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Expected Impact of Industry 4.0 Technologies on Sustainable Development: A study in the context of Brazil's Plastic Industry

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ABSTRACT

The impact of Industry 4.0 technologies on sustainability based on economic, environmental, and social aspects is gaining increasing attention from researchers. In this study, we investigated these impacts using the Triple Bottom Line perspective for sustainable development. A sustainability-oriented model for evaluating the influence of Industry 4.0 technologies on sustainable metrics is proposed. This model analyses the impact of Industry 4.0 technologies on several key performance indicators related to sustainable development. The model was tested in the plastics industry which has a high potential of Industry 4.0 technological aggregation in emerging economies. A fuzzy TOPSIS multi-criteria method was used to classify Industry 4.0 technologies, identifying those with the strongest and weakest impacts on sustainable development. As a result, we show that the internet of things, cyber-physical systems, sensors, and big data implementation are drivers for sustainable development. We also evidenced that these technologies are associated with substantial positive impacts on economic metrics. However, there was a much smaller positive influence on environmental and social metrics, suggesting an imbalance on the Triple Bottom Line perspective for the plastics industry. In addition, we found negative impacts from robots on job creation and low influence from cloud computing and system integration technologies for sustainable development. Based on these findings, our work contributes to the decision-making process by aiding managers, process engineers, and stakeholders in understanding and estimating the expected impacts from Industry 4.0 technologies on economic, environmental, and social aspects for sustainable development.

KEYWORDS: Industry 4.0; sustainability; triple bottom line; technologies.

1 Introduction

Since the first industrial revolution in the 18th century, the world has dealt with the challenge of producing more goods from limited and depleting natural resources to meet growing demand. Consequently, this has generated negative environmental and social impacts (Beier et al., 2018; Müller et al., 2018b). In 2011, the term "Industry 4.0" was introduced and it immediately captured the attention of industries and governments worldwide (Ghobakhloo, 2018; Nascimento et al., 2019) due to the opportunity to transform entire production systems and processes through digitisation (da Costa et al., 2019). Industry 4.0 has generated the potential for several technological advancements. However, as previously stated by Norman and MacDonald (2004), organisations should base their principles in sustainable development when adopting technologies. Organisations which focus on sustainable development seek to achieve a balance between economic, environmental, and social pillars from the triple bottom line (TBL) perspective (Kiel et al., 2017). However, it is not simple for industries to develop sustainability in their operations (Luthra and Mangla, 2018b). Consequently, the impacts of Industry 4.0 on sustainability and how it can contribute to sustainable development from an economic, environmental, and social point of view are gaining more attention from researchers (Ghobakhloo et al., 2020).

Although there are some studies which focus on the influence of smart manufacturing on environmental and economic aspects (Gu et al., 2018), the impacts of these practices on sustainability still require further investigation (Ford and Despeisse, 2016; Müller et al., 2018a). For instance, it is important to consider the social impacts of Industry 4.0 such as the replacement of human beings by machines and new technologies (Digilina et al., 2017). Conversely, new technologies can also lead to better working conditions such as improved safety and decentralised decision-making (Ruppert et al., 2018). Consequently, there are still many challenges and opportunities (e.g. resource efficiency, costs, work organisation, and synchronism between ICT and people) for sustainable development in Industry 4.0 (Stock and Seliger, 2016; de Sousa Jabbour et al., 2018). Given this scenario, it is essential to understand and evaluate the relationship between the principles of sustainable development and Industry 4.0 technologies (Piccarozzi et al., 2018; de Sousa Jabbour et al., 2018). If organisations understood this relationship, they would be able to identify opportunities and challenges during the implementation of these technologies. Therefore, this would enable synchronicity from production systems to organisational strategies (Müller et al., 2018b) and allow for the prediction of technological impacts on the TBL pillars.

In countries with emerging economies (e.g. Brazil), there are economic barriers that industries need to overcome in order to reach this new industrial stage. Furthermore, issues such as environmental and social aspects are typically not the top priority in many industries (Frank et al., 2016a; Dalenogare et al., 2018). Generally, economic barriers are a major issue for all industries that pursue digitisation. However, this is especially significant for small and medium-sized enterprises (SMEs) (Mittal et al., 2018). In comparison to large companies, SMEs face more significant financial and economic challenges in order to adapt to turbulent environments such as Industry 4.0 which generates technological and market shifts (Engelen et al., 2014; Hozdić, 2015). In countries where the economy is mainly composed of SMEs (e.g. Brazil), investing in Industry 4.0 to achieve environmental and social benefits may be a high-risk strategy (Benitez et al., 2020). Moreover, the main industrial innovation activities of most Brazilian companies are focused in technology acquisition rather than in market orientation (R&D investment) (Frank et al., 2016a). Consequently, enterprises (especially SMEs from emerging countries) struggle to adapt to Industry 4.0 with its large market shifts and technologically turbulent environments (Sahi et al., 2020). These enterprises face several financial limitations when planning their strategy regarding the TBL perspective. Therefore, they cannot achieve sustainable development due to environmental and social indicators being neglected from their plans (Ghobakhloo, 2020). In Brazil, there are industries that present sustainability reports based on the three pillars of the TBL, but their development and implementation are not discussed (Nara et al., 2019a; Hansen et al., 2018). These reports are mainly focused on the opportunities and challenges of Brazilian industry and they do not present the impact of technology adoption during this process (de Sousa Jabbour et al., 2015; Hansen et al., 2018). In addition, the National Confederation of the Industries (Confederação Nacional das Indústrias – CNI) report shows that the main efforts of Brazilian industries in relation to digital technologies have been to increase productivity, whilst social and environmental benefits are deprecated when investing in Industry 4.0 technologies (CNI, 2016). Thus, the investments of Brazilian industries in Industry 4.0 technologies are mainly focused on the economic pillar. This demonstrates an imbalance in the TBL for sustainable development.

Nevertheless, technology adoption includes sociotechnical aspects which demonstrate where the environment and people can be inserted into technology strategy (Frank et al., 2019). In addition, the environment and people are classified as aspects from the TBL perspective. Therefore, assessing these aspects is imperative while adopting Industry 4.0 technology for sustainable development in industry. Due to these issues, this study seeks to identify the potential impact of the implementation of Industry 4.0 technologies on sustainable development according to the TBL pillars. Most studies within the literature (e.g. Kiel et al., 2017; Machado et al., 2020; Tiwari and Khan, 2020; Müller, 2020; Ghobakhloo, 2020) adopted a qualitative approach to describe the impacts of Industry 4.0 on the TBL pillars and did not present empirical evidence. Conversely, some recent studies such as those by Kamble et al. (2020) and Li et al. (2020) provided empirical evidence regarding the positive influence of Industry 4.0 technologies on sustainable development. However, these studies did not perform an in-depth analysis on the TBL pillars grouping their metrics in one single variable and grouping different Industry 4.0 technologies providing a general picture of the phenomenon. Bai et al. (2020) provided a more thorough analysis by considering several Industry 4.0 technologies individually. However, all TBL metrics were grouped together and consequently, the results did not show how Industry 4.0 technologies influenced distinct metrics for sustainable development. Thus, our study aims to investigate Industry 4.0 technologies by individually considering several technologies and TBL indicators. Furthermore, as a representative of the emerging economies that have significantly improved industrial activities in recent years (Frank et al., 2016a), this study focuses on the contribution of Industry 4.0 technologies on sustainable development in the Brazilian plastics industry. Similarly to how the automobile industry in Germany is the one of the most developed industries regarding Industry 4.0 technology adoption (Pikas et al., 2016), the plastics industry in Brazil is a sector that heavily utilises digital technologies for processes and products (CNI, 2016). In general, this study seeks to show that Industry 4.0 technologies have the potential to increase the sustainability of the plastics industry in Brazil as previous studies from Varela et al. (2019) and Bonilla et al. (2018) have demonstrated a positive correlation between the Industry 4.0 and TBL indicators. Thus, this article aims to answer the following research question: *what are the impacts of Industry 4.0 technologies on the economic, environmental, and social pillars of the TBL for sustainable development?*

To answer the aforementioned question, a sustainability-oriented evaluation model for Industry 4.0 was proposed. This model was composed of four phases and included Industry 4.0 technologies and key performance indicators (KPIs) for sustainable development. In Phase 1, the technologies that comprise Industry 4.0 were identified and those that were considered the most relevant to the plastics industry were selected. In Phase 2, the KPIs that can be used to measure sustainable development in industries were grouped into the TBL pillars. In Phase 3, the evaluation model was structured and after a survey carried out with specialists, the potential impact of Industry 4.0 technologies on KPIs for sustainable development was obtained. In Phase 4, a Fuzzy TOPSIS multi-criteria method was operationalised whilst considering the experts' opinion to classify the technologies of Industry 4.0 in terms of their impact on sustainable development. As a result, the study demonstrated that the internet of things (IoT), cyber-physical systems (CPS), sensors, and big data technologies are drivers for sustainable development. Furthermore, we observed low influence from cloud computing and system integration technologies on all of the TBL pillars. These findings contribute to managers in understanding and estimating the expected impacts of the different technologies in each sustainable KPI. The results can also help organisations, researchers, and policy makers to achieve sustainability in the context of Industry 4.0. Finally, the results can be used to enforce the laws and policies of sustainable development which would promote the implementation of these technologies in developing countries as a driver for sustainability.

The remaining sections of this paper are structured as follows. In Section 2, the theoretical background for Industry 4.0 is provided and sustainability, the TBL pillars, and KPIs are introduced in this context. Section 3 introduces the research method and discusses the application of our quantitative approach within the plastics industry. The results and discussion are presented in Sections 4 and 5, respectively. Finally, the conclusions of the study are presented in Section 6.

2 Literature review

Industries throughout the world are currently undergoing a new revolution called Industry 4.0. This revolution is the combination of advanced manufacturing techniques and information technologies for the creation of smart systems (Wei et al., 2017). Industry 4.0 is creating smart manufacturing systems by changing modes of operation, design, product services, and production systems (Rüßmann et al., 2015). It is a new technological and future oriented perspective with the purpose of increasing the effectiveness and efficiency of the entire industrial chain (Lu, 2017; Dalenogare et al., 2018). Essentially, Industry 4.0 is based on the emergence of new technologies including additive manufacturing, cloud computing, the IoT, CPS, and big data (Mittal et al., 2017; Ghobakhloo, 2018; Moeuf et al., 2018). Together, these technologies can provide a better control of operations, allowing for the real-time adaptation and flexibility depending on the demands. They also enable the generation of small, customised production batches (Rüßmann et al., 2015; Zhong et al., 2017). The major benefits of these technologies are the creation of smart systems that provide better energy consumption efficiency at the factory level, and consequently have a positive environmental impact (Dalenogare et al., 2018). As a result, these systems can help companies to achieve circular economies and pursue new, green, and environmentally friendly strategies for product development (de Sousa Jabbour et al., 2018; Tseng et al., 2018). This means that Industry 4.0 technologies promote sustainable development by impacting industrial systems, environmental resources, and the wider society (Ghobakhloo, 2018). Therefore, it is imperative to analyse the impact of Industry 4.0 technologies from a sustainability perspective by considering economic, environmental, and social aspects.

2.1 Industry 4.0 and sustainability

There is growing interest in sustainability practices for organisations (Braccini and Margherita, 2019). This is because for a manufacturing organisation to be globally competitive and sustainable, it is necessary to apply cleaner technologies in different aspects (Bhandari et al., 2019). According to the World Commission on Environment and Development (WCED, 1987), sustainability is usually defined as the intelligent and responsible use of resources to meet the needs of the present people without compromising the needs of future generations. Thus, to understand and study sustainable development and its impacts, the TBL perspective suggested by Elkington (1998) is widely utilised because it simultaneously considers economic, environmental, and social pillars in organisations. Despite being in its infancy, it is expected that Industry 4.0 and digital transformation will have significant consequences on TBL sustainability (de Sousa Jabbour et al., 2018, Kamble et al., 2018). However, little is known for certain about the implications of Industry 4.0 on the TBL pillars for sustainable development. There is very limited research on this topic and the sustainability implications of Industry 4.0 in terms of economic, environmental, and social impacts from manufacturing digitisation requires further exploration. Due to this, a literature search was carried out to identify the state-of-the-art research regarding the relationship between Industry 4.0 and sustainability through the TBL perspective. The investigation was carried out through an extensive and systematic review in the Scopus database. Since this article aims to identify which Industry 4.0 technologies have the strongest and weakest impacts on sustainable development, works that focused on the impacts of Industry 4.0 on sustainability through the TBL perspective were identified. Table 01 summarises the search filters used to retrieve articles from the Scopus database.

Table 01 – Scopus search filters

Filter	Search 1 (S1)	Search 2 (S2)	Search 3 (S3)
Document type	Article	Article	Article
Search in	Title, abstract or keywords	Title, abstract or keywords	Title, abstract or keywords
Subject areas	Engineering; Decision Sciences; Business, Economics, Econometrics and Finance	Engineering; Decision Sciences; Business, Economics, Econometrics and Finance	Engineering; Decision Sciences; Business, Economics, Econometrics and Finance
Years	2016 to 2020	2016 to 2020	2016 to 2020
Search terms	“sustainability” AND “industry 4.0” OR “advanced manufacturing” AND/OR “plastic industry” AND “social”	“sustainability” AND “industry 4.0” OR “advanced manufacturing” AND/OR “plastic industry” AND “economic”	“sustainability” AND “industry 4.0” OR “advanced manufacturing” AND/OR “plastic industry” AND “environmental”

The keywords and search filters were applied and initially 43, 44, and 40 articles were identified in the database in S1, S2, and S3, respectively. During the identification phase, duplicated records were removed, resulting in 127 articles. In the screening phase, titles and abstracts were analysed and 35 articles were selected. This excluded 92 articles that were not related to the subject. In the third phase, the remaining 35 articles were assessed for eligibility. Consequently, 16 articles were excluded as they did not have any relation to Industry 4.0 and sustainability indicators or had a superficial relation. Finally, in a snowball approach, a chapter review and two case studies were added due to their direct relevance to the topic. Therefore, the 22 articles presented in Table 02 were used to conduct our research. Table 02 also highlights the studies' proposals, contributions, and main limitations related to the TBL perspective.

Table 02 – Literature review about Industry 4.0 and Sustainability

Author	Journal	Proposal	Contributions	Limitations
Ford et al. (2016)	*Journal of Cleaner Production*	Investigated sustainability implications during the adoption of Industry 4.0 technologies.	Summarised the advantages and challenges, as well as discussing the implications of additive manufacturing on sustainability.	The advantages and some implications that new technologies have on sustainability are presented. However, these are not related to any of the TBL pillars.
Kiel et al. (2017)	*International Journal of Innovation Management*	Presented the effects of Industry 4.0 on the economic, environmental, and social aspects of the TBL.	Presented the sustainable development of Industry 4.0 and considers TBL aspects such as public context. The results demonstrated that data and information should be checked, and that the technical integration of all aspects must be completed.	The study focused on specific sectors in Germany which demonstrates that studies can and should be performed in other sectors/countries. Furthermore, the study does not state which are the main indicators that should be focused on in order to achieve positive results from the TBL.
Tseng et al. (2018)	*Resources, Conservation & Recycling*	Leveraged some research opportunities regarding the implementation of sustainable industrial networks.	This analysis showed research gaps regarding technological innovations in Industry 4.0. The authors portray the need for using technologies such as big data and IoT to achieve gains across the TBL perspectives.	Lack of empirical and quantitative investigation regarding the technological applications required to balance the TBL pillars.
Luthra and Mangla (2018a)	*Process Safety and Environment Protection*	Analysed the main challenges to achieve sustainable development. This involved showing which	Identified and presented a ranking for the main factors that link Industry 4.0 with sustainability. This ranking system was	Presented a ranking of factors but did not show which link these factors have with the TBL pillars. Furthermore, it was not

		aspects should be prioritised to achieve positive results in emerging economies.	divided into organisational, strategic, technological, legal, and ethical issues.	shown how these factors positively/negatively impact each aspect of the TBL.
Beier et al. (2018)	*Applied Sciences*	Investigated how the environmental pillar potentially benefits from industrial production where Industry 4.0 activities will be applied.	Presented the expectations of managers regarding the impacts that Industry 4.0 has on resource efficiency, sustainable energy, and transparency.	Focused on the manager's perception of environmental impacts but did not consider social and economic aspects. Furthermore, it was not stated which indicators should or can be controlled for companies to meet the sustainability aspects of the TBL.
Kamble et al. (2018)	*Process Safety and Environmental Protection*	Proposed a sustainable Industry 4.0 framework based on the findings of their review.	Presented a framework relating the benefits of Industry 4.0 with social and environmental factors.	Did not establish any relationship with the financial factors (economic pillar) of the TBL.
Braccini and Margherita (2019)	*Sustainability*	Investigated the sustainability implications in the adoption of Industry 4.0 technologies.	Contributed to the literature by identifying two trajectories of interaction between the three dimensions of the TBL.	The trajectories do not explain the technological impacts on the TBL pillars.
Machado et al. (2020)	*International Journal of Production Research*	Presented a conceptual structure formed by the previously identified technological principles and pillars of Industry 4.0. Furthermore, the possible link with the pillars of sustainability was presented.	Identified the concepts of sustainable manufacturing and the use of new technologies that may allow Industry 4.0 to have positive impacts on all pillars of sustainability.	The study is limited in identifying some technologies of Industry 4.0 and possible sustainability opportunities, citing aspects of the TBL. The research does not state which Industry 4.0 technologies can be leveraged to achieve positive results for aspects of the TBL.
Kamble et al. (2020)	*International Journal of Production Research*	Covered how Industry 4.0 and lean manufacturing can optimise the sustainable development of companies.	Showed that Industry 4.0 has a direct impact on the sustainable development of organisations and affects the economic, environmental, and social pillars of the TBL.	The results of the study are limited to the perception of managers of Indian companies. Furthermore, it was not demonstrated which indicators produce the most positive results when seeking adherence to aspects of the TBL.

Ghobakhloo (2020)	*Journal of Cleaner Production*	Proposed a power and dependence diagram for the sustainability functions of Industry 4.0.	Evidenced that the simple implementation of Industry 4.0 activities does not guarantee a good performance in sustainability.	This study showed that there is a lack of understanding regarding how the sustainability of Industry 4.0 is distributed throughout the world and from different sectors on the TBL pillars.
Beier et al. (2020)	*Journal of Cleaner Production*	Identified the main aspects of sustainability that emerge with the implementation of Industry 4.0.	Demonstrated that Industry 4.0 does not seem to be sharply defined. Consequently, there is a need for systemic studies that reliably estimate the actual sustainability implications of Industry 4.0.	The implementation of Industry 4.0 and the monitoring of social, environmental, and economic impacts is not performed in most of the studies. Different terms are also used imprecisely within the articles.
Yadav et al. (2020)	*Journal of Cleaner Production*	Developed a framework to overcome sustainable supply chain management (SSCM) challenges through Industry 4.0.	A total of 28 SSCM challenges were identified and effective strategies to overcome SSCM adoption failures were suggested.	The study presented strategies for implementing sustainable activities. However, it did not present what the impacts of these activities will be from the social, environmental, and financial standpoints (i.e. the TBL pillars).
Tiwari and Khan (2020)	*Journal of Cleaner Production*	Simplified the attributes of the cloud-based Industry 4.0 framework and investigated its relationship with the social, financial, and environmental aspects of the TBL.	Presented an empirical formulation of the cloud-based Industry 4.0 contribution to the TBL aspects.	The study connects the main activities from a cloud-based system to each TBL pillar. However, it does not cover the potential impacts during implementation.
Bai et al. (2020)	*International Journal of Production Economics*	Examined Industry 4.0 technologies in terms of their applications and sustainability implications.	Evidenced that the adoption of Industry 4.0 technologies can improve sustainability.	Each technology has a different relationship to industry and sustainability. Therefore, every technology should be individually evaluated. However, this is not the case in the study.
Culot et al. (2020)	*International Journal of Production Economics*	Examined Industry 4.0 technologies in terms of their applications in different contexts.	The Industry 4.0 categorisation helps to better understand several areas such as sustainability in the field. Consequently, this can serve as a basis for future research to approach the	The study conducted an excellent analysis of Industry 4.0 technologies. However, it does not cover the technological influence on the TBL pillars.

			phenomenon across multiple areas.	
Ramirez-Peña et al. (2020)	*Journal of Cleaner Production*	Connected each of the key enabling Industry 4.0 technologies with the most significant supply chain paradigms.	Identified the key factors in a conceptual model applied to a shipbuilding supply chain.	Performed a systematic literature review and developed a conceptual model focused on shipbuilding. However, it did not include the impacts on the TBL pillars.
Fatimah et al. (2020)	*Journal of Cleaner Production*	Investigated the fundamental issues and opportunities related to developing a sustainable and smart country-wide waste management system using Industry 4.0 technologies.	Proposed a new design of smart and sustainable waste management which could achieve satisfactory economic, social, and environmental waste management performance.	Focused on the collection of urban waste in Indonesia and how Industry 4.0 technologies can contribute to a more efficient collection. A distinct limitation was that the study did not focus on manufacturing industries.
Luthra et al. (2020)	*International Journal of Production Research*	Aimed to examine the drivers of Industry 4.0 to diffuse sustainability in supply chains.	Provided an initial effort to investigate the key drivers of Industry 4.0 to achieve high TBL gains in supply chains. India was used as an example of a country with an emerging economy.	The study did not indicate the main Industry 4.0 technologies that influence each pillar of the TBL.
Li et al. (2020)	*International Journal of Production Economics*	Explored how digital technologies influence economic and environmental performance in Industry 4.0 context.	Provided managerial insights into how to promote economic and environmental sustainability in the Industry 4.0 era.	The results only focused on economic and environmental gains. Social gains were not addressed, although they are also a part of the TBL perspective.
Jabbour et al. (2020)	*Resources Policy*	Reviewed the literature to find evidence on how Industry 4.0 can enhance the circular economy.	Offered novel ideas regarding the theory and practice of operations management in the circular economy.	Focused on the circular economy but did not state the main Industry 4.0 technologies that influence each pillar of the TBL.

Sartal et al. (2020)	*Advances in Mechanical Engineering*	Presented an overview of the main concepts related to sustainable manufacturing, as well as metrics to evaluate organisation's sustainability performance.	The positive environmental and economic impacts of sustainable manufacturing appear to be fairly widespread.	The results evidenced that there is a lack of consensus regarding the true social impact of Industry 4.0.
Müller (2020)	*IGI Global - Customer Satisfaction and Sustainability Initiatives in the Fourth Industrial Revolution*	Studied Industry 4.0 context on the TBL perspective.	To structure the existing literature, a framework was developed, and the findings were categorised into ecological and social aspects.	Performed a systematic literature review and developed a framework. However, the financial impacts were not addressed, and these findings were not verified in practice.

Our literature review suggests that the majority of studies focused on how Industry 4.0 principles such as interoperability, connectivity, and integration will impact the sustainable development of organisations (Luthra and Mangla, 2018a; Kamble et al., 2018; Ghobakhloo, 2020; Beier et al., 2020; Tiwari and Khan, 2020; Sartal et al., 2020; Müller, 2020). Some of these studies highlight the importance of sociotechnical aspects (e.g. people, technology, organisations, and the external environment) for technology implementation to promote sustainable development in organisations (Kiel et al., 2017; Beier et al., 2020). In addition, Bai et al. (2020), Li et al. (2020), and Kamble et al. (2020) highlight that sociotechnical elements can show positive effects on the implementation of Industry 4.0 technologies in the TBL pillars. Conversely, some studies analyse the influence of Industry 4.0 technologies on the circular economy in distinct industrial cases (Braccini and Margherita, 2019; Fatimah et al., 2020; Jabbour et al., 2020) or in sustainable supply chains (Ramirez-Peña et al., 2020; Luthra et al., 2020, Sellitto et al., 2019). Overall, our review shows that researchers are exploring the potential positive impacts from Industry 4.0 technology adoption on sustainable development (Tseng et al., 2018; Kamble et al., 2020; Machado et al., 2020). However, some works portray a significant concern regarding the potentially negative impacts of Industry 4.0 on each TBL pillar. For instance, some researchers (Chen et al., 2015; Ghobakhloo, 2020; Yadav et al., 2020) have expressed concern regarding the impact of Industry 4.0 technology implementation on social aspects such as job availability and occupational health and safety. According to Kang et al. (2016) and Beier et al. (2020), the automation and digitalisation of processes could lead to the loss of several job roles. Moreover, despite that the application of Industry 4.0 technologies promotes the improvement of manufacturing processes (Ford and

Despeisse, 2016), energy efficiency, and pollution and waste reduction (Kusiak, 2018), their implementation leads to other environmental concerns such as increased energy consumption and resource scarcity (Kamble et al. 2018; Beier et al., 2020; Yadav et al., 2020; Culot et al., 2020). Although technologies such as IoT and CPS improve the energy efficiency of manufacturing through process optimisation, their implementation will cause an initial increase in energy demand. This is problematic, especially in emerging countries such as Brazil that lack developed innovation activities for renewable energy system implementation as they predominantly utilise non-renewable energy sources, such as fossil fuels (Blanco et al., 2017; Frank et al., 2018).

Furthermore, with the implementation of new equipment, obsolete equipment will be discarded (Bonilla et al., 2018). Consequently, it is conceivable that Industry 4.0 will cause further negative environmental impacts with the emission of harmful gases such as CO_2 and the creation of high levels of waste, especially in the manufacturing process (Birkel et al., 2019, Sellitto et al., 2018). Finally, in regards to the economic aspect, even though the main short- and medium-term benefits of Industry 4.0 are related to cost reduction and productivity increase, its implementation could have the opposite effect (Dalenogare et al., 2018; Ghobakhloo, 2020). As aforementioned, the main industrial activities of many emerging countries are from SMEs (Frank et al., 2016a; Dalenogare et al., 2018). Therefore, changing manufacturing protocols and implementing new technology can pose a significant challenge to these companies. This is because most of these SMEs use old machines in their manufacturing (Frank et al., 2019). Adding this to the lack of technical expertise and standardised systems, these implementations can incur large costs for SMEs which can impact a country’s economic balance (Dalenogare et al., 2018; Luthra and Mangla, 2018a; Benitez et al., 2020). Thus, Industry 4.0 technologies may not possess a perfect balance of social, environmental, and economic aspects which makes them potentially harmful to their adopters (Kiel et al., 2017). Therefore, we aim to improve knowledge within this area by analysing the benefits and harms from different Industry 4.0 technology implementations in the TBL pillars. We analyse several KPIs from each TBL pillar and describe sustainable development through KPI metrics.

2.2 Triple Bottom Line in Industry 4.0: sustainable development by key performance indicators

KPIs are used to facilitate performance evaluation through comparable performance measures (Bai and Sarkis, 2014). They provide synthesised and relevant information about system performance which enables more accurate decisions regarding objectives and strategies (Podgórski, 2015). Generally, KPIs are metrics which measure the level of performance and success of an organisation or of a certain process (Nara et al., 2019a). KPI metrics support the decision-making process of firms and industries by providing measurable insights regarding processes (Baierle et al., 2020). Moreover, these metrics are directly impacted by technologies operationalisation in processes. Consequently, the adoption of new technology has a direct influence on KPI metrics (Nara et al., 2019b). This means that KPIs can provide metrics related to sustainable development which are influenced by technologies. Several sustainability reports from distinct industrial sectors have been examined within the literature (e.g. Frank et al., 2016b) to measure KPIs and their impacts. Subsequently, there is not a consensus regarding KPIs metrics and reports have been produced by many organisations (both Brazilian and international) which have prevented KPI selection for one specific segment. Examples of these Brazilian and international organisations are the Brazilian Plastic Industry Association (ABIPLAST), the National Confederation of the Industries (CNI), the Global Reporting Initiative, and PlasticsEurope.

As previously stated, several KPIs and metrics have been developed over the past decade to allow sustainable practices to be assessed in industrial processes. Generally, metrics are categorised according to the TBL pillars: environmental, economic, and social performance (Esmaeilian et al., 2016). The review in Table 02 suggests that there is a conflict in the literature regarding KPIs for the TBL pillars in the Industry 4.0 context. We evidenced this by analysing the limitations of previous studies that related Industry 4.0 to the TBL perspective. Some studies (Beier et al., 2018; Kamble et al., 2020) have highlighted the lack of clear KPIs to measure the impact of Industry 4.0 technologies on the TBL pillars. Moreover, the literature does not demonstrate how to measure the benefits and harms from Industry 4.0 technologies on sustainable development using standardised KPIs. As there are many KPIs from several fields and areas, a literature review was performed to choose the KPIs for each TBL pillar. Consequently, the KPIs presented in Table 05 (Section 3.2) were selected from articles that focused on measuring sustainable development in manufacturing. This analysis method was selected because the key objective of Industry 4.0 is smart manufacturing by implementing digital and emerging technologies (Dalenogare et al., 2018; Frank et al., 2019). According to Machado et al. (2020), sustainable development is a consequence of the implementation of Industry 4.0 technologies in manufacturing. The impacts of implementing these technologies should be measured by KPIs that allow their results to be understood from different perspectives. These perspectives are aligned to the TBL pillars which incorporate a series of KPIs to measure sustainable development. For a company with a balanced profile, each aspect of the TBL should have equal magnitudes (Stoycheva et al., 2018). This means that an implemented technology may not have equal positive effects in all KPIs which would potentially lead to imbalance in the

TBL pillars upon its adoption. Therefore, the implementation of Industry 4.0 technologies may not have a perfect balance of social, environmental, and economic aspects.

3 Methods

This study aims to identify the impacts of implementing Industry 4.0 on sustainable development in the plastics industry. Therefore, an evaluation model based on Industry 4.0 technologies and KPIs for sustainable development linked to the TBL pillars was proposed. This model was built and analysed through a Fuzzy TOPSIS multi-criteria method. A study protocol with four phases was defined as detailed in Figure 01.

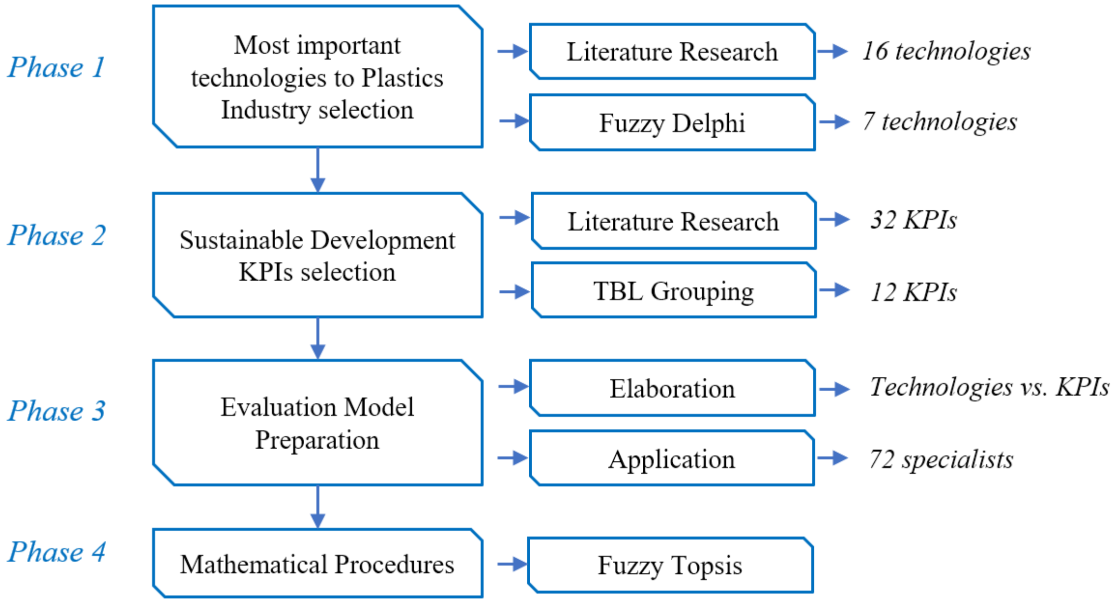

Figure 01 – Methodological procedure steps

Figure 01 demonstrates the four phases of the methodological procedure. The following sections describe the four phases in detail.

3.1 Selection of Industry 4.0 technologies

A literature review was performed to identify relevant technologies to the development of Industry 4.0. To identify high-quality articles, the literature review was conducted using the Scopus database with a main search term of “Industry 4.0 technologies”. The following search filters were proposed:

- Publication year: 2016-2020;
- Publication type: Articles;
- Subject areas: All.

The aim of this search was to identify the most common Industry 4.0 technologies. However, the search produced more than 5,000 related articles. Thus, to refine the search, only articles with more than 100 citations were selected. This left only 60 articles, of which a further 28 were excluded due to a lack of relevance or because they were published in proceedings or book chapters. Moreover, articles were only included if they provided technical details regarding at least one Industry 4.0 technology in order to deepen our understanding of their implementation. As a final sample, 32 papers were selected as presented in Table 03. The results of this search highlighted 16 technologies that are essential for the development of Industry 4.0. These technologies and their references are presented in Table 03.

Table 03 – Key Technologies for the Development of Industry 4.0

Authors X Technologies	*(Boyes et al., 2018)*	*(Cao et al., 2017)*	*(Chen et al., 2017)*	*(Dalenogare et al., 2018)*	*(Frank et al., 2019)*	*(Ghobakhloo, 2018)*	*Hofmann et al. (2017)*	*(Ivanov et al., 2019)*	*(Kamble et al., 2018)*	*(Kang et al., 2016)*	*(Li, 2018)*	*(Li et al., 2017)*	*(Longo et al., 2017)*	*(Lu, 2017)*	*(Moeuf et al., 2018)*	*(Müller et al., 2018)*	*(Oesterreich and Teuteberg, 2016)*	*(Posada et al., 2015)*	*(Qi and Tao, 2018)*	*(Qin et al. (2016)*	*(Rojko, 2017)*	*(Roy et al., 2016)*	*(Tao et al., 2017)*	*(Tao and Zhang, 2017)*	*(Thoben et, al. 2017)*	*(Wan et al., 2016)*	*(Wollschlaeger et al., 2017)*	*(Xu et al., 2018)*	*(Zawadzki et al., 2016)*	*(Zezulka et al., 2016)*	*(Zheng et al., 2018)*	*(Zhong et al., 2017)*
Average citations	*102*	*104*	*173*	*120*	*106*	*202*	*304*	*105*	*167*	*375*	*142*	*183*	*102*	*547*	*143*	*132*	*210*	*252*	*157*	*232*	*103*	*106*	*109*	*174*	*218*	*284*	*449*	*340*	*104*	*111*	*116*	*433*
Internet of things	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Big data analytics	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x	x
Cloud computing	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x	x	x		x	x	x	x	x	x	x	x			x	x
Cyber physical systems	x	x	x		x	x	x	x		x	x		x		x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x
Additive manufacturing				x	x	x		x	x	x	x				x	x	x				x	x							x		x	
Augmented and virtual reality					x	x		x	x	x			x		x		x	x			x	x							x		x	
Cybersecurity									x						x			x			x	x										x
System integration		x		x	x	x						x						x												x		
Autonomous and collaborative robots			x		x	x		x			x				x		x	x		x	x	x	x			x	x	x				
Digitalization and virtualization			x	x	x			x			x					x		x	x		x			x		x	x	x				
Simulation				x		x		x	x				x		x		x		x			x	x						x			
Industrial internet	x		x	x	x	x						x				x	x	x			x		x		x	x	x	x				
Smart sensors	x	x	x	x	x			x		x							x		x			x			x	x	x	x		x	x	
Machine to machine communication	x	x			x	x		x				x			x	x						x						x				
Mobile systems and devices	x	x	x			x		x				x	x	x			x				x	x	x			x	x	x			x	
Artificial intelligence		x			x						x		x						x				x					x			x	

From the technologies that are deemed essential for the development of Industry 4.0, those that are most relevant to the plastics industry were selected. However, the intention of this method was not to highlight that any one technology is more important than another, but to utilise the opinions of experts in the field to identify which technologies have greater applicability. This can help to stimulate the technological development of these companies. Therefore, our choice to focus on the Brazilian plastics industry was because this industrial sector is one of the most employable in Brazil and generates 312,000 jobs (ABIPLAST, 2018). In addition, the average rate of innovation implementation in plastic product manufacturing processes in Brazil is 40.9% which is significantly lower than the world average of 51.3% (CNI, 2016). This result shows the potential of Industry 4.0 technological aggregation to innovate production processes in the Brazilian plastics industry.

Thus, we developed a survey for experts in the field in order to verify the importance of each Industry 4.0 technology in the Brazilian plastics industry. This involved preparing a questionnaire to collect the experts' opinions regarding the importance of each technology listed in Table 03. The Google Forms online platform was utilised for the survey and the answer options and their respective scores for each technology were defined as: 1 = not important, 3 = important, 5 = very important, and 7 = extremely important. A group of 21 experts on this topic were then selected. This group consisted of seven professors of industrial engineering, four researchers from the Industry 4.0 field, four managers from the plastics industry, and six engineers who work directly with these technologies in industry. The link to the questionnaire was sent by email to the group and 10 days were given as a maximum response time. Finally, the answers were collected and tabulated into an electronic spreadsheet for analysis.

The Fuzzy-Delphi method (Wudhikarn, 2018) was chosen to assist in overcoming problems related to a lack of consensus between the responses of the 21 experts. The Fuzzy-Delphi method was created to solve ambiguity-related problems of expert consensus in the Delphi technique by applying Fuzzy theory in semantic variables (Murray et al., 1985). The method weighs the maximum and minimum values of the collected opinions as end points of fuzzy triangular numbers. In order to derive the statistical effect and avoid the impact of extreme values, the geometric mean is considered as a degree of association of these numbers. The method is operationalised through equation 1 (Ma et al., 2011):

$$G_i = \frac{(U_i - L_i) + (M_i - L_i)}{3} + L_i \quad (1)$$

where G_i is the consensus value among the experts, U_i is the maximum value, L_i is the minimum value, and M_i is the geometric mean of the answers. The final ranking is presented in Table 04.

Table 04 – Importance Ranking of Industry 4.0 technologies related to plastics industry

Technologies	G_i
Big data analytics [BIG DATA]	5.27
Smart sensors [SENSORS]	5.11
Cloud computing and manufacturing [CLOUD]	5.08
System integration [SYS_INT]	5.08
Cyber physical systems [CPS]	5.05
Autonomous and collaborative robots [ROBOTS]	5.02
Internet of things [IoT]	5.01
Mobile systems and devices [MOBILE]	4.92
Artificial intelligence [AI]	4.91
Digitalization and virtualization [DIGITAL]	4.89
Machine to machine communication [M2M]	4.86
Simulation [SIMUL]	4.75
Industrial internet [IND_NET]	4.74
Additive manufacturing [AM]	4.62
Cybersecurity [CSECURITY]	4.27
Augmented and virtual reality [AVR]	3.93

The consensus values among the experts ranged from 3.93 for augmented and virtual reality (AVR) technology to 5.27 for big data technology. The intention of this phase was to select the most relevant technologies with a potentially significant impact on the development of the plastics industry. Therefore, only the technologies classified between very important and extremely important by the Fuzzy-Delphi method ($G_i \geq 5$) were selected. As a result, 7 out of the 16 technologies were selected: big data, sensors, cloud, SYS_INT, CPS, robots, and IoT.

Moreover, the Friedman test was performed to validate and assess whether there were significant differences between the results obtained in Table 04. This allowed for a comparison of the application degree between the selected technologies. Since data were collected using an ordinal scale (Likert scale), a non-parametric statistical test was applied. Therefore, we opted for the logical fundaments of the Friedman test that provide a non-parametric proof applicable to these situations as recommended by Siegel and Castellan Jr. (1988). The test equation is as follows:

$$T_1 = \frac{12}{nK(K+1)} \sum_{k=1}^{K} R_{.k}^2 - 3n(K+1) \qquad (2)$$

Where $\mathrm{R.k} = \sum_{\mathrm{k}=1}^{\mathrm{K}} \mathrm{R}_{\mathrm{ik}}$ is the sum of the ranks for the technologies k over the n experts that evaluated each technology. In our study, k=16 represents the 16 technologies from Table 04 and n=21 represents the 21 experts that responded to the survey. The Friedman test documents (Appendix A) are as follows: $\chi^2 = 45.622$, df = 15, and p = 0.000061 at a level of significance of

0.05. As a conclusion, the null hypothesis was rejected, and it can be inferred that at least two of the variables are significantly different from each other. Moreover, the non-parametric ranking shows that five of our seven selected technologies from the Fuzzy-Delphi method have high ratings which strengthened our technology selection procedure. Although CPS and robots received a relatively low rating, they were still included within the final analysis as the Fuzzy-Delphi method was adopted as a preliminary stage for the Fuzzy TOPSIS analysis.

3.2 Sustainable development key performance indicators selection

Phase 2 was also based on a literature review where the main KPIs used to measure sustainable development in organisations and industries were identified. The Scopus database was utilised and the literature review was conducted using three main search terms: “sustainability”, “manufacturing”, and “KPI[1]”. The following search filters were utilised:

- Search in: Title, abstract, or keywords;
- Publication year: All;
- Publication type: Articles;
- Subject areas: Engineering, Environmental science, Business, Management and Accounting, Decision Sciences, Economics, Econometrics, and Finance.

The literature review identified the commonly mentioned KPIs with a link to sustainable development which allowed for them to be measured in the TBL perspective. Over 4,000 relevant articles were initially found and from this, the titles and abstracts were reviewed to identify relevance to sustainability metrics related to manufacturing industries. This refining process left 135 relevant articles. The articles were then reviewed to identify those that described at least 5 KPIs. Consequently, this left 20 articles for the analysis. After the analysis, 32 KPIs that can be used to measure sustainable development in the plastics industry were identified. These KPIs, as well as their frequency of occurrence are presented in Table 05.

[1] For KPIs, we utilised the following terms: key performance indicator, indicator, and metric.

Table 05 – Sustainable Development KPIs: % of occurrence of indicators x authors

Indicators / **Authors**	**(Amrina and Vilsi, 2015)**	**(Baumgartner and Ebner, 2010)**	**(Bohlmann *et al.*, 2018)**	**(Bottani *et al.*, 2017)**	**(Chen *et al.*, 2015)**	**(de Oliveira *et al.*, 2018)**	**(Gunasekaran and Spalanzani, 2012)**	**(Hon, 2005)**	**(Hubbard, 2009)**	**(Hussey *et al.*, 2001)**	**(Jayal *et al.*, 2010)**	**(Kocmanová and Dočekalová, 2014)**	**(Rauch and Newman, 2009)**	**(Richards and Gladwin, 1999)**	**(Sikdar, 2003)**	**(Song and Moon, 2018)**	**(Stoycheva *et al.*, 2018)**	**(Sulistiarini *et al.*, 2018)**	**(Tanzil and Beloff, 2006)**	**(Roca and Searcy, 2012)**	**Percentage of occurrence**
Energy efficiency and consumption	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	*95%*
Waste generation and disposal	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	*95%*
Pollutant and effluent emission	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	*95%*
Water consumption	x	x	x	x		x	x	x	x			x	x	x	x		x	x	x	x	*80%*
Occupational health and safety	x	x	x	x	x	x				x	x	x			x	x	x	x	x	x	*75%*
Raw material consumption	x	x			x	x			x		x	x	x	x	x	x	x	x	x		*70%*
Training and education of human resources	x	x		x	x	x		x	x	x		x				x	x	x		x	*65%*
Use of renewable or recycling resources		x		x	x	x					x	x	x	x		x		x	x	x	*60%*
Profitability			x	x	x	x			x	x		x			x	x	x		x	x	*60%*
Reputation and community investments		x	x	x		x			x			x				x	x	x	x	x	*55%*
Work conditions	x	x			x	x				x	x						x	x	x	x	*50%*
Cost of manufacturing	x				x	x	x				x	x			x	x			x		*45%*
Employee turnover				x	x	x		x	x	x		x							x	x	*45%*
Return on investment			x	x		x	x		x	x						x	x				*40%*
Cost of materials	x					x	x				x	x			x	x			x		*40%*
Work injuries	x			x			x	x		x				x					x	x	*40%*
Salary and benefits		x		x		x				x					x			x	x	x	*40%*
Market Share				x		x		x	x	x		x								x	*35%*
Revenue				x		x		x	x	x		x								x	*35%*
Sustainable or eco-friendly products		x		x			x				x	x						x	x		*35%*
Full time/part time employee rate	x			x	x	x		x									x			x	*35%*
Carbon footprint				x				x	x			x			x					x	*30%*
Use of non-renewable resources		x		x		x				x					x	x					*30%*
Stakeholder collaboration		x	x			x			x			x							x		*30%*
Use of chemicals and hazardous materials				x		x	x								x					x	*25%*
Employee satisfaction									x			x			x	x				x	*25%*
Gender equity	x	x		x				x												x	*25%*
Laws and policies compliance		x				x											x		x	x	*25%*
Climate change					x										x					x	*15%*
Increase of customers			x	x					x												*15%*
Human rights										x	x	x									*15%*

Sales growth	x	x	*10%*

The literature review resulted in a data set of 32 KPIs. However, some KPIs followed similar approaches to one another. Thus, to reduce the amount of data, the 32 KPIs were grouped into new KPI families that are simply referred to as KPIs in Table 06. This process resulted in 12 KPIs that were then grouped into the TBL pillars using an approach based on similarities between the KPIs and TBL pillars. All these approaches were performed by means of theoretical grouping. Theoretical grouping is a way of illustrating how different constructs or categories are underpinned by certain theories, and how the theories and constructs may overlap (Suddaby, 2010). This grouping method was utilised to align each KPI to a TBL pillar. For example, the energy efficiency (ENERGY) and water and raw materials consumption (WRM) KPIs were placed into the economic and environmental pillars of the TBL, respectively. This was due to their strong association to both pillars within the literature. Table 06 shows the TBL pillars, IDs, KPIs, and previous KPIs.

Table 06 – KPIs groups in accordance to TBL pillars

TBL Pillar	ID	KPIs	Previous KPIs
Economic	PROFIT	Profitability	Return on investment; Profitability
	COSTS	Manufacturing costs	Cost of manufacturing; Cost of materials
	SALES	Sales and Market Share	Increase of customers; Market share; Sales growth; Revenue
Economic and Environmental	ENERGY	Energy efficiency	Energy efficiency and consumption
	WRM	Water and raw materials consumption	Water consumption; Raw material consumption
Environmental	RRR	Use of renewable and recycling resources	Sustainable or eco-friendly products; Use of renewable or recycling resources
	TWD	Total waste disposal	Use of non-renewable resources; Use of chemicals and hazardous materials; Waste generation and disposal
	PEE	Pollutant and effluent emission	Climate change; Carbon footprint; Pollutant and effluent emission
Social	OHS	Occupational health and safety	Work conditions; Work injuries; Occupational health and safety
	HRR	Human resources and rights	Training and education of human resources; Employee satisfaction; Salary and benefits; Human rights; Gender equity
	JOBS	Job creation	Employee turnover; Full time/part time employee rate
	CRC	Community and regulatory compliance	Laws and policies compliance; Stakeholder collaboration; Reputation and community investments

3.3 Construct validity and reliability

The grouping of KPIs into the TBL pillars presented in Table 06 originated from theoretical analyses. Consequently, it was necessary to verify the statistical strength of these variables in the grouped metrics in order to prove that the groups were appropriately organised and there was a real statistical relationship. Therefore, in regards to validity and reliability, a series of statistical tests were performed to measure the KPI selection and TBL construct building. Initially, data cleaning was performed by selecting all the respondents' answers regarding Industry 4.0 technology knowledge in each KPI and aggregating them through the mean in one single variable. The same

Likert scale used in the questionnaire in Section 3.4 was utilised to provide five answer options: (1) very negative, (2) negative, (3) no change, (4) positive, and (5) very positive. Essentially, all technology answers related to a specific KPI were consolidated into one variable named according to the ID presented in Table 06. These KPIs were then grouped into three main constructs related to the TBL pillars using the theoretical grouping procedure through a literature review (Suddaby, 2010). For construct validity, a correlation analysis for KPI variables and their TBL groupings was performed. According to Hair et al. (2009), the evaluation of construct validity requires that the correlations of the measured variables must be related to the construct. This is necessary because correlations that fit the expected pattern contribute evidence of construct validity (Peter, 1981). Therefore, the tests indicated that all variables are related to the TBL pillars and are significant at $p < 0.01$. Moreover, for construct reliability, all variables were submitted to Cronbach's alpha (α) and composite reliability tests. All variables and construct values were beyond or close to the threshold level of 0.7 as suggested by Hair et al. (2009). Therefore, this inferred a reasonable reliability level. Finally, Table 07 presents the bivariate correlation matrix with descriptive scales and reliability estimates.

Table 07 – Descriptive statistics, validity and reliability estimates

			Cronbach's alpha (α)	Composite reliability (CR)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
KPIs	1	PROFIT	0.763	0.875	-														
	2	COSTS	0.724	0.866	.804**	-													
	3	SALES	0.807	0.796	.811**	.730**													
	4	ENERGY	0.704	0.862	.753**	.789**	.634**	-											
	5	WRM	0.781	0.813	.771**	.778**	.692**	.853**	-										
	6	RRR	0.815	0.694	.721**	.712**	.765**	.656**	.795**	-									
	7	TWD	0.741	0.717	.640**	.620**	.628**	.615**	.740**	.771**	-								
	8	PEE	0.757	0.709	.614**	.597**	.580**	.595**	.676**	.743**	.897**	-							
	9	OHS	0.749	0.843	.657**	.640**	.428**	.734**	.726**	.490**	.608**	.637**	-						
	10	HRR	0.620	0.759	.611**	.589**	.469**	.605**	.626**	.542**	.467**	.465**	.718**	-					
	11	JOBS	0.719	0.764	.310**	0.224	.386**	0.188	.263*	.527**	.345**	.330**	0.106	.474**	-				
	12	CRC	0.682	0.760	.572**	.510**	.384**	.516**	.620**	.645**	.642**	.638**	.665**	.698**	.604**	-			
TBL pillars	13	Economic	0.940	0.965	.919**	.909**	.864**	.895**	.910**	.813**	.721**	.681**	.705**	.643**	.307**	.576**	-		
	14	Environmental	0.938	0.945	.791**	.791**	.745**	.843**	.919**	.894**	.903**	.877**	.721**	.612**	.372**	.689**	.909**	-	
	15	Social	0.876	0.879	.622**	.549**	.503**	.572**	.656**	.702**	.650**	.660**	.691**	.775**	.740**	.931**	.645**	.730**	-

* p<.05. ** p<.01.

3.4 Survey preparation

After the selection of the main technologies and KPIs, Phase 3 was implemented to create the evaluation model used for the plastics industry specialists in Brazil. The evaluation model was designed for the experts and could highlight the potential impact of each Industry 4.0 technology on each of the 12 sustainable development KPIs. Consequently, this made it possible to obtain a cross-sectional assessment between Industry 4.0 and sustainable development for the plastics industry. The model was translated into a questionnaire containing ten questions: two to outline the individual expert's profile, one to verify the knowledge of the experts regarding the technologies, and seven for the experts to assess the potential impact of Industry 4.0 technologies on sustainable development KPIs. The full questionnaire is presented in Appendix B. The survey-related questions for the mathematical analysis were then presented:

Question I: referring to market segmentation that includes the company's profile.

Question II: referring to the number of employees of the company.

Question III: referring to the level of knowledge of Industry 4.0 technologies.

Not all experts were likely to have knowledge of all technologies (Question III) and it was imperative to identify whether the respondent's information was valid. Therefore, in this part of the questionnaire, experts selected the level of knowledge they had in each of the seven technologies. Four options were considered: (1) no knowledge, (2) theoretical knowledge, (3) moderate practical knowledge, and (4) advanced practical knowledge. Moreover, if the respondent indicated the first option (no knowledge), their responses regarding the impacts of this technology on KPIs for sustainable development were not included in the subsequent analysis. Hence, this reduced the scores assigned to each technology that constituted the specific KPI answer during the application of the Fuzzy TOPSIS method.

Questions IV-X: referring to the potential impact of each technology on selected sustainable development KPIs.

Finally, the respondent needed to indicate the expected impact of each technology (selected from Table 04) on each KPI (selected from Table 06). For each question, there were five answer options: (1) very negative, (2) negative, (3) no change, (4) positive, and (5) very positive.

3.5 Sample selection and size

The questionnaire was prepared using the Google Forms tool and applied with the support of the ABIPLAST. This organisation is the main reference for the plastics industry in Brazil and includes a total of 12,100 companies, 322,900 professionals, and 23 state labour unions. Its aim is to defend the interests of the plastics industry and assist it through services and initiatives, promoting competitiveness, and technological advances focused on sustainability (ABIPLAST, 2018). The questionnaire was sent to 400 technical specialists and managers linked to ABIPLAST companies in the southern region of Brazil. The potential respondents were selected by ABIPLAST representatives due to their technical and management knowledge related to technology implementation in the plastics industry. A total of 72 people answered the survey questionnaire, resulting in an 18% response rate. Moreover, some respondents were also contacted due to uncomplete answers regarding positioning the importance of research for the plastics industry. The final sample size was influenced due to the certain degree of difficulty for the respondents in answering questions related to Industry 4.0. However, as previous studies in the literature have demonstrated (e.g. Holbrook et al., 2008), there is no consensus regarding an ideal sample size for surveys. For instance, Visser et al. (1996) showed that surveys with lower response rates (~20%) yielded more accurate measurements compared to surveys with higher response rates (60-70%). Thus, the survey was conducted with small, medium, and large companies which represented several segments from manufactures of agricultural products to clothing. Referring to the sampling profile, the data are presented in Figure 02.

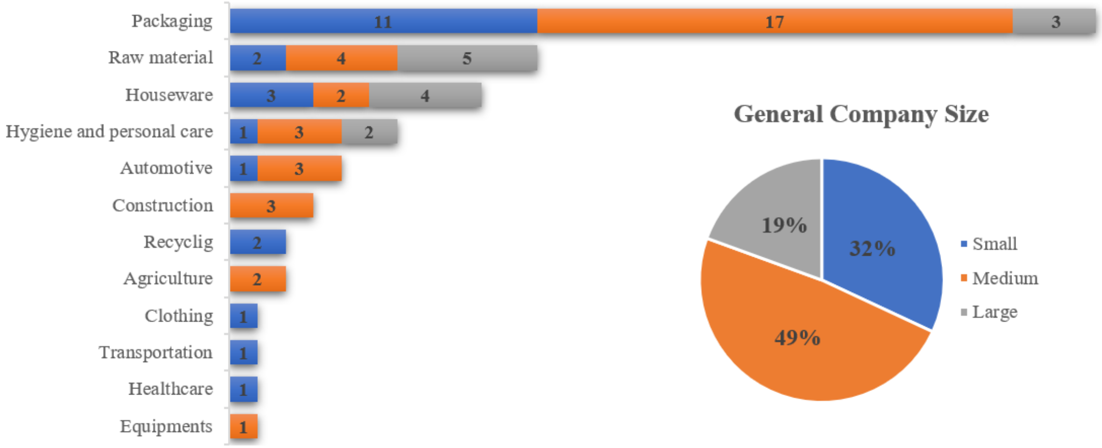

Figure 02 – Survey sampling profile[2]

3.6 Mathematical procedures

In Phase 4 we applied the Fuzzy TOPSIS method to analyze which Industry 4.0 technologies have the greatest potential for sustainable development in the plastics industry. A Multi-Criteria Decision Making (MCDM) method was utilized for this purpose (Turskis and Zavadskas, 2010).

[2] Small companies (up to 99 employees), Medium-sized companies (up to 499 employees), and Large companies (over 500 employees).

According to Junior et al. (2014), this method presents better adaptation for criteria selection, providing agility and a more robust analysis.

The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method consists in evaluating the alternatives according to their distances to the ideal solution (Hwang and Yoon, 1981). This technique is based on the concept that an evaluation of an alternative by n attributes can be represented by a point in three-dimensional space, in which geometric relationships can be formed between m points (locations). An ideal alternative will have the best values for all considered attributes, while the negatives will have the worst attribute values. TOPSIS defines solutions as points that are both farthest from the negative ideal point and closest to the ideal point (Chu, 2002). Chen and Hwang (1992), Liang (1999), and Chen (2000) incorporated fuzzy sets in TOPSIS method due to the need to includee the uncertainty of the response language to the attribute weights. Additionally, Cevik Onar et al. (2014) applied fuzzy numbers rather than clear numbers for the performance of the alternatives. Thus, Fuzzy TOPSIS method was carried out through the following steps:

Step a. Convert the answers from questions IV to X to a numerical scale, where: very negative = −2; negative = −1; no change = 0; positive = 1; very positive = 2.

Step b. The Fuzzy TOPSIS method itself, described by Chen (2000) and Parhizgar and Keshavarz (2016):

Step b1: Form a committee of decision makers and then identify the evaluation criteria. Data referring to the answers of question III that indicated “without knowledge” in the technologies were removed. The response rate (number of decision makers) considered for each technology is presented in Table 08.

Table 08 – Response rate for each technology

Technology	**Qty**	**%**
BIG DATA	62	86.1%
SENSORS	70	97.2%
CLOUD	72	100%
SYS_INT	65	90.3%
CPS	41	56.9%
ROBOTS	66	91.7%
IoT	64	88.9%

Step b2. Then, evaluation criteria are determined. In this study, the criteria are 12 KPIs, while the alternatives are seven technologies.

Step b3. After that, appropriate linguistic variables are chosen for evaluating criteria and alternatives. The Table 09 presents the linguistic variables chosen.

Table 09 - Linguistic variables for the importance weight of each criteria

Linguistic variables for the importance weight of each criteria	
Very low	(0, 0, 1)
Low	(0, 1, 3)
Medium Low	(1, 3, 5)
Medium	(3, 5, 7)
Medium High	(5, 7, 9)
High	(7, 9, 10)
Very High	(9, 10, 10)

In order to understand which technologies are the most aligned for each TBL pillar, the Fuzzy TOPSIS method was applied in four distinct scenarios. Scenario I considers all TBL pillars with equal weights, which represents a balanced profile company (Stoycheva *et al.*, 2018). However, scenarios II, III, and IV consider different importance for economic, environmental, and social aspects. Thus, we expected to distinguish which technologies have the greatest potential to impact the different aspects of sustainable development. The weights assigned for each scenario are shown in Table 10.

Table 10 – KPIs linguistic variables weights for each scenario

Scenario	**Description**	**Linguistic variables weight**		
		Economic	**Environmental**	**Social**
I	Balanced	Medium	Medium	Medium
II	Economic	Very high	Low	Low
III	Environmental	Low	Very high	Low
IV	Social	Low	Low	Very high

Step b4. Construct the fuzzy decision matrix with the fuzzy rating and weights. The fuzzy ratings of decision makers are described as triangular fuzzy numbers $\tilde{R}_k = (a_k, b_k, c_k)$, $k = 1, 2, \ldots, K$, then the aggregated fuzzy rating can be determined as $\tilde{R} = (a, b, c)$, $k = 1, 2, \ldots, K$, where

$$a = \min(a_k), \qquad b = \frac{1}{k}\sum_{k=1}^{k} b_k\,, \qquad c = \max(c_k) \tag{3}$$

The fuzzy numbers used are the final averages of KPIs for each technology, where b is the average of averages of the KPIs for each TBL aspect. That is, the value b of the "Economic" pillar is the average of the PROFIT, COSTS, SALES, ENERGY, and WRM KPIs. The model considers the minimum value a among the averages found in the KPIs group for each TBL pillar; and the maximum values c among the highest value found in the averages of the respective KPI group. Then, the aggregated fuzzy weights $\tilde{w}_{ij}$ of each criterion are calculated as $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$, where

$$w_{j1} = \min(w_{jk1}), \qquad w_{j2} = \frac{1}{k}\sum_{k=1}^{k} w_{jk2}\,, \qquad w_{j3} = \max(w_{jk3}) \tag{4}$$

Then, the decision fuzzy matrix:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \dots & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \dots & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \dots & \dots & \tilde{x}_{mn} \end{bmatrix}, \widetilde{W} = (\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n) \quad (5)$$

Here $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\widetilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$; $i = 1, 2, \dots m$, $j = 1, 2, \dots n$ can be approximated by positive triangular fuzzy numbers.

Step b5. Normalization of the decision fuzzy matrix, as follows:

$$\tilde{R} = [\tilde{r}_{ij}]_{m*n} \quad (6)$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in C \quad (7)$$

Where C are the set of “Economic”, “Environmental” or “Social” criteria and:

$$c_j^* = max_i c_{ij} \text{ if } j \in C \quad (8)$$

Step b6. Construction of the weighted normalized fuzzy matrix $\tilde{V}$, defined as:

$$\tilde{V} = [\tilde{V}_{ij}]_{m*n}, i = 1, 2, \dots, m; j = 1, 2, \dots, n, \tilde{V}_{ij} = \tilde{r}_{ij} * \widetilde{W}_{ij} \quad (9)$$

Here $\widetilde{W}_{ij}$ represents the importance weight of criterion C_j. According to the weighted normalized fuzzy decision matrix, the elements $\tilde{V}_{ij}$ $\forall i, j$ are normalized positive triangular fuzzy numbers and their ranges belong to the closed interval [0; 1].

Step b7. Determine the fuzzy positive-ideal solution (FPIS, A^+) and the fuzzy negative-ideal solution (FNIS, A^-), as follows:

$$A^+ = (\tilde{V}_1^+, \tilde{V}_2^+, \dots, \tilde{V}_n^+) \quad (10)$$

$$A^- = (\tilde{V}_1^-, \tilde{V}_2^-, \dots, \tilde{V}_n^-) \quad (11)$$

Where $\tilde{V}_j^+ = \max_i[\tilde{v}_{ij3}]$ and $\tilde{V}_j^- = \min_i[\tilde{v}_{ij1}]$, $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$.

Step b8. Calculate the distance of each alternative from FPIS and FNIS, respectively, determined as:

$$d_i^+ = \sqrt{\frac{1}{3}\sum_{j=1}^{n}(\tilde{V}_{ij} - V_j^+)^2} \quad (12)$$

$$d_i^- = \sqrt{\frac{1}{3}\sum_{j=1}^{n}(\tilde{V}_{ij} - V_j^-)^2} \quad (13)$$

Where d (;) is the distance measurement between two fuzzy numbers (FPIS and FNIS).

Step b9. Calculate the closeness coefficient CC_i of each alternative, determined as:

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1, 2, \dots, m. \quad (14)$$

Step b10. Final rankings, according to the higher closeness coefficient.

References

ABIPLAST, 2018. Available at: <http://www.abiplast.org.br/publicacoes/perfil2018/>. Access: 16 may 2020.

Amrina, E. and Vilsi, A. L., 2015. Key performance indicators for sustainable manufacturing evaluation in cement industry. Procedia CIRP. 26, 19-23. https://doi.org/10.1016/j.procir.2014.07.173.

Attaran, M., 2017. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. Business Horizons. 60(5), 677-688. https://doi.org/10.1016/j.bushor.2017.05.011.

Bai, C., Dallasega, P., Orzes, G. and Sarkis, J., 2020. Industry 4.0 technologies assessment: A sustainability perspective. International Journal of Production Economics. In press. https://doi.org/10.1016/j.ijpe.2020.107776.

Bai, C. and Sarkis, J., 2014. Determining and applying sustainable supplier key performance indicators. Supply Chain Management: An International Journal. 19(3), 275-291. https://doi.org/10.1590/0103-6513.20180020.

Baierle, I. C., Schaefer, J. L., Sellitto, M. A., Fava, L. P., Furtado, J. C., & Nara, E. O. B. (2020). MOONA software for survey classification and evaluation of criteria to support decision-making for properties portfolio. International Journal of Strategic Property Management, 24(4), 226-236. https://doi.org/10.3846/ijspm.2020.12338.

Baumgartner, R. J. and Ebner, D., 2010. Corporate sustainability strategies: sustainability profiles and maturity levels. Sustainable Development. 18(2), 76-89. https://doi.org/10.1002/sd.447

Beier, G., Niehoff, S., & Xue, B., 2018. More Sustainability in Industry through Industrial Internet of Things? Applied Sciences, 8(2), 219. doi:10.3390/app8020219.

Beier, G., Ullrich, A., Niehoff, S., Reißig, M., & Habich, M., 2020. Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes–A literature review. Journal of Cleaner Production, 120856. https://doi.org/10.1016/j.jclepro.2020.120856.

Ben-Daya, M., Hassini, E. and Bahroun, Z., 2019. Internet of things and supply chain management: a literature review. International Journal of Production Research. 57(15-16), 4719-4742. https://doi.org/10.1080/00207543.2017.1402140.

Benitez, G. B., Ayala, N. F., & Frank, A. G., 2020. Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation. International Journal of Production Economics, in press.

Bhagawati, M. T., Manavalan, E., Jayakrishna, K. and Venkumar, P., 2019. Identifying Key Success Factors of Sustainability in Supply Chain Management for Industry 4.0 Using DEMATEL Method. Proceedings of International Conference on Intelligent Manufacturing and Automation, Lecture Notes in Mechanical Engineering. 583-591. https://doi.org/10.1007/978-981-13-2490-1_54.

Bhandari, D., Singh, R. K. and Garg, S. K., 2019. Prioritisation and evaluation of barriers intensity for implementation of cleaner technologies: Framework for sustainable production. Resources, Conservation and Recycling. 146, 156-167. https://doi.org/10.1016/j.resconrec.2019.02.038.

Birkel, H. S., Veile, J. W., Müller, J. M., Hartmann, E. and Voigt, K.-I., 2019. Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers. Sustainability. 11(2), 384. https://doi.org/10.3390/su11020384.

Blanco, G., Amarilla, R., Martinez, A., Llamosas, C., & Oxilia, V. (2017). Energy transitions and emerging economies: A multi-criteria analysis of policy options for hydropower surplus utilization in Paraguay. Energy Policy, 108, 312-321. https://doi.org/10.1016/j.enpol.2017.06.003.

Bohlmann, C., Krumbholz, L. and Zacher, H., 2018. The triple bottom line and organizational attractiveness ratings: The role of pro-environmental attitude'. Corporate Social Responsibility and Environmental Management. 25 (5), 912-919. https://doi.org/10.1002/csr.1507.

Bonilla, S., Silva, H., Terra da Silva, M., Franco Gonçalves, R. and Sacomano, J., 2018. Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges. Sustainability. 10(10), 3740. https://doi.org/10.3390/su10103740.

Bottani, E., Gentilotti, M. C. and Rinaldi, M., 2017. A fuzzy logic-based tool for the assessment of corporate sustainability: a case study in the food machinery industry. Sustainability. 9(4), 583. https://doi.org/10.3390/su9040583.

Boyes, H., Hallaq, B., Cunningham, J. and Watson, T., 2018. The industrial internet of things (IIoT): An analysis framework. Computers in industry. 101, 1-12.

Braccini, A. and Margherita, E., 2019. Exploring organizational sustainability of industry 4.0 under the triple bottom line: The case of a manufacturing company. Sustainability. 11(1), 36. https://doi.org/10.3390/su11010036.

Cao, H., Zhang, X. and Chen, X., 2017. The concept and progress of intelligent spindles: a review. International Journal of Machine Tools and Manufacture. 112, 21-52.

Cevik Onar, S., Oztaysi, B. and Kahraman, C., 2014. Strategic decision selection using hesitant fuzzy TOPSIS and interval type-2 fuzzy AHP: a case study. International Journal of Computational intelligence systems. 7(5), 1002-1021. https://doi.org/10.1080/18756891.2014.964011.

Chen, C.-T., 2000. Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy sets and systems. 114(1), 1-9. https://doi.org/10.1016/S0165-0114(97)00377-1.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G. and Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production. 107, 615-625. https://doi.org/10.1016/j.jclepro.2015.05.009.

Chen, S.-J. and Hwang, C.-L., 1992. Fuzzy multiple attribute decision making methods. In: Fuzzy Multiple Attribute Decision Making. Lecture Notes in Economics and Mathematical Systems. 375, 289-486. https://doi.org/10.1007/978-3-642-46768-4_5.

Chen, B., Wan, J., Shu, L., Li, P., Mukherjee, M. and Yin, B., 2017. Smart factory of industry 4.0: Key technologies, application case, and challenges. IEEE Access. 6, 6505-6519.

Chu, T.-C., 2002. Facility location selection using fuzzy TOPSIS under group decisions. International journal of uncertainty, fuzziness and knowledge-based systems. 10(06), 687-701. https://doi.org/10.1142/S0218488502001739.

Chukwuekwe, D. O., Schjølberg, P., Rødseth, H. and Stuber, A., 2016. Reliable, Robust and Resilient Systems: Towards Development of a Predictive Maintenance Concept within the Industry 4.0 Environment. EFNMS Euro Maintenance Conference.

CNI, 2016. Indústria 4.0: novo desafio para a indústria brasileira. Sondagem Especial Indústria 4.0 - Indicadores CNI. (in Portuguese). http://www.portaldaindustria.com.br/estatisticas/sondesp-66-industria-4-0.

Culot, G., Nassimbeni, G., Orzes, G. and Sartor, M., 2020. Behind the definition of industry 4.0: Analysis and open questions. International Journal of Production Economics. In press. https://doi.org/10.1016/j.ijpe.2020.107617.

da Costa, M. B., Dos Santos, L. M. A. L., Schaefer, J. L., Baierle, I. C., & Nara, E. O. B., 2019. Industry 4.0 technologies basic network identification. Scientometrics. doi:10.1007/s11192-019-03216-7

Dalenogare, L. S., Benitez, G. B., Ayala, N. F. and Frank, A. G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics. 204, 383-394. https://doi.org/10.1016/j.ijpe.2018.08.019.

de Oliveira, A. C., Sokulski, C. C., da Silva Batista, A. A. and de Francisco, A. C., 2018. Competencies for sustainability: A proposed method for the analysis of their interrelationships. Sustainable Production and Consumption. 14, 82-94. https://doi.org/10.1016/j.spc.2018.01.005.

de Sousa Jabbour, A. B. L., de Oliveira Frascareli, F. C. and Jabbour, C. J. C., 2015. Green supply chain management and firms' performance: Understanding potential relationships and the role of green sourcing and some other green practices. Resources, Conservation and Recycling. 104, 366-374. https://doi.org/10.1016/j.resconrec.2015.07.017.

de Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C. and Godinho Filho, M., 2018. When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. Technological Forecasting and Social Change. 132, 18-25. https://doi.org/10.1016/j.techfore.2018.01.017.

Digilina, O. B., Teslenko, I. B. and Abdullaev, N. V., 2019. Industry 4.0: Contents, Problems and Perspectives. In: Perspectives on the Use of New Information and Communication Technology (ICT) in the Modern Economy. Advances in Intelligent Systems and Computing. 726, 32-38. https://doi.org/10.1007/978-3-319-90835-9_4.

Elkington, J., 1998. Partnerships from cannibals with forks: The triple bottom line of 21st-century business. Environmental quality management. 8(1), 37-51. https://doi.org/10.1002/tqem.3310080106.

Engelen, A., Kube, H., Schmidt, S. and Flatten, T. C., 2014. Entrepreneurial orientation in turbulent environments: The moderating role of absorptive capacity. Research Policy. 43(8), 1353-1369. https://doi.org/10.1016/j.respol.2014.03.002.

Esmaeilian, B., Behdad, S. and Wang, B., 2016. The evolution and future of manufacturing: A review. Journal of Manufacturing Systems. 39, 79-100. https://doi.org/10.1016/j.jmsy.2016.03.001.

Fatimah, Y. A., Govindan, K., Murniningsih, R. and Setiawan, A., 2020. A sustainable circular economy approach for smart waste management system to achieve sustainable development goals: Case study in Indonesia. Journal of Cleaner Production. In press. https://doi.org/10.1016/j.jclepro.2020.122263.

Fettermann, D. C., Cavalcante, C. G. S., Almeida, T. D. d. and Tortorella, G. L., 2018. How does Industry 4.0 contribute to operations management?. Journal of Industrial and Production Engineering. 35(4), 255-268. https://doi.org/10.1080/21681015.2018.1462863.

Ford, S. and Despeisse, M., 2016a. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of Cleaner Production. 137, 1573-1587. https://doi.org/10.1016/j.jclepro.2016.04.150.

Frank, A. G., Cortimiglia, M. N., Ribeiro, J. L. D. and de Oliveira, L. S., 2016. The effect of innovation activities on innovation outputs in the Brazilian industry: Market-orientation vs. technology-acquisition strategies. Research Policy. 45(3), 577-592. https://doi.org/10.1016/j.respol.2015.11.011.

Frank, A. G., Dalle Molle, N., Gerstlberger, W., Bernardi, J. A. B. and Pedrini, D. C., 2016b. An integrative environmental performance index for benchmarking in oil and gas industry. Journal of cleaner production. 133, 1190-1203. https://doi.org/10.1016/j.jclepro.2016.06.064.

Frank, A. G., Dalenogare, L. S. and Ayala, N. F., 2019. Industry 4.0 technologies: Implementation patterns in manufacturing companies. International Journal of Production Economics. 210, 15-26. https://doi.org/10.1016/j.ijpe.2019.01.004.

Frank, A. G., Gerstlberger, W., Paslauski, C. A., Lerman, L. V., & Ayala, N. F., 2018. The contribution of innovation policy criteria to the development of local renewable energy systems. Energy Policy, 115, 353-365. https://doi.org/10.1016/j.enpol.2018.01.036.

Garcia-Arroyo, J. and Osca, A., 2019. Big data contributions to human resource management: a systematic review. The International Journal of Human Resource Management. 1-26. https://doi.org/10.1080/09585192.2019.1674357.

Ghadimi, P., Wang, C. and Lim, M. K., 2019. Sustainable supply chain modeling and analysis: Past debate, present problems and future challenges. Resources, Conservation and Recycling. 140, 72-84. https://doi.org/10.1016/j.resconrec.2018.09.005.

Ghobakhloo, M., 2018. 'The future of manufacturing industry: A strategic roadmap toward Industry 4.0. Journal of Manufacturing Technology Management. 29(6), 910-936. https://doi.org/10.1108/JMTM-02-2018-0057.

Ghobakhloo, M., 2020. Industry 4.0, Digitization, and Opportunities for Sustainability. Journal of Cleaner Production, 119869. doi:10.1016/j.jclepro.2019.119869.

Gu, F., Guo, J., Hall, P. and Gu, X., 2018. An integrated architecture for implementing extended producer responsibility in the context of Industry 4.0. International Journal of Production Research. 57(5), 1-20. https://doi.org/10.1080/00207543.2018.1489161.

Gunasekaran, A. and Spalanzani, A., 2012. Sustainability of manufacturing and services: Investigations for research and applications. International journal of production economics. 140(1), 35-47. https://doi.org/10.1016/j.ijpe.2011.05.011.

Guo, R., Lv, S., Liao, T., Xi, F., Zhang, J., Zuo, X., Cao, X., Feng, Z. and Zhang, Y., 2020. Classifying green technologies for sustainable innovation and investment. Resources, Conservation and Recycling. 153, 104580. https://doi.org/10.1016/j.resconrec.2019.104580.

Hair, J.F., Black, W.C., Babin, B.J. and Anderson, R.E., 2009. Multivariate Data Analysis: A Global Perspective, Upper Saddle River: Prentice Hall.

Hansen, U. E., Nygaard, I., Romijn, H., Wieczorek, A., Kamp, L. M. and Klerkx, L., 2018. Sustainability transitions in developing countries: Stocktaking, new contributions and a research agenda. 84, 198-203. https://doi.org/10.1016/j.envsci.2017.11.009

Heyer, C., 2010. Human-robot interaction and future industrial robotics applications. IEEE/RSJ International Conference on Intelligent Robots and Systems. 4749-4754. https://doi.org/10.1109/IROS.2010.5651294.

Hofmann, E. and Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Computers in industry, 89, 23-34.

Holbrook, A. L., Krosnick, J. A. and Pfent, A., 2008. The causes and consequences of response rates in surveys by the news media and government contractor survey research firms. Advances in telephone survey methodology. 1, 499-528.

Hon, K. K. B., 2005. Performance and evaluation of manufacturing systems. CIRP annals. 54(2), 139-154. https://doi.org/10.1016/S0007-8506(07)60023-7.

Hozdić, E., 2015. Smart factory for industry 4.0: A review. International Journal of Modern Manufacturing Technologies. 7(1), 28-35.

Hubbard, G., 2009. Measuring organizational performance: beyond the triple bottom line. Business strategy and the environment. 18(3), 177-191. https://doi.org/10.1002/bse.564.

Hussey, D. M., Kirsop, P. L. and Meissen, R. E., 2001. Global reporting initiative guidelines: an evaluation of sustainable development metrics for industry. Environmental Quality Management. 11(1), 1-20. https://doi.org/10.1002/tqem.1200.

Hwang, C.-L. and Yoon, K., 1981. Methods for multiple attribute decision making. Multiple attribute decision making. 186, 58-191.

Ivanov, D., Dolgui, A. and Sokolov, B., 2019. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. International Journal of Production Research. 57(3), 829-846. https://doi.org/10.1080/00207543.2018.1488086.

Jabbour, C. J. C., Fiorini, P. D. C., Wong, C. W., Jugend, D., Jabbour, A. B. L. D. S., Seles, B. M. R. P., ... & da Silva, H. M. R. (2020). First-mover firms in the transition towards the sharing economy in metallic natural resource-intensive industries: Implications for the circular economy and emerging industry 4.0 technologies. Resources Policy. 66, in press. https://doi.org/10.1016/j.resourpol.2020.101596.

Jayal, A., Badurdeen, F., Dillon Jr, O. and Jawahir, I., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology. 2(3), 144-152. https://doi.org/10.1016/j.cirpj.2010.03.006.

Junior, F. R. L., Osiro, L. and Carpinetti, L. C. R., 2014. A comparison between Fuzzy AHP and Fuzzy TOPSIS methods to supplier selection. Applied Soft Computing. 21, 194-209. https://doi.org/10.1016/j.asoc.2014.03.014.

Junior, J. A. G., Busso, C. M., Gobbo, S. C. O. and Carreão, H., 2018. Making the links among environmental protection, process safety, and industry 4.0. Process Safety and Environmental Protection. 117, 372-382. https://doi.org/10.1016/j.psep.2018.05.017.

Kamble, S. S., Gunasekaran, A. and Gawankar, S. A., 2018. Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. Process Safety and Environmental Protection. 117, 408-425. https://doi.org/10.1016/j.psep.2018.05.009.

Kamble, S., Gunasekaran, A., & Dhone, N. C., 2020. Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. International Journal of Production Research, 1–19. doi:10.1080/00207543.2019.1630772.

Kang, H. S., Lee, J. Y., Choi, S., Kim, H., Park, J. H., Son, J. Y., Kim, B. H. and Do Noh, S., 2016. Smart manufacturing: Past research, present findings, and future directions. International Journal of Precision Engineering and Manufacturing-Green Technology. 3(1), 111-128. https://doi.org/10.1007/s40684-016-0015-5.

Kiel, D., Müller, J. M., Arnold, C. and Voigt, K.-I., 2017. Sustainable industrial value creation: Benefits and challenges of industry 4.0. International Journal of Innovation Management. 21(08), 1740015. https://doi.org/10.1142/S1363919617400151.

Kocmanová, A. and Dočekalová, M., 2014. Corporate sustainability: environmental, social, economic and corporate performance. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis. 59(7), 203-208. https://doi.org/10.11118/actaun201159070203

Kusiak, A., 2018. Smart manufacturing. International Journal of Production Research, 56(1-2), 508-517. https://doi.org/10.1080/00207543.2017.1351644.

Li, L., 2018. China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". Technological Forecasting and Social Change. 135, 66-74. https://doi.org/10.1016/j.techfore.2017.05.028.

Li, Y., Dai, J. and Cui, L., 2020. The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model. International Journal of Production Economics. In press. https://doi.org/10.1016/j.ijpe.2020.107777.

Li, X., Li, D., Wan, J., Vasilakos, A. V., Lai, C. F. and Wang, S., 2017. A review of industrial wireless networks in the context of industry 4.0. Wireless networks. 23(1), 23-41.

Liang, G.-S., 1999. Fuzzy MCDM based on ideal and anti-ideal concepts. European Journal of Operational Research. 112(3), 682-691. https://doi.org/10.1016/S0377-2217(97)00410-4.

Longo, F., Nicoletti, L. and Padovano, A., 2017. Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. Computers & industrial engineering. 113, 144-159. https://doi.org/10.1016/j.cie.2017.09.016.

Lu, Y., 2017. Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration. 6, 1-10. https://doi.org/10.1016/j.jii.2017.04.005.

Luthra, S., Kumar, A., Zavadskas, E. K., Mangla, S. K. and Garza-Reyes, J. A., 2020. Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy. International Journal of Production Research. 58(5), 1505-1521. https://doi.org/10.1080/00207543.2019.1660828.

Luthra, S. and Mangla, S. K., 2018a. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. Process Safety and Environmental Protection, 117, 168-179. https://doi.org/10.1016/j.psep.2018.04.018.

Luthra, S. and Mangla, S. K., 2018b. When strategies matter: Adoption of sustainable supply chain management practices in an emerging economy's context. Resources, Conservation and Recycling. 138, 194-206. https://doi.org/10.1016/j.resconrec.2018.07.005.

Ma, Z., Shao, C., Ma, S. and Ye, Z., 2011. Constructing road safety performance indicators using fuzzy delphi method and grey delphi method. Expert Systems with Applications. 38(3), 1509-1514. https://doi.org/10.1016/j.eswa.2010.07.062.

Machado, C. G., Winroth, M. P. and Ribeiro da Silva, E. H. D., 2020. Sustainable manufacturing in Industry 4.0: an emerging research agenda. International Journal of Production Research. 1-23. https://doi.org/10.1080/00207543.2019.1652777.

Mittal, S., Khan, M. A., Romero, D. and Wuest, T., 2017. Smart manufacturing: characteristics, technologies and enabling factors. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 233(5), 1342-1361. https://doi.org/10.1177/0954405417736547.

Mittal, S., Khan, M. A., Romero, D. and Wuest, T., 2018. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of manufacturing systems. 49, 194-214. https://doi.org/10.1016/j.jmsy.2018.10.005.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S. and Barbaray, R., 2018. The industrial management of SMEs in the era of Industry 4.0. International Journal of Production Research. 56(3), 1118-1136. https://doi.org/10.1080/00207543.2017.1372647.

Müller, J. M. 2020. Industry 4.0 in the Context of the Triple Bottom Line of Sustainability: A Systematic Literature Review. In Custoner Satisfaction and Sustainability Initiatives in the Fourth Industrial Revolution. Hershey: IGI Global, pp. 1-20.

Müller, J. M., Kiel, D. and Voigt, K.-I., 2018a. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. Sustainability. 10(1), 247. https://doi.org/10.3390/su10010247.

Müller, J.M., Buliga, O., Voigt, K.-I., 2018b. Fortune favors the prepared: how SMEs approach business model innovations in Industry 4.0. Technol. Forecast. Soc. Chang. 132 (1), 2e17.

Murray, T. J., Pipino, L. L. and van Gigch, J. P., 1985. A pilot study of fuzzy set modification of Delphi. Human Systems Management. 5(1), 76-80. https://doi.org/10.3233/HSM-1985-5111.

Nara, E. O. B., Gelain, C., Ribas Moraes, J. A., Benitez, L. B., Schaefer, J. L., & Baierle, I. C., 2019a. Analysis of the sustainability reports from multinationals tobacco companies in southern Brazil. Journal of Cleaner Production. doi:10.1016/j.jclepro.2019.05.399.

Nara, E. O. B., Sordi, D. C., Schaefer, J. L., Schreiber, J. N. C., Baierle, I. C., Sellitto, M. A., & Furtado, J. C., 2019b. Prioritization of OHS key performance indicators that affecting business competitiveness – A demonstration based on MAUT and Neural Networks. Safety Science, 118, 826–834. doi:10.1016/j.ssci.2019.06.017

Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Rocha-Lona, L., Tortorella, G., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: a business model proposal. J. Manuf. Technol. Manag. 30 (3), 607e627.

Norman, W. and MacDonald, C., 2004. Getting to the bottom of "triple bottom line". Business Ethics Quarterly. 14(2), 243-262. https://doi.org/10.2307/3857909.

Oesterreich, T. D. and Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Computers in industry. 83, 121-139. https://doi.org/10.1016/j.compind.2016.09.006.

Parhizgar, M. M. and Keshavarz, E., 2016. Prioritising of factors effective on marketing relationship using FAHP and fuzzy TOPSIS methods. International Journal of Logistics Systems and Management. 24(4), 489-516. https://doi.org/10.1504/IJLSM.2016.077284.

Peter, J. P.,1981. Construct validity: a review of basic issues and marketing practices. Journal of Marketing Research, 133-145.

Piccarozzi, M., Aquilani, B. and Gatti, C., 2018. Industry 4.0 in Management Studies: A Systematic Literature Review. Sustainability. 10(10), 3821. https://doi.org/10.3390/su10103821.

Pikas, B., Zhang, X., Peek, W., & Lee, T., 2016. The Transformation and Upgrading of the Chinese Manufacturing Industry: Based on "German Industry 4.0". Journal of Applied Business and Economics, 18(5). https://doi.org/10.33423/jabe.v18i5.870.

Podgórski, D., 2015. Measuring operational performance of OSH management system–A demonstration of AHP-based selection of leading key performance indicators. Safety science. 73, 146-166. https://doi.org/10.1016/j.ssci.2014.11.018.

Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., De Amicis, R., Pinto, E. B., Eisert, P., Döllner, J. and Vallarino, I., 2015. Visual computing as a key enabling technology for industrie 4.0 and industrial internet. IEEE computer graphics and applications. 35(2), 26-40. https://doi.org/10.1109/MCG.2015.45.

Qi, Q. and Tao, F., 2018. Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. Ieee Access. 6, 3585-3593.

Ramirez-Peña, M., Sotano, A. J. S., Pérez-Fernandez, V., Abad, F. J. and Batista, M., 2020. Achieving a sustainable shipbuilding supply chain under I4. 0 perspective. Journal of Cleaner Production. 244, in press. https://doi.org/10.1016/j.jclepro.2019.118789.

Rajput, S. and Singh, S. P., 2018. Identifying Industry 4.0 IoT enablers by integrated PCA-ISM-DEMATEL approach. Management Decision. 57(8), 1784-1817. https://doi.org/10.1108/MD-04-2018-0378.

Rauch, J. N. and Newman, J., 2009. Defining sustainability metric targets in an institutional setting. International Journal of Sustainability in Higher Education. 10(2), 107-117. https://doi.org/10.1108/14676370910945927.

Richards, D. J. and Gladwin, T. N., 1999. Sustainability metrics for the business enterprise. Environmental Quality Management. 8(3), 11-21. https://doi.org/10.1002/tqem.3310080303.

Roca, L. C. and Searcy, C., 2012. An analysis of indicators disclosed in corporate sustainability reports. Journal of Cleaner Production. 20(1), 103-118. https://doi.org/10.1016/j.jclepro.2011.08.002.

Rojko, A., 2017. Industry 4.0 concept: background and overview. International Journal of Interactive Mobile Technologies (iJIM). 11(5), 77-90.

Roy, R., Stark, R., Tracht, K., Takata, S. and Mori, M., 2016. Continuous maintenance and the future–Foundations and technological challenges. Cirp Annals. 65(2), 667-688.

Ruppert, T., Jaskó, S., Holczinger, T. and Abonyi, J., 2018. Enabling Technologies for Operator 4.0: A Survey. Applied Sciences. 8(9), 1650. https://doi.org/10.3390/app8091650.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M., 2015. Industry 4.0: The future of productivity and growth in manufacturing industries. Boston Consulting Group. 9.

Sahi, G. K., Gupta, M. C.,and Cheng, T. C. E., 2020. The effects of strategic orientation on operational ambidexterity: A study of indian SMEs in the industry 4.0 era. International Journal of Production Economics. 220, in press. https://doi.org/10.1016/j.ijpe.2019.05.014.

Sartal, A., Bellas, R., Mejías, A. M. and García-Collado, A., 2020. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Advances in Mechanical Engineering. 12(5). https://doi.org/10.1177/1687814020925232.

Sellitto, M. A. (2018). Reverse logistics activities in three companies of the process industry. Journal of Cleaner Production, 187, 923-931. https://doi.org/10.1016/j.jclepro.2018.03.262.

Sellitto, M. A., Hermann, F. F., Blezs Jr, A. E., & Barbosa-Póvoa, A. P. (2019). Describing and organizing green practices in the context of Green Supply Chain Management: Case studies. Resources, Conservation and Recycling, 145, 1-10. https://doi.org/10.1016/j.resconrec.2019.02.013.

Shamim, S., Cang, S., Yu, H. and Li, Y., 2016. Management approaches for Industry 4.0: A human resource management perspective. 2016 IEEE Congress on Evolutionary Computation (CEC). 5309-5316. https://doi.org/10.1109/CEC.2016.7748365.

Shin, S.-J., Woo, J. and Rachuri, S., 2014. Predictive analytics model for power consumption in manufacturing. Procedia Cirp. 15, 153-158. https://doi.org/10.1016/j.procir.2014.06.036.

Siegel, S. C. and Castellan, J. R., 1988. Nonparametric statistics for the behavioural sciences. New York, McGraw-Hill.

Sikdar, S. K., 2003. Sustainable development and sustainability metrics. AIChE journal. 49(8), 1928-1932. https://doi.org/10.1002/aic.690490802.

Song, Z. and Moon, Y., 2018. Sustainability metrics for assessing manufacturing systems: a distance-to-target methodology. Environment, Development and Sustainability. 21(6), 2811-2834. https://doi.org/10.1007/s10668-018-0162-7.

Stock, T. and Seliger, G., 2016. Opportunities of sustainable manufacturing in industry 4.0. Procedia Cirp. 40, 536-541. https://doi.org/10.1016/j.procir.2016.01.129.

Stoycheva, S., Marchese, D., Paul, C., Padoan, S., Juhmani, A.-s. and Linkov, I., 2018. Multi-criteria decision analysis framework for sustainable manufacturing in automotive industry. Journal of Cleaner Production. 187, 257-272. https://doi.org/10.1016/j.jclepro.2018.03.133.

Suddaby, R., 2010. Editor's comments: Construct clarity in theories of management and organization. Suddaby, R. (2010). Academy of Management Review, 35, 346–357. https://doi:10.5465/amr.2010.51141319.

Sulistiarini, E. B., Suparman, S., Santoso, P. B. and Tama, I. P., 2018. A conceptual framework of sustainable development strategy as “corporate responsibility” in manufacturing industry. Environmental Quality Management. 27(3), 147-161. https://doi.org/10.1002/tqem.21539.

Tanzil, D. and Beloff, B. R., 2006. Assessing impacts: Overview on sustainability indicators and metrics. Environmental Quality Management. 15(4), 41-56. https://doi.org/10.1002/tqem.20101.

Tao, F. and Zhang, M., 2017. Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing. Ieee Access. 5, 20418-20427.

Tao, F., Cheng, J., Cheng, Y., Gu, S., Zheng, T. and Yang, H., 2017. SDMSim: a manufacturing service supply–demand matching simulator under cloud environment. Robotics and computer-integrated manufacturing. 45, 34-46.

Thiede, S., 2018. Environmental sustainability of cyber physical production systems. Procedia CIRP. 69, 644-649. https://doi.org/10.1016/j.procir.2017.11.124.

Thoben, K. D., Wiesner, S. and Wuest, T., 2017. “Industrie 4.0” and smart manufacturing-a review of research issues and application examples. International journal of automation technology. 11(1), 4-16.

Tiwari, K., & Khan, M. S., 2020. Sustainability Accounting and Reporting in the Industry 4.0. Journal of Cleaner Production, 120783. doi:10.1016/j.jclepro.2020.120783.

Tortorella, G. L. and Fettermann, D., 2018. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research. 56(8), 2975-2987. https://doi.org/10.1080/00207543.2017.1391420.

Tseng, M. L., Tan, R. R., Chiu, A. S., Chien, C. F., & Kuo, T. C., 2018. Circular economy meets industry 4.0: can big data drive industrial symbiosis?. Resources, Conservation and Recycling, 131, 146-147. https://doi.org/10.1016/j.resconrec.2017.12.028.

Turskis, Z. and Zavadskas, E. K., 2010. A new fuzzy additive ratio assessment method (ARAS-F); Case study: The analysis of fuzzy multiple criteria in order to select the logistic centers location. Transport. 25(4), 423-432. https://doi.org/10.3846/transport.2010.52.

Varela, L., Araújo, A., Ávila, P., Castro, H. and Putnik, G., 2019. Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability. Sustainability. 11(5), 1439. https://doi.org/10.3390/su11051439.

Visser, P. S., Krosnick, J. A., Marquette, J. and Curtin, M., 1996. Mail surveys for election forecasting? An evaluation of the Columbus Dispatch poll. Public Opinion Quarterly, 60(2), 181-227. https://doi.org/10.1086/297748.

Wan, J., Tang, S., Shu, Z., Li, D., Wang, S., Imran, M. and Vasilakos, A. V., 2016. Software-defined industrial internet of things in the context of industry 4.0. IEEE Sensors Journal. 16(20), 7373-7380.

Wang, G., Gunasekaran, A., Ngai, E. W. and Papadopoulos, T., 2016. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. International Journal of Production Economics. 176, 98-110. https://doi.org/10.1016/j.ijpe.2016.03.014.

WCED, 1987. World commission on environment and development. Our common future, 17, 1-91.

Wei, Z., Song, X. and Wang, D., 2017. Manufacturing flexibility, business model design, and firm performance. International Journal of Production Economics. 193, 87-97. https://doi.org/10.1016/j.ijpe.2017.07.004.

Wollschlaeger, M., Sauter, T. and Jasperneite, J., 2017. The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. IEEE industrial electronics magazine. 11(1), 17-27.

Wudhikarn, R. Improving the intellectual capital management approach using the hybrid decision method. Journal of Intellectual Capital, 2018.

Xu, M., Cai, H. and Liang, S., 2015. Big data and industrial ecology. Journal of Industrial Ecology. 19(2), 205-210. https://doi.org/10.1111/jiec.12241.

Xu, L. D., Xu, E. L. and Li, L., 2018. Industry 4.0: state of the art and future trends. International Journal of Production Research. 56(8), 2941-2962.

Yadav, G., Luthra, S., Jakhar, S., Mangla, S. K., & Rai, D. P., 2020. A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case. Journal of Cleaner Production, 120112. doi:10.1016/j.jclepro.2020.120112.

Yin, Y., Stecke, K. E. and Li, D., 2018. The evolution of production systems from Industry 2.0 through Industry 4.0. International Journal of Production Research. 56(1-2), 848-861. https://doi.org/10.1080/00207543.2017.1403664.

Zawadzki, P. and Żywicki, K., 2016. Smart product design and production control for effective mass customization in the Industry 4.0 concept. Management and Production Engineering Review.

Zezulka, F., Marcon, P., Vesely, I. and Sajdl, O., 2016. Industry 4.0–An Introduction in the phenomenon. IFAC-PapersOnLine. 49(25), 8-12.

Zhang, L., Mai, J., Li, B. H., Tao, F., Zhao, C., Ren, L. and Huntsinger, R. C., 2014. Future manufacturing industry with cloud manufacturing. Cloud-Based Design and Manufacturing (CBDM. 127-152. https://doi.org/10.1007/978-3-319-07398-9_5.

Zhang, Y., Liu, S., Liu, Y., Yang, H., Li, M., Huisingh, D. and Wang, L., 2018. The 'Internet of Things' enabled real-time scheduling for remanufacturing of automobile engines. Journal of cleaner production. 185, 562-575. https://doi.org/10.1016/j.jclepro.2018.02.061.

Zheng, P., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., Mubarok, K., ... and Xu, X., 2018. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. Frontiers of Mechanical Engineering. 13(2), 137-150.

Zhong, R. Y., Xu, X., Klotz, E. and Newman, S. T., 2017. Intelligent manufacturing in the context of industry 4.0: a review. Engineering. 3(5), 616-630. https://doi.org/10.1016/J.ENG.2017.05.015.

Appendix A – Friedman non-parametric test and relative ratings

Technologies	Mean	Median	Mean Rank	Rating
Big data analytics [BIG DATA]	6.047	7.000	11.119	1
Cybersecurity [CSECURITY]	5.761	7.000	10.119	2
Smart sensors [SENSORS]	5.571	5.000	10.095	3
System integration [SYS_INT]	5.476	5.000	9.833	4
Cloud computing and manufacturing [CLOUD]	5.381	5.000	9.452	5
Artificial intelligence [AI]	5.381	5.000	9.285	6
Internet of things [IoT]	5.190	5.000	8.976	7
Digitalization and virtualization [DIGITAL]	5.190	5.000	8.833	8

Autonomous and collaborative robots [ROBOTS]	5.095	5.000	8.690	9
Mobile systems and devices [MOBILE]	5.000	5.000	8.357	10
Cyber physical systems [CPS]	4.809	5.000	7.857	11
Machine to machine communication [M2M]	4.809	5.000	7.833	12
Industrial internet [IND_NET]	4.428	3.000	7.000	13
Simulation [SIMUL]	4.523	5.000	6.833	14
Augmented and virtual reality [AVR]	4.142	3.000	6.047	15
Additive manufacturing [AM]	4.047	3.000	5.666	16

Friedman Test ($N = 21$; $\chi^2 = 45.622$; $df = 15$; $p = 0.000061$).

Appendix B – Questionnaire

Impact of Industry 4.0 technologies on sustainable development in plastics industry

1. Which market segmentation best fits your product?

( ) Agriculture
( ) Automotive
( ) Construction
( ) Electronics
( ) Packaging
( ) Hygiene and personal care
( ) Recycling
( ) Health care
( ) Transportation
( ) Housewares

( ) Machines and equipment
( ) Raw material
( ) Clothing

2. What is the number of employees in your company?
( ) Up to 99 employees
( ) From 100 to 499 employees
( ) More than 499 employees

Industry 4.0 technologies

3. Check your level of knowledge in relation to the technologies below.

	None	Only theoretical knowledge	Moderate practical knowledge	Advanced practical knowledge
Cyber-Physical Systems				
Internet of Things				
Cloud Computing				
Big Data				
Robotics (autonomous and collaborative robots)				
Systems integration				
Smart Sensors				

Industry 4.0 technologies vs. Sustainable development indicators

In the following questions (4-10), indicate, according to your perception, the possible impacts of these technologies on sustainable development indicators.

4. What is the impact of Big Data on the items below?*

	Very negative	Negative	No change	Positive	Very positive
Profitability					
Material and manufacturing costs					
Billing, sales, and market share					
Energy efficiency and energy consumption					
Consumption of water, inputs, and raw materials					
Use of renewable and recycling resources					
Generation of waste and harmful materials					
Pollutants and effluents emission					

Working conditions, occupational health and safety					
Human resources and rights: qualification, benefits and satisfaction, diversity, and gender equity					
Generation and maintenance of jobs					
Reputation with the community and regulatory compliance					

*Questions 4-10 are the same and correspond to: big data, cloud computing, systems integration, IoT, autonomous and collaborative robots, intelligent sensors and cyber-physical systems, respectively.