A Big Data analytics and Artificial Intelligence framework to enhance industrial sustainability

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Abstract:

Purpose: This article aims to examine how emerging technologies related to Big Data and Artificial Intelligence (AI) can contribute to improving sustainability in the industrial sector and to analyze the methods of integrating such technologies to develop an intelligent sustainability framework. **Method**: Big Data and AI offers numerous advantages, like better resource management, increased energy efficiency, and waste reduction, consequently leading to improved environmental sustainability. The authors, following an in-depth literature review, investigated how the analysis of Big Data, collected through a multitude of sensors and analyzed using machine learning algorithms, neural networks, and deep learning, can identify patterns to optimize production and maintenance processes. **Results**: such technologies can be employed to predict machine failures, optimize production processes, and improve product quality, thus contributing to the economic and environmental sustainability of manufacturing companies, with also reference to reducing carbon footprint. Furthermore, the implementation of an intelligent sustainability framework not only brings immediate benefits in terms of operational efficiency but also helps improve the position of companies facing future challenges such as climate change and increasingly stringent regulatory pressures. **Conclusions**: Industry 4.0 (I4.0) is an innovative paradigm promising to revolutionize various sectors, requiring an in-depth understanding of its applications. Its implementation requires a gradual approach, starting from small pilots to prove rapid and significant results. Among the sectors that can benefit most from this transformation, the manufacturing industry emerges as one of the main candidates, especially regarding sustainability. Ultimately, the integration of such technologies represents an opportunity to enhance the competitiveness of businesses towards a more sustainable industrial future.

Keywords: Big Data, Artificial Intelligence AI, Machine Learning ML, Deep Learning DL, Sustainability.

1. Introduction

Sustainability is a must-have characteristic of every company (Pinna et al., 2018), in particular the environmental one (Gavrus et al., 2024). Climate change is a severe global issue and carbon emissions (Demartini et al., 2023) and energy are widely studied in many different fields (Chinese et al., 2022; Fresia et al., 2024; Tonelli et al., 2016). In this context, renewable energy are a key topic (Bracco and Fresia, 2023), as much as energy savings (Fresia and Bracco, 2023). I4.0, applied in many different sectors, from I4.0, to warehouse (Mosca et al., 2022a) and healthcare (R. Mosca et al., 2023) is the other current topic. AI is the simulation of human intelligence through algorithms and techniques such as Machine Learning and Deep Learning (Oluyisola et al., 2020). From a supply chain perspective, it impacts in all areas where it can perform task that previously required human intelligence (Liao et al., 2022). From an internal perspective, AI along with other Industry 4.0 technologies, can address a wide range of issues, from skill shortages to take complex decisions, to challenges in distributing and managing large amount of information from different sources (Zhu et al., 2022). AI is closely linked to Big Data, that refers to the flow of a large amount of data. (Kunkel et al., 2022).The concept of Big Data can be represented with the 5V model (Zheng et al., 2020): A large Volume of data, GBs and TBs per hour; Variety in type, not only structured data; High Velocity of generation; A great potential Value; The need to be controlled in terms of Veracity. Big Data analysis allow uncovering and highlighting patterns otherwise invisible(Bressanelli et al., 2018; Waqas et al., 2021). For better decisions and clear understanding, data must be of high quality, hence clean and filtered, and provided in real-time (Gupta et al., 2021). The aim is to analyze how these 2 technologies impact on the sustainability of companies, optimizing resources use, reducing waste and costs through the Porter’s value chain (Liu and Wang, 2024). The issue of sustainability is of great relevance both in terms of a general sensitivity to environmental problem (Gómez et al., 2023) and in the context of increasing instability in demand and supply markets, due to recent disruptive events related to the COVID pandemic and wars (Kunkel et al., 2022). This paper is divided into a problem statement with related research questions, the methodology followed, the literature review, the evaluation of AI and Big Data impact over Porter’s value chain, a framework to integrate them, followed by an implementation roadmap. Finally results, discussions and conclusions are presented.

2. Literature Review

The term I4.0 is the integration of embedded systems to Cyber-Physical-Systems, a combination of physical and digital worlds (Mahnashi et al., 2023), and underscores the comprehensive digitalization of all physical resources and their integration into digital environments (Agrawal et al., 2022). Consequently, emerging technologies are rendering industries smarter, more automated and more sustainable (Mezair et al., 2022; Tripathy et al., 2023). The results of this review are resumed in Appendix A, where to each primary activity of Porter's value chain are associated AI, Big Data and their impact.

Inbound Logistics *(AI: 1, Big Data: 3, Both: 1):* due to resources unavailability, industries should leverage data, information, and knowledge to the fullest extent to achieve sustainability goals (Garg et al., 2019). Moreover, industries must take proud in their transformation to avoid environmental criticism (Pons et al., 2022); enhanced industrial and corporate competitiveness is directly linked to sustainability strategies (Ahmad et al., 2020; Garg et al., 2016). Sustainable development is the foremost, recognized concern for today's industrial companies, necessitating a rethink and revolutionization of current design, production and usage pattern (Zheng et al., 2020).

Operations *(AI: 7, Big Data: 1, Both: 3):* Businesses must create a data-oriented system to meet sustainability objectives, which play a crucial role across all phases of asset lifecycle management (El Bazi et al., 2023). AI can enhance analytical capabilities (Asif et al., 2019). For instance, an artificial neural network (ANN) can predict the optimal part designs for 3D printers (Sangwan et al., 2023). AI prominently supports highly automated manufacturing (Liao et al., 2022; Zhu et al., 2022). Big data analytics-powered AI can improve supply chain performance (Bag et al., 2021). Sustainability entails development that meets present needs without compromising future generations' abilities to meet their own needs, without sacrificing quality, cost, operational reliability, operational performance and energy efficiency, while minimizing ecological damage and enhancing profitability (Amjad et al., 2020; Gómez et al., 2023; Zhang and Dong, 2023). Currently the pace of production and consumption is approaching environmentally unsustainable levels (Sánchez-García et al., 2024). Recent technological advancements are opportunities to enhance the circular economy and sustainable development (Dwivedi et al., 2022).

Outbound Logistics (*AI: 0, Big Data: 1, Both: 2*): Digital technologies are expected to foster information exchange and facilitate collaboration on sustainability issues among firms (Kunkel et al., 2022). I4.0 technologies such as actuators and sensors within the IIoT system, have the capacity to generate significant volume of big data information (Gupta et al., 2021). Big Data can contribute to sustainable industry by promoting practical ideas to achieve sustainable development goals, bolstering eco-effective performance, and gaining competitive advantages in today's volatile market. Data collection and analysis of from both internal and external industry environment can suggest improvements and benefits (Waqas et al., 2021).

Marketing and Sales *(AI: 2, Big Data: 2, Both: 2):* This transformation positively impacts both customers, reducing time-to-market, enhancing customer responsiveness, enabling customized mass production, and the environment, without escalating production costs, fostering a more flexible and conducive work environment, and advocating for the efficient utilization of natural resources and energy (Bu et al., 2021; Javed et al., 2023). Many companies are struggling to manage their production systems due to escalating market uncertainty (Oluyisola et al., 2020). I4.0 supports the implementation of the Circular Economy, which principles are reuse, recycling and regeneration (Sánchez-García et al., 2024), by increasing resource efficiency, extending lifespan, and closing the loop (Bressanelli et al., 2018; Oliveri et al., 2022).

Services (*AI: 2, Big Data: 1, Both: 1*): I4.0 cannot be fully realized without sustainable development, which is indispensable for market success, economic growth, and minimal environmental impact. Therefore, companies are keen on developing all processes from client order to product delivery, within a sustainability framework (Gavrus et al., 2024). If sustainable production aims to effectively utilize resources (Löfgren et al., 2022), I4.0 can facilitate this objective (Dwivedi et al., 2022). Furthermore, challenges regarding the correct implementation of I4.0 within the Circular Economy framework are still under research (Moktadir and Ren, 2023).

3. Problem Statement and Research questions

Sustainability is one of the main concerns of any kind of entity, both public and private. However, the goal of 0 emissions and environmental impact, in the optic of UN SGD 13, is still far to achieve. Moreover, I4.0 technologies, although able to provide great insight, are not carefully analyzed linked to sustainability. There is therefore the need for a framework able to integrate those technologies, especially Big Data and AI, which can be the base to meet UN SGD 8 and 9. To achieve this problem solution, it has been translated into 3 research questions (RQ): 1) How Big Data and AI are related? 2) How do these technologies impact on Sustainability? 3) How can they be integrated into a Sustainability 4.0 framework?

4. Methodology

To ensure the highest quality and innovation, the initial step of this research has involved thorough exploration of existing literature on the Scopus database, as it is the most important. To do that, the 3 strings of keywords used are: ("Big Data" OR "Artificial Intelligence" OR "AI" OR "Big Data analytics" OR "Machine Learning" OR "Deep Learning" OR "Neural Network" OR "natural language processing" e "LLM") AND ("Sustainab*" OR "Green" OR "Carbon Footprint") AND (("Framework" OR "Roadmap" OR "Implementation") AND ("Industry")). These strings follow a logical path, starting with the limitation of the research field to AI and Big Data. The second string connects these technologies to the context of sustainability. Thirdly, to focus on the implementation of the technologies in Industry, the third string is added. With these strings, 2262 documents were initially found. To reduce this number, it was used the search for "Keywords" only, resulting in 77 documents. Furthermore, to focus on the most innovative and recent papers, the year range was restricted to 2015-2024, as more than 90% of the documents were written during this period. This reduces the number to 70. Finally, the only other 2 filters used are articles on journals and written in English. The final number of articles is 45, of which 42 are available to read and 30 are within the scope of the research. To this amount, 31 have been added with a snowballing.

Once done the literature review, AI and Big Data have been studied on their impact over sustainability, following the Porter's value chain. After that, a framework integrating them has been developed alongside an implementation roadmap.

5. Big Data and AI for Sustainability in value chain

The integration of Big Data and Artificial Intelligence (AI) into industrial processes marks a revolutionary step towards sustainable manufacturing, fundamentally reshaping how resources are managed, and efficiencies are achieved across the entire value chain. Various topics within the framework of Porter's value chain model aim to build a comprehensive approach to enhancing sustainability. The strategic integration of Big Data and AI into Porter's value chain ensures that each activity, from inbound logistics to service, is optimized for sustainability. By leveraging these technologies, industries can significantly reduce waste, improve resource efficiency, and minimize their environmental footprint. This holistic approach embeds sustainability into the core of business practices, contributing to a sustainable industrial future. Please note that Big Data is essential for identifying patterns within data structures that would otherwise remain invisible. However, a pre-analytical phase is recommended to avoid overloading the central server with vast amounts of data. To achieve this, an edge architecture is employed on data collection devices to sample and retain only the necessary data. Additionally, an intermediate fog architecture, such as gateway concentrators, is used to integrate and pre-analyze data, thereby reducing latency in the cyclical process from monitoring to feedback. Artificial Intelligence leverages this data minimizing project risk, especially if associated to a digital twin (Allahi et al., 2017; Cassettari et al., 2010; Lanzini et al., 2023; Mosca et al., 2009). Following the Porter's value chain, the impact of AI and Big Data on sustainability are analysed.

5.1 Inbound Logistics

Supply Chain Optimization: AI optimizes supply chain management, particularly with data from IoT devices, which minimizes logistics-related emissions by suggesting optimal delivery routes, better inventory management, and predictive demand planning. Enhanced logistics efficiency reduces also carbon emissions and fuel consumption, contributing to environmental sustainability (Mosca et al., 2022a).

5.2 Operations

Advanced Manufacturing Technologies: The synergy of Big Data and AI facilitates advanced manufacturing technologies, such as 3D printing and automated robotics, which are less wasteful due to their precision and the ability to produce on-demand (Sangwan et al., 2023). AI optimization of material usage and reduction of overproduction leads to significant waste reduction and more sustainable manufacturing practices.

Energy Efficiency: AI-driven systems enhance energy efficiency (Zhu et al., 2022) by dynamically adjusting energy usage based on real-time production needs and external factors such as weather conditions, reducing unnecessary consumption. Lower energy consumption directly translates to a reduced carbon footprint (Famoso et al., 2024).

Predictive and Prescriptive Maintenance: Predictive analytics powered by AI can forecast machinery malfunctions and, allow preemptive maintenance, integrating different models (Arena et al., 2021), that minimizes downtime and extends the lifespan of equipment. This aspect is particularly important when concerning hazardous substances (Peron et al., 2023). Beyond continuous production flow, it also mitigates the environmental impact associated with manufacturing new parts, disposing of old equipment prematurely, and the potential disruption (Palacín et al., 2021)., AI algorithms, due to their great capability of learning and predicting, can be successfully applied to forecasting also in different fields (Cassettari et al., 2017), taking great value from data science (Arena et al., 2022). Realizing a true prescriptive maintenance is then possible to make it evolve into a philosophy towards continuous improvement (Lee et al., 2020). This approach not only ensures continuous production flow but also reduces the environmental impact associated with manufacturing new parts and disposing of old equipment prematurely (Cassettari et al., 2017).

5.3 Outbound Logistics

Smarter Product Design: AI integration with Big Data enables the development of smarter product designs that are easier to recycle and maintain (Bressanelli et al., 2018). By analyzing product usage data collected via sensors and customer feedback, AI can help design products that last longer and are easier to dismantle for recycling. AI supports the circular economy by ensuring products, components, and materials maintain their usefulness over time.

5.4 Marketing and Sales

Informed Decisions: The confluence of Big Data and AI provides immediate benefits in terms of operational efficiency and cost reduction, equipping industries with tools to make informed decisions that align with both business objectives and environmental stewardship. Enhanced decision-making processes lead to better sustainability practices and improved overall efficiency (Cassettari et al., 2013a).

5.5 Service

Accurate Sustainability Reports: AI aids in regulatory compliance by monitoring and managing environmental impacts through real-time data analysis. This helps industries stay ahead of regulatory requirements and contribute to a more sustainable public image. AI-generated sustainability reports reflect true environmental impact, fostering transparency and accountability.

Safety and Health: AI and Big Data enhance employee health and safety by predicting and mitigating risks, ensuring safer work environments, in line with UN SDG 3.. By analyzing vast datasets, AI identifies potential hazards before they cause harm. Reduces accidents and improves overall workplace safety, taking into consideration every kind of worker (Peron et al., 2022). This concern is also useful when it concerns biohazard or diseases spreads (Roberto Mosca et al., 2023). Innovative applications of Health and Safety 4.0 are provided by Mosca et al. (Mosca et al., 2022b, 2021).

As industries continue to evolve under the influence of these technologies, the promise of a sustainable industrial future becomes increasingly tangible, ensuring that the environmental, economic and social pillars of sustainability are addressed holistically (El Bazi et al., 2023; Gupta et al., 2021; Zheng et al., 2020). Moreover, the importance of sustainable, renewable energy sources is increasingly recognized in efforts to reduce environmental pollution and enhance energy security (Bendato et al., 2017).

6 Sustainability 4.0 framework

The strategic integration of Big Data and Artificial Intelligence (AI) into an intelligent sustainability framework is fundamental for industrial processes highly efficient and, environmentally responsible. Simulation can help in that (Cassettari et al., 2013b). Developing this framework requires a systematic approach to integrate technological solutions, exploiting Big Data analytical with AI. AI can search through massive, complex datasets of Big Data to uncover patterns and insights crucial for identifying the most impactful areas for sustainability improvements, such as energy consumption, resource allocation and waste management. Authors proceed developing their innovative Sustainability 4.0 framework, presented in Appendix B, which combine AI and Big Data.

6.1 Goal Setting

Define Sustainability Goals: The first step is defining the specific sustainability achievements the company desires. These can include reducing environmental footprint, minimizing water and energy consumption, lowering chemical waste, reducing spare parts requirements, and decreasing defects. It is essential that these sustainability improvements are achieved without compromising efficiency and productivity.

6.2 Data Collection Infrastructure

Identify Key Data Points: Determine what specific data is important to measure. This includes energy usage, raw material inputs, operational efficiency, and output quality.

Deploy IoT Sensors: Install IoT sensors and smart devices across various stages of the production process to collect Big Data in real-time. Ensure that the data collected is relevant to the sustainability goals set in the first step.

6.3 Data Aggregation and Preliminary Analysis

Preliminary Data Cleaning: Ensure that the collected data is of high quality by performing initial data cleaning and filtering. Eliminating irrelevant or inaccurate data, reduces the data flow and avoiding latency.

Centralize Data: Aggregate data into a centralized Big Data platform. This platform provides a comprehensive view of the production processes in real-time.

6.4 Data Analysis and Algorithm Selection

Select Suitable Algorithms: Leverage machine learning models and AI algorithms to analyze the collected data. The selection of algorithms should be based on the specific needs and characteristics of the company. It is crucial to choose algorithms that align with the company's data structure and sustainability objectives.

Predictive and Prescriptive Maintenance Algorithms: Use algorithms designed for predictive maintenance, to forecast machinery failures and identify conditions that waste energy or materials, and for prescriptive maintenance, providing tips and actions to prolong equipment life span.

Operational Optimization Algorithms: Apply algorithms that can optimize production processes, reduce resource waste, and decrease environmental footprint.

6.5 Implementation of Digital Twins

Develop Digital Twins: Integrate AI with Big Data to create digital twins for simulations and scenario analyses. Digital twins allow for testing and optimizing sustainability outcomes without the risk and expense of altering the physical system.

Scenario Testing: Conduct simulations to identify the most effective strategies for improving sustainability before actual implementation.

6.6 Continuous Monitoring and Feedback Loops

Real-Time Monitoring: Continuously monitor the performance of implemented solutions using real-time data analysis. AI systems should be employed to provide ongoing feedback and adapt to new data.

Adaptive Learning: Implement feedback loops where AI systems learn from past decisions and outcomes to refine future predictions and recommendations. This ensures the framework remains effective over time, dynamically adjusting to evolving environmental standards and regulations.

6.7 Decision Support Systems

Integrate AI-Driven Insights: Incorporate AI-driven insights into the decision-making fabric of the organization. AI can help managers make more informed choices that prioritize sustainability while aligning with business objectives.

Sustainability Dashboards: Develop sustainability dashboards that provide real-time insights into key performance indicators such as resource savings, energy efficiency, and waste reduction.

6.8 Reporting and Compliance

Generate Accurate Sustainability Reports: AI can create accurate and transparent sustainability reports that reflect the true environmental impact of the company's operations and public image, meeting regulations.

Regulatory Compliance: Ensure that the framework helps the company stay ahead of regulatory requirements, avoiding penalties and fostering a sustainable public image.

6.9 Safety and Health

Enhance Workplace Safety: Utilize AI and Big Data to predict and mitigate risks, ensuring safer work environments. By analyzing vast datasets, AI can identify potential hazards before they cause harm, improving overall workplace safety.

6.10 Framework Effectiveness

Regular Reviews and Updates: Periodically update the framework to ensure it remains aligned with the latest technological advancements and sustainability standards.

Stakeholder Engagement: Involve stakeholders in the review process to gather feedback and ensure that the framework meets their expectations and requirements.

8 Results

The **first result** is that literature agrees on the positive impact of I4.0 on energy consumption and savings. Also, Circular Economy is favored by digital technologies. **The second result** is that Big Data is considered very useful for sustainability, both when coming from the inside of the company and from the environment. **The third result** is that Big Data powered AI can provide great knowledge. This leads also to taking better decisions about sustainability and safety. **The fourth result** is that is missing in literature a framework that relates sustainability with I4.0. **The last result** is the great impact that Sustainability 4.0 framework can have both directly and indirectly on emissions and environmental impacts of companies. With an economic saving, too.

9 Discussion, conclusion and future work agenda

I4.0 can have a huge impact on sustainability and circular economy. However, a framework which relate these topics is still missing. Big Data and AI can provide great insights in the processes and bring big improvements, like energy savings, resource optimization, better recyclable products. Big Data can be the base for better AI models, which requires high amounts of data of high quality. Answering RQ1, the aggregation of data is then a suitable way to relate them. Both AI and Big Data can in fact improve sustainability all across the value chain (RQ2). They can then be integrated to successfully create a Sustainability 4.0 framework (RQ3). It can profoundly impact an industry's environmental footprint by systematically analyzing and optimizing each stage of production and enhancing operational efficiency. This enable a higher sustainability as energy and resources are better used and outputs are designed and produced in optic to minimize environmental impact. Authors' framework is therefore a viable solution for the problem statement, as it perfectly integrates Big Data and AI for a better sustainability. As AI is applied in many different sectors (Briatore et al., 2023), it is important to study the integration with Big Data and other I4.0 technologies. IoT, Digital Twins and Cyber Physical Systems mainly, creating full systems, like in (Mosca et al., 2022c). Moreover, also Resilience and its connection with Sustainability should be addressed.

References

Agrawal, S., Sahu, A., Kumar, G., 2022. A conceptual framework for the implementation of Industry 4.0 in legal informatics. Sust. Comp.: Inf. and Syst. 33.

Ahmad, S., Miskon, S., Alabdan, R., Tlili, I., 2020. Exploration of influential determinants for the adoption of business intelligence system in the textile and apparel industry. Sustainability 12.

Allahi, F., Cassettari, L., Mosca, M., 2017. Stochastic risk analysis and cost contingency allocation approach for construction projects applying Monte Carlo simulation, Eng. and Comp. Science , pp. 385–391.

Amjad, M.S., Rafique, M.Z., Hussain, S., Khan, M.A., 2020. A new vision of LARG Manufacturing — A trail towards Industry 4.0. CIRP J. M. Sci. T. 31, 377–393.

Arena, S., Manca, G., Murru, S., Orrù, P.F., Perna, R., Reforgiato Recupero, D., 2022. Data Science Application for Failure Data Management and Failure Prediction in the Oil and Gas Industry: A Case Study. Appl. Sci. 12.

Arena, S., Roda, I., Chiacchio, F., 2021. Integrating modelling of maintenance policies within a stochastic hybrid automaton framework of dynamic reliability. Appl. Sci. 11, 1–18.

Asif, Z., Chen, Z., Zhu, Z.H., 2019. An integrated life cycle inventory and artificial neural network model for mining air pollution management. Int. J. Environ. Sci. Technol. 16, 1847–1856.

Bag, S., Pretorius, J.H.C., Gupta, S., Dwivedi, Y.K., 2021. Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. Tech. For. Soc. Cha 163.

Bendato, I., Cassettari, L., Mosca, R., Williams, E., Mosca, M., 2017. A stochastic methodology to evaluate the optimal multi-site investment solution for photovoltaic plants. J. Clean. Prod. 151, 526–536.

Bracco, S., Fresia, M., 2023. Energy Management System for the Optimal Operation of a Grid-Connected

Building with Renewables and an Electric Delivery Vehicle, EUROCON 2023, pp. 472–477.

Bressanelli, G., Adrodegari, F., Perona, M., Saccani, N., 2018. Exploring how usage-focused business models enable circular economy through digital technologies. Sustainability 10.

Briatore, F., Revetria, R., Rozhok, A., 2023. A Literature Review on Applied AI to Public Administration: Insights from Recent Research and Real-Life Examples, in: Front. in Art. Inte. and App. IOS Press.

Bu, L., Zhang, Y., Liu, H., Yuan, X., Guo, J., Han, S., 2021. An IIoT-driven and AI-enabled framework for smart manufacturing system based on three-terminal collaborative platform. Adv. Eng. Inf. 50.

Cassettari, L., Bendato, I., Mosca, M., Mosca, R., 2017. A new stochastic multi source approach to improve the accuracy of the sales forecasts. Foresight 19, 48–64.

Cassettari, L., Giribone, P.G., Mosca, M., Mosca, R., 2010. The stochastic analysis of investments in industrial plants by simulation models with control of experimental error: Theory and application to a real business case. Appl. Math. Sci. 4, 3823–3840.

Cassettari, L., Mosca, M., Mosca, R., Rolando, F., 2013a. The yearly production of a manufacturing plant studied by DES combined with RSM high level designs and neural networks. Int.J. Math. Com. Sim. 7.

Cassettari, L., Mosca, M., Mosca, R., Rolando, F., 2013b. An healthcare process reengineering using discrete event simulation, in: Lect. Notes Eng. Comput. Sci. Presented at the Lecture Notes in Engineering and Computer Science, pp. 1174–1179.

Chinese, D., Orrù, P.F., Meneghetti, A., Cortella, G., Giordano, L., Benedetti, M., 2022. Symbiotic and optimized energy supply for decarbonizing cheese production: An Italian case study. Energy 257.

Demartini, M., Ferrari, M., Govindan, K., Tonelli, F., 2023. The transition to electric vehicles and a net zero economy: A model based on circular economy, stakeholder theory, and system thinking approach. J. Clean. Prod. 410.

Dwivedi, A., Moktadir, M.A., Chiappetta Jabbour, C.J., de Carvalho, D.E., 2022. Integrating the circular economy and industry 4.0 for sustainable development: Implications for responsible footwear production in a big data-driven world. Tech. For. Soc. Change 175.

El Bazi, N., Mabrouki, M., Laayati, O., Ouhabi, N., El Hadraoui, H., Hammouch, F.-E., Chebak, A., 2023. Generic Multi-Layered Digital-Twin-Framework-Enabled Asset Lifecycle Management for the Sustainable Mining Industry. Sustainability 15.

Famoso, F., Oliveri, L.M., Brusca, S., Chiacchio, F., 2024. A Dependability Neural Network Approach for Short-Term Production Estimation of a Wind Power Plant. Energies 17.

Fresia, M., Bordo, L., Delfino, F., Bracco, S., 2024. Optimal day-ahead active and reactive power management for microgrids with high penetration of renewables. Energy Conversion and Management: X 100598.

Fresia, M., Bracco, S., 2023. Electric Vehicle Fleet Management for a Prosumer Building with Renewable Generation. Energies 16.

Garg, A., Sarma, S., Panda, B.N., Zhang, J., Gao, L., 2016. Study of effect of nanofluid concentration on response characteristics of machining process for cleaner production. J. Clean. Prod. 135, 476–489.

Garg, R., Aggarwal, H., Centobelli, P., Cerchione, R., 2019. Extracting knowledge from big data for sustainability: A comparison of machine learning techniques. Sustainability 11.

Gavrus, C., Petre, I.M., Pârv, L., 2024. Industry 4.0—Premise for Sustainability: Implementation Degree in Manufacturing Companies from Romania. Sustainability 16.

Gómez, Á.L.P., Maimó, L.F., Celdrán, A.H., Clemente, F.J.G., 2023. SUSAN: A Deep Learning based anomaly detection framework for sustainable industry. Sustainable Computing: Informatics and Systems 37.

Gomez-Carmona, O., Casado-Mansilla, D., Lopez-De-Ipina, D., Garcia-Zubia, J., 2022. Optimizing Computational Resources for Edge Intelligence Through Model Cascade Strategies. IEEE Internet Things J. 9, 7404–7417.

Gupta, S., Justy, T., Kamboj, S., Kumar, A., Kristoffersen, E., 2021. Big data and firm marketing performance: Findings from knowledge-based view. Technol. Forecast. Soc. Change 171.

Javed, S., Tripathy, A., Deventer, J.V., Mokayed, H., Paniagua, C., Delsing, J., 2023. An approach towards demand response optimization at the edge in smart energy systems using local clouds. Smart Energy 12.

Kunkel, S., Matthess, M., Xue, B., Beier, G., 2022. Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry. Resour. Conserv. Recycl. 182.

Lanzini, M., Adami, N., Benini, S., Ferretti, I., Schieppati, G., Spoto, C., Zanoni, S., 2023. Implementation and integration of a Digital Twin for production planning in manufacturing, EMSS, Cal-Tek srl.

Lee, J., Ni, J., Singh, J., Jiang, B., Azamfar, M., Feng, J., 2020. Intelligent Maintenance Systems and Predictive Manufacturing. J Manuf Sci Eng Trans ASME 142.

Liao, M., Lan, K., Yao, Y., 2022. Sustainability implications of artificial intelligence in the chemical industry: A conceptual framework. J. Ind. Ecol. 26, 164–182.

Liu, R., Wang, Y., 2024. Enhancing Enterprise Value Creation Through Intelligent Digital Transformation of the Value Chain: A Deep Learning and Edge Computing Approach. J. Knowl. Econ.

Löfgren, J., Tarasov, D., Koitto, T., Rinke, P., Balakshin, M., Todorović, M., 2022. Machine Learning Optimization of Lignin Properties in Green Biorefineries. ACS Sust. Chem. Eng. 10, 9469–9479.

Mahnashi, I., Salah, B., Ragab, A.E., 2023. Industry 4.0 Framework Based on Organizational Diagnostics and Plan–Do–Check–Act Cycle for the Saudi Arabian Cement Sector. Sustainability 15.

Mezair, T., Djenouri, Y., Belhadi, A., Srivastava, G., Lin, J.C.-W., 2022. A sustainable deep learning framework for fault detection in 6G Industry 4.0 heterogeneous data environments. Comput Commun 187, 164–171.

Moktadir, M.A., Ren, J., 2023. Modeling challenges for Industry 4.0 implementation in new energy systems towards carbon neutrality: Implications for impact assessment policy and practice in emerging economies. Resour. Conserv. Recycl. 199.

Mosca, R., G.Bruzzone, A., Cassettari, L., Mosca, M., 2009. Risk analysis for industrial plants projects: An innovative approach based on simulation techniques with experimental error control, EMSS 2009.

Mosca, Roberto, Mosca, M., Briatore, F., Currò, F., 2023. Full Sanitization of Buildings with Industry 4.0 Management and Economic Advantages. Wseas Trans. On Business And Economics 20, 2059–2065.

Mosca, R., Mosca, M., Pagano, S., Revetria, R., Galli, G., 2021. Engineering 4.0 to Improve the Safety of Plant Operators in a Metalworking Company of International Importance: The Ansaldo Energia Case, Eng. Comput. Sci., Newswood Limited, pp. 196–201.

Mosca, R., Mosca, M., Revetria, R., Currò, F., Briatore, F., 2023. An innovative 4.0 system to prevent the spreading of the diseases which threaten the globalized world. Health Technol. 13, 781–789.

Mosca, R., Mosca, M., Revetria, R., Currò, F., Briatore, F., 2022a. Smart Inventory 4.0: Advanced version. Proceedings of the Summer School Francesco Turco.

Mosca, R., Mosca, M., Revetria, R., Currò, F., Briatore, F., 2022b. Engineering Solutions 4.0 in the fight against the spread of Covid 19 A new Methodology including processes, procedures and devices. Proceedings of the Summer School Francesco Turco.

Mosca, R., Mosca, M., Revetria, R., Currò, F., Briatore, F., 2022c. Through Engineering 4.0 the Safe Operating Block for Patients and Medical Staff. Lecture Notes in Engineering and Computer Science 2244, 114–123.

Oliveri, L.M., Chiacchio, F., D'Urso, D., Matarazzo, A., Cutaia, L., Luciano, A., 2022. Circular Economy and Industrial Symbiosis in Sicily, IFIP Ad. in Inf. and Comm. Tech., pp. 432–439.

Oluyisola, O.E., Sgarbossa, F., Strandhagen, J.O., 2020. Smart production planning and control: Concept, use-cases and sustainability implications. Sustainability 12.

Palacín, I., Gibert, D., Planes, J., Arena, S., Orrù, P.F., Melis, M., Annis, M., 2021. Anomaly Detection for Diagnosing Failures in a Centrifugal Compressor Train, Front. Artif. Intell. Appl., IOS Press BV, pp.

Peron, M., Arena, S., Micheli, G.J.L., Sgarbossa, F., 2022. A decision support system for designing win–win interventions impacting occupational safety and operational performance in ageing workforce contexts. Saf. Sci. 147.

Peron, M., Arena, S., Paltrinieri, N., Sgarbossa, F., Boustras, G., 2023. Risk assessment for handling hazardous substances within the European industry: Available methodologies and research streams. Risk Anal. 43, 1434–1462.

Pinna, C., Demartini, M., Tonelli, F., Terzi, S., 2018. How Soft Drink Supply Chains drive sustainability: Key Performance Indicators (KPIs) identification, CIRP, Elsevier B.V., pp. 862–867.

Pons, A., Rius, J., Vintró, C., Gallart, A., 2022. Analysis of Twitter posts for evaluation of Corporate Social Responsibility in the leather industry. J. Eng. Fibers Fabr. 17.

Sánchez-García, E., Martínez-Falcó, J., Marco-Lajara, B., Manresa-Marhuenda, E., 2024. Revolutionizing the circular economy through new technologies: A new era of sustainable progress. Env. Technol. Innov. 33.

Sangwan, K.S., Kumar, R., Herrmann, C., Sharma, D.K., Patel, R., 2023. Development of a cyber physical production system framework for 3D printing analytics. Appl. Soft Comput. 146.

Tonelli, F., Bruzzone, A.A.G., Paolucci, M., Carpanzano, E., Nicolò, G., Giret, A., Salido, M.A., Trentesaux, D., 2016. Assessment of mathematical programming and agent-based modelling for off-line scheduling: Application to energy aware manufacturing. CIRP Annals 65, 405–408.

Tripathy, S.S., Bebortta, S., Gadekallu, T.R., 2023. Sustainable Fog-Assisted Intelligent Monitoring Framework for Consumer Electronics in Industry 5.0 Applications. IEEE Trans Consum Electron 1–1.

Waqas, M., Honggang, X., Ahmad, N., Khan, S.A.R., Iqbal, M., 2021. Big data analytics as a roadmap towards green innovation, competitive advantage and environmental performance. J. Clean. Prod. 323.

Zhang, X., Dong, F., 2023. What affects residents' behavioral intentions to ban gasoline vehicles? Evidence from an emerging economy. Energy 263.

Zheng, P., Li, X., Peng, T., Wang, Y., Zhang, G., 2020. Industrial smart product-service system development for lifecycle sustainability concerns. IET Collab. Intell. Manuf. 2, 197–201.

Zhu, S., Ota, K., Dong, M., 2022. Green AI for IIoT: Energy Efficient Intelligent Edge Computing for Industrial Internet of Things.IEEE T.G.C.N.6, 79–88.

Appendix A. ARTICLES ANALYSIS

Activity	Impact	N° art	Cit
Inbound logistics	*AI:* Enhances predictive analytics for optimizing resource allocation. *Big Data:* Provides comprehensive insights to streamline supply chain operations for sustainability.	*AI: 1* *Big Data: 3* *Both: 1*	*AI:* (Garg et al., 2019) *Big Data:* (Ahmad et al., 2020; Garg et al., 2016; Pons et al., 2022) *Both:* (Zheng et al., 2020)
Operations	*AI:* Enhances automated manufacturing and predictive maintenance. *Big Data:* Optimize asset lifecycle management and improve overall supply chain performance.	*AI: 7* *Big Data: 1* *Both: 3*	*AI:* (Amjad et al., 2020; Asif et al., 2019; Gomez-Carmona et al., 2022; Liao et al., 2022; Sangwan et al., 2023; Zhang and Dong, 2023; Zhu et al., 2022) *Big Data:* (Dwivedi et al., 2022) *Both:* (Bag et al., 2021; El Bazi et al., 2023; Sánchez-García et al., 2024)
Outbound logistics	*AI:* Facilitates real-time tracking and efficient route planning. *Big Data: P*romotes collaboration and enhances eco-effective performance through comprehensive data analysis.	*AI: 0* *Big Data: 1* *Both: 2*	*AI:* *Big Data:* (Waqas et al., 2021) *Both:* (Gupta et al., 2021; Kunkel et al., 2022)
Marketing & sales	*AI:* Enhances customer responsiveness and enables customized mass production. *Big Data:* Reduces time-to-market and supports efficient resource utilization, promoting sustainability.	*AI: 2* *Big Data: 2* *Both: 2*	*AI:* (Bu et al., 2021; Javed et al., 2023) *Big Data:* (Bressanelli et al., 2018; Oliveri et al., 2022) *Both:* (Oluyisola et al., 2020; Sánchez-García et al., 2024)
Services	*AI:* Optimize resource utilization from client order to delivery. *Big Data:* Facilitates sustainable development by enhancing process efficiency and minimizing environmental impact	*AI: 2* *Big Data: 1* *Both: 1*	*AI:* (Gavrus et al., 2024; Löfgren et al., 2022) *Big Data:* (Dwivedi et al., 2022) *Both:* (Moktadir and Ren, 2023)

Appendix B. SUSTAINABILITY 4.0 FRAMEWORK