable IT infrastructure and sufficient resources are an essential criterion for the implementation of the different technologies of Industry 4.0. If the infrastructure and networks are not powerful enough to allow efficient communication between new machines and tools, the potential of Industry 4.0 will never be exploited.

Today, one can assume that the IT infrastructure of most automotive companies is not yet fully able to support this digital transformation and investments will be necessary. In addition to the development of digital-specific skills to interpret and use the data, the data flow in the processes is the first necessity. The exchange of data between the different machines and tools

will have to be instantaneous, at the risk of real trouble on the different production lines. Therefore, the internal connection must be reliable and extremely fast to manage this flow of information. As we have discussed, cloud computing may be a solution for some companies that would prefer to rely on providers to guarantee a faster, cheaper implementation and only for certain services. Nevertheless, internal networking, which is the communication between machines independently of external systems, will still have to be guaranteed to support this closed communication loop. We can suggest that the help and expertise from IT consultants would also be an appropriate strategic decision to ensure the consistency of potential investments.

From their side, governments must also become the drivers of these innovations and ensure that their country has an efficient infrastructure to promote these benefits and advantages. The installation of an efficient internet network, especially in rural areas, must be among the political priorities. For example, 5G seems to offer great opportunities to expand the capacity of wireless networks and ensure a much faster internet connection than today. Local and national authorities must take the necessary measures and adopt a strong networking strategy to switch to Industry 4.0.

Finally, even if companies upgrade their infrastructure to become more intelligent, it is still necessary to ensure the compatibility of these technologies and tools. Thus, we can also underline that one of the major challenges of Industry 4.0 is to define and adopt standards. The objective is to improve and increase the reliability, predictability and efficiency of the different elements involved. By standardizing data, tools, machines and their communication, processes

9.2.4. Emerging countries

A large majority of automotive companies, in order to increase profitability and reduce costs, outsource large parts of their value-added processes to suppliers located in emerging countries. However, these countries generally have limited technological capacity. These suppliers from emerging countries, which are generally lower-level suppliers, do not have the capital and information required for these new technologies, which are a prerequisite for undertaking large-scale investments in automation to optimize production. Moreover, the IT infrastructure is generally very underdeveloped and cannot currently handle large amounts of data at a fast pace.

In addition to this technological backwardness, these emerging countries generally encounter other difficulties and concerns such as political instability, the use of child labor,

very low or sometimes unpaid wages, corruption or health and safety concerns. From an environmental point of view, some of these countries do not yet have sustainability in their culture and in their handling of the industry. This discrepancy in mentality generally leads to greater pollution and other environmental damage. Furthermore, the emergence of Industry 4.0 can potentially cause a problem regarding employment in emerging countries. If these countries fail to adapt to the change in industry, and if they fail to transform their education system, they could lose a significant market share and find it difficult to transform their economic systems towards high value-added manufacturing.

Scientific research on the potential impacts of Industry 4.0 and its technologies on emerging countries and their businesses is still quite limited. However, the interest for this problematic is really important and these emerging countries must also become aware of the digital revolution that will affect the industry. These countries have to adjust their economic development model, but also their legislative framework, especially regarding labor law. Automotive companies must take all these issues into account in their supplier network in order to include the economic, social and environmental notions that define sustainable development. Even if the human and financial efforts will surely be important, they will have to assist them and invest in their industry to take full advantage of the new technologies and not to widen the gap with these countries.

10. Conclusion

Since its first appearance in the Brundland Commission nearly 30 years ago, the concept of sustainability has evolved and now implies the consideration of social and economic aspects together with the environmental aspect. The current situation requires us as a society to act now to assure our sustainability and that of future generations. Putting sustainable development at the heart of its strategy and activities brings today a real competitive advantage for automotive companies. The objective of this research was to determine if Industry 4.0 could promote sustainability in the supply chain. Based on the automotive industry, we can now say that the various technologies that are part of it can, under certain conditions, and depending on their use, support sustainability.

From an environmental point of view, Industry 4.0 technologies can reduce dependency on resources, improve their monitoring and optimize their use. This also creates products that are more environmentally friendly and more easily recyclable. Better traceability of raw materials also provides information on their origin and environmental impact. Finally, Industry 4.0 enables to promote the principle of reverse logistics and to improve the life cycle of products. From a social point of view, it promotes employee training and introduces them to new knowledge and skills. Daily work can also be improved by the involvement of these technologies in dangerous and stressful tasks, to let employees focus on cognitive actions. Furthermore, Industry 4.0 makes it much easier to identify child labor, human rights violations, and poor working conditions. From an economic point of view, Industry 4.0 fosters innovation and gives automotive companies access to processes and opportunities that were previously not possible. The better visibility of the entire value chain also facilitates decision making. In addition, the considerable savings in resources and energy consumption allow automotive companies to save money in various aspects and thus increase their profitability. The technologies also improve risk awareness and facilitate the adaptation of companies to their environment, ensuring better business performance.

However, even if Industry 4.0 can enhance the sustainability of the supply chain, some risks and challenges have been identified that can impact companies, workers, and society in different ways. By moving to more digitalized activities, companies are more vulnerable to cyber criminality and must therefore protect themselves to avoid production interruptions. Moreover, the performance, speed and reliability of technology can potentially become a threat to employees and cause unemployment. Therefore, it is important that these technologies are

developed and implemented with the sole purpose of assisting humans or substituting them for dangerous and tedious actions. Another risk is the energy consumption of these technologies because, although useful in some functions to reduce this consumption, some of them require a continuous and strong energy need. It is therefore essential that companies and authorities turn to renewable or cleaner energy. In terms of skills, the adoption and use of these technologies requires a high level of knowledge. The challenge is that technological development is evolving faster than the knowledge of employees. Finally, if automotive companies want to benefit from the full potential of Industry 4.0, a solid IT infrastructure is needed.

What we can conclude about the technologies is that it would be most efficient if companies adopted them with sustainability as a primary objective. As we have discussed in this research, significant cost savings and profitability opportunities will follow. Some of these technologies are still very new and their capabilities need to be developed with a sustainable approach. Obviously, the automotive industry has been chosen here as an illustration, but Industry 4.0 can offer its potential to other industries. All these concepts and applications are very new and need to be closely monitored for future benefits.

Given the nascent emergence of these technologies and the fact that companies are just starting to implement them for the most part, it is crucial to be able to retrieve reports and figures regarding these theoretical assets to draw more concrete conclusions. To conclude, it seems obvious that the collaboration and cooperation between the different actors of the economic world will be determinant to support the sustainable development and to face one of the biggest challenges that our society has known so far.

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