The integration of sustainability and automation to enhance manufacturing in Industry 4.0

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Abstract

Industry 4.0 has presented unparalleled prospects and complexities within the manufacturing industry. One of the significant challenges is the seamless integration of sustainability measures alongside rapid advancements in automation. This paper aims to analyze the potential synergistic integration of sustainability and automation to improve manufacturing processes within the framework of Industry 4.0. This paper presents a conceptual framework that aligns sustainable practices with automation technologies. Furthermore, this paper discusses the barriers to integration and ethical considerations. The findings suggest that thoughtful incorporation of both sustainability and automation boosts productivity and economic benefits and leads to environmentally and socially responsible manufacturing. This paper is intended for academics and researchers interested in the future directions of sustainable manufacturing in the era of Industry 4.0.

Introduction

Industry 4.0 signifies a substantial revolution in manufacturing, where cutting-edge technology maximizes efficiency while reducing resource usage. Industry 4.0 is a German initiative integrating production with information technology [1]. The contemporary industrial revolution utilizes sophisticated digital technologies, for example, artificial intelligence (AI), big data analytics, the Internet of Things (IoT), and robotics, to establish intelligent factories that exhibit enhanced efficiency, adaptability, and the ability to make well-informed choices to mitigate environmental consequences. In the context of Industry 4.0, integrating sustainability and automation signifies a progressive strategy that seeks to enhance manufacturing procedures and tackle the pressing imperative for industries to adjust to and mitigate the impacts of environmental transformation.

As we progress into the 21st century, there is a growing emphasis on the need for sustainable development, prompting sectors to adopt methods that promote long-term ecological equilibrium and the preservation of resources. In this context, integrating sustainability and automation in manufacturing is a beacon of innovation and responsibility, promising to revolutionize how products are designed, produced, distributed, and recycled. This introduction investigates the potential benefits of incorporating sustainability and automation into Industry 4.0. Doing so can improve manufacturing practices, resulting in a more sustainable, efficient, and competitive industry. This method guarantees that the industry can fulfill present requirements while preserving the capacity of future generations to fulfill their own needs. Nevertheless, smoothly incorporating these technologies into the manufacturing environment is full of obstacles. Many barriers, including technical and infrastructural challenges, workforce adaptation, and cybersecurity concerns, pose significant constraints. Moreover, the ethical considerations accompanying the widespread adoption of AI and other digital technologies in manufacturing underscore the need for careful deliberation and proactive management.

Although introducing Industry 4.0 technology offers advantages to supply chains, significant progress remains to be made [2-3]. A recent survey done by Deloitte in 19 countries indicates that only 14% of chief executive officers express confidence in their firm's readiness to integrate the changes associated with Industry 4.0 effectively. The Industry 4.0 Global Expert Survey conducted by McKinsey reveals that, on average, just 40% of enterprises have successfully implemented Industry 4.0 [4]. Furthermore, this percentage varies dramatically across different nations. Most organizations have not made any advancements due to the numerous obstacles encountered in implementing Industry 4.0. Studies have demonstrated that adopting Industry 4.0 is an intricate undertaking, and numerous organizations in various nations are encountering challenges due to diverse obstacles [5]. Hence, it is imperative to recognize the obstacles and their interconnections that might facilitate the development of a mitigation plan, ultimately resulting in a more seamless integration of Industry 4.0 [6]. A limited number of scholars have done scientific studies on the obstacles that hinder the implementation of Industry 4.0 technology. Prior studies have relied on empirical data collected through survey research [7-8] and interview case studies [9-10]. Subsequent studies have concentrated on constructing a structural model identifying the obstacles to implementing Industry 4.0 [11-12]. Integrating sustainability and automation within the Industry 4.0 framework presents a compelling directive for curriculum enhancement in engineering technology programs. The adaptation of ENGT 4210 to "Industrial Automation Systems" by one of the coauthors of this work, Manimaran et al. [13] provides a template for embedding these concepts into educational syllabi. The course has been recalibrated to meet the evolving landscape of the industrial sector by integrating contemporary resources such as a new textbook and simulation software, exemplified by LabVIEW. This approach ensures that the pedagogical content is not only current but also relevant to the dynamic nature of industrial technology. Fourteen summer 2022 and eleven summer 2023 ENGT 4210 students presented PowerPoint presentations on area industry subjects for APSU. The topics covered included IIOT, ISA 95, Digital Twin, Soft PLC, IIOT API, Digital Transformation, Smart Instruments, Cyber-Physical Protection Systems, Open PLCs, Automation Development, Digital Sustainability, Augmented Reality, and Automating Automation. In the Spring 2022 Industrial Advisory Board (IAB) meeting, the Engineering Technology IAB discussed Industry 4.0's importance in the Clarksville, Montgomery, and Hopkinsville industrial regions. The department continues incorporating pieces of this emerging technology into the ET curriculum. Implement capstone projects or labs where students use CFD [14-17] software to simulate and analyze manufacturing processes, focusing on reducing carbon footprint, enhancing energy efficiency, using mathematical modeling, and incorporating smart automation techniques [18-21].

As we explore the complexities of Industry 4.0, it is crucial to tackle the obstacles to integration and the emerging ethical quandaries. This preliminary investigation examines the obstacles and moral concerns associated with incorporating sophisticated technology into production processes within Industry 4.0, laying the foundation for a more thorough examination. This emphasizes the significance of adopting a well-rounded strategy that acknowledges the transformative potential of these technologies in manufacturing while also understanding and tackling the associated difficulties. This research examines the significant applications of sustainability in Industry 4.0, specifically in the manufacturing industry.

The Concept of Sustainability

Sustainability in the context of Industry 4.0 is about harnessing the power of new technologies to create manufacturing processes that are more efficient, flexible, environmentally friendly, and socially responsible. It involves rethinking production lifecycles, energy use, material consumption, and waste management to mitigate environmental impact while addressing the ethical implications of technological adoption on the workforce and society. The integration of sustainability into Industry 4.0 is driven by a growing recognition that economic success cannot be measured solely by traditional metrics of productivity and profit. Instead, it requires a broader perspective that includes the planet's well-being and inhabitants. This shift is not just about compliance with regulations or the pursuit of green credentials; it is about creating a competitive advantage and unlocking new value streams in a world that increasingly values responsible and ethical business practices. Sustainable manufacturing encompasses the fundamental components of manufacturing, namely processes, products, and systems that facilitate economic growth and the creation of sustainable value in industries [22]. To achieve sustainability in manufacturing, each of these three factors must independently showcase the advantages in the social, economic, and environmental dimensions [23]. Sustainable manufacturing refers to incorporating systems and diverse processes to create products of superior quality while minimizing resource consumption, utilizing sustainable resources, and ensuring the safety of consumers, employees, and communities [24].

The use of sustainable practices in manufacturing is increasing, and organizations that participate in environmentally friendly or green initiatives are improving their efficiency, reducing costs, differentiating themselves from competitors, and positioning themselves to be proactive in complying with regulations. The manufacturing industry faces increasing scrutiny from consumers, workers, and partners, highlighting the importance of manufacturers implementing sustainable efforts. Increased productivity typically leads to reduced production expenses, increased profitability, and enhanced market competitiveness, resulting in more competitive pricing and a significant sustainability impact [25–27].

Barriers to the adoption of Industry 4.0

Most academics agree that the obstacles associated with adopting Industry 4.0 have yet to be thoroughly examined in the existing literature and require additional investigation [28-30]. Some researchers have systematically analyzed the barriers to implementing Industry 4.0. For example, one study suggests that a lack of skilled workers, conflicts among workers due to changing working environments, a shortage of financial resources, concerns about data security, low degrees of standardization, and a poor understanding of integration and systems architecture are the main obstacles to implementing Industry 4.0. Nevertheless, until now, these obstacles have only been examined separately, predominantly from a technological standpoint. Implementing Industry 4.0 involves an intricate process where several aspects interact. Thus, it is necessary to analyze all these factors thoroughly [31].

It is commonly acknowledged in existing research that several impediments hurt digitalization activities in manufacturing organizations [32-33]. The obstacles presented by the external

environment and the immediate task environment hinder organizations from adopting digitalization technology and the concepts that come with it. The influence of external obstacles can be comprehended through the lens of contingency theory. Donaldson et al. [34] state that the contingency approach suggests external factors influence a firm's strategy and performance. A firm's success is determined by the alignment between its structure, processes, and the environment in which it operates [35-36]. Several scholars have documented the effects of contingency when studying the implementation of operations management principles in various settings [37]. Several studies suggest that the firm's actions are influenced by external factors outside the firm's control, such as government legislation and the behavior of competitors [38-39]. Prajogo et al. [40] conducted an empirical study on 207 Australian manufacturing enterprises, using contingency theory to analyze the inspiration of external factors on the firm's creative activities. The contextual variables have been categorized into four primary groups: national culture and context, strategy context, firm size, and other organizational context variables such as industry type and age of the manufacturing facility [41].

Future Research Directions

This section explores prospective avenues for study to attain manufacturing sustainability using Industry 4.0 technology. Several significant study areas identified in the literature analysis can be further investigated in future studies, as outlined in the subsequent discussion on research gaps.

Lean Production Systems: Research articles on lean manufacturing highlight the advantages of implementing lean production systems in large-scale manufacturing processes [42-43]. These studies elucidate how lean manufacturing can effectively meet customer demands. The researcher examines the tangible consequences of implementing lean-enabled Industry 4.0 activities and outlines potential research areas about applying lean-enabled practices in small and large companies [44-45]. Varela et al. [42] examined the correlation between lean methods and Industry 4.0 technology and discovered a strong connection between sustainability pillars and Industry 4.0. More research is needed on integrating lean principles with Industry 4.0. Understanding the effects of lean manufacturing processes facilitated by Industry 4.0 technologies would be highly intriguing. A potential approach for future research is proposing an integrated framework that combines lean principles with Industry 4.0 technologies. This framework aims to improve performance and reduce waste in manufacturing processes.

Establish a correlation between sustainability principles and the critical factors of Industry 4.0: Most research on Industry 4.0 originates from industrialized countries, indicating their more significant emphasis on this topic. Nevertheless, poorer nations have shown limited interest and progress in embracing Industry 4.0, primarily due to the need for more technological developments and the necessary resources for its implementation. The researchers [46-47] examined the potential research prospects of Industry 4.0 technologies in attaining sustainability by identifying influential elements. More research is needed on the correlation between sustainability and Industry 4.0 elements in business practices. Moreover, it is necessary to include the components associated with political and risk-related aspects. Bhanot et al. [48] discussed the impact of these elements on sustainability. In order to effectively integrate sustainability practices into Industry 4.0 manufacturing, it is essential to incorporate these

elements into the existing Industry 4.0 theories. This will be beneficial in establishing rules for new industry areas. In future research, hybrid multi-criteria decision-making approaches, decision-making in uncertainty, and statistical tools can be applied to find out how the factors related to Industry 4.0 and sustainability affect each other and how they are related.

The influence of a sustainable supply chain in the context of Industry 4.0: The use of Industry 4.0 technologies has caused significant disruptions in supply chains, leading manufacturing industries to reassess and redesign their supply chain systems [49]. Several novel technologies have arisen over the past few years, causing significant changes to conventional supply chain operations. Currently, industries are restructuring their business models and adjusting to digital supply chain models. The digitalization of the supply chain is facilitated by innovative and transformative technologies such as big data analytics, artificial intelligence (AI), machine learning, automation, blockchain, and the Internet of Things (IoT) [50]. Research has indicated that implementing digital technology in supply chains reduces operational expenses by 30%, inventory needs by 70%, and missed sales opportunities by 60% [51-52]. Long-term investments and substantial efforts are necessary for the digital transformation of supply chain practices. This will facilitate operational efficiency and cost minimization in supply chain operations. Subsequent research might investigate the influence of sustainable supply chains on intelligent manufacturing, the process of reassembling used products, the management of the flow of goods in the opposite direction, and the practice of reusing and recycling products. Nevertheless, there is a scarcity of research on environmental concerns in supply chains that utilize blockchain technology [51].

Conclusion

In conclusion, integrating sustainability into the fabric of Industry 4.0 represents a pivotal shift in manufacturing paradigms, promising to redefine efficiency and productivity and ensure the long-term viability of our planet's resources. The concept of sustainability, when embedded within the innovative ecosystems of Industry 4.0, offers a roadmap for manufacturing practices that are not only technologically advanced but also environmentally sound and socially responsible. Combining Industry 4.0 technologies, including artificial intelligence (AI), the Internet of Things (IoT), big data analytics, advanced robotics, and sustainable manufacturing principles, can significantly enhance resource efficiency, reduce waste, and conserve energy. This transformative approach encourages the adoption of circular economy models, where the lifecycle of materials is maximized, and the environmental impact of manufacturing processes is minimized. Moreover, sustainability in Industry 4.0 extends beyond environmental concerns, encompassing economic and social dimensions that promote equitable growth, workforce development, and community well-being. By leveraging digital technologies to create more sustainable manufacturing processes, businesses can achieve cost savings, enhance brand reputation, and foster innovation, all while contributing to the global sustainability agenda. The future of manufacturing in Industry 4.0 lies in the harmonious integration of technological advancements with sustainability principles. This requires a collaborative effort among policymakers, industry leaders, researchers, and the wider community to develop standards, policies, and practices that encourage sustainable development. The workforce's ability to

effectively navigate this new landscape and thoroughly reap the benefits of sustainable manufacturing will heavily rely on education and training. As we move forward, the challenge will be to balance rapid technological evolution with the imperative to preserve our environment for future generations. The concept of sustainability in Industry 4.0 is not just a trend but a necessary evolution towards a more resilient, equitable, and sustainable future. By embracing this approach, the manufacturing industry can lead the way in demonstrating that technological progress and environmental stewardship can go hand in hand, ensuring prosperity and well-being for all.

References:

[1] L. Adolph, T. Anlahr, H. Bedenbender, A. Bentkus, L. Brumby, and C. Diedrich, *German standardization roadmap: Industry 4.0. Version 2. Berlin: DIN eV*. 2016.

[2] L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, "The expected contribution of Industry 4.0 technologies for industrial performance," *Int. J. Prod. Econ.*, vol. 204, pp. 383–394, 2018.

[3] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," *Int. J. Prod. Econ.*, vol. 210, pp. 15–26, 2019.

[4] D. Mckinsey, *Industry 4.0 after the initial hype." Where manufacturers are finding value and how they can best capture it*. 2016.

[5] S. Luthra and S. K. Mangla, "Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies," *Process Saf. Environ. Prot.*, vol. 117, pp. 168–179, 2018.

[6] S. S. Kamble, A. Gunasekaran, and R. Sharma, "Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry," *Comput. Ind.*, vol. 101, pp. 107–119, 2018.

[7] M. Türkeș, I. Oncioiu, H. Aslam, A. Marin-Pantelescu, D. Topor, and S. Căpușneanu, "Drivers and barriers in using industry 4.0: A perspective of SMEs in Romania," *Processes (Basel)*, vol. 7, no. 3, p. 153, 2019.

[8] J. Stentoft, K. W. Jensen, K. Philipsen, and A. Haug, "Drivers and barriers for industry 4.0 readiness and practice: A SME perspective with empirical evidence," in *Proceedings of the 52nd Hawaii International Conference on System Sciences*, 2019.

[9] D. Horváth and R. Z. Szabó, "Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?," *Technol. Forecast. Soc. Change*, vol. 146, pp. 119–132, 2019.

[10] C. G. Machado, M. Winroth, D. Carlsson, P. Almström, V. Centerholt, and M. Hallin, "Industry 4.0 readiness in manufacturing companies: challenges and enablers towards increased digitalization," *Procedia CIRP*, vol. 81, pp. 1113–1118, 2019.

[11] A. Ghadge, M. Er Kara, H. Moradlou, and M. Goswami, "The impact of Industry 4.0 implementation on supply chains," *J. Manuf. Technol. Manag.*, vol. 31, no. 4, pp. 669–686, 2020.

[12] S. Karadayi-Usta, “An interpretive structural analysis for industry 4.0 adoption challenges,” *IEEE Trans. Eng. Manage.*, vol. 67, no. 3, pp. 973–978, 2020.

[13] R. C. Manimaran and M. K. Pallikonda, “Integration of Professional Publications in the Implementation of Industry 4.0 to Augment the Learning Experience in ETAC of ABET ET Programs,” in *2023 ASEE Annual Conference & Exposition*, 2023.

[14] H. Ahmed, H. Sadat, and S. Nasrazadani, “High-Fidelity Conjugate Heat Transfer Simulation of Micro-Channel Heat Exchanger,” *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 106, no. 1, pp. 165–181, 2023.

[15] H. Ahmed, S. Nasrazadani, and H. Sadat, “Comparison of Thermal Effectiveness and Crevice Corrosion Risk of Fin Geometry on All-Aluminum Microchannel Heat Exchangers,” *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 105, no. 2, pp. 192–203, 2023.

[16] H. Ahmed, “Structural design and its impact on thermal efficiency and corrosion of all-aluminum microchannel heat exchangers, [Dissertation]” Denton: University of North Texas Libraries, 2023. DOI: 10.12794/metadc2179279. https://digital.library.unt.edu/ark:/67531/metadc2179279/

[17] H. Ahmed, “A review on corrosion of all aluminum microchannel heat exchangers,” in *Corrosion Engineering - Recent Breakthroughs and Innovative Solutions [Working Title]*, IntechOpen, 2024. DOI: 10.5772/intechopen.1005180

[18] M. A. Haider and J. L. Alberd, (in press) *Design a learning model to integrate IoT applications into Engineering Curriculum*. 2024 ASEE CIEC.

[19] M. A. Haider, H. Ahmed, and M. K. Pallikonda, (in press) *Empowering Economic and Occupational Freedom through the Transformation of Engineering Technology education from 2 Years to 4 Years Degrees*. 2024 ASEE CIEC.

[20] F. Irany, S. Akwafuo, T. Abah, and A. Mikler, “Estimating the Transmission Risk of COVID-19 in Nigeria: A Mathematical Modelling Approach,” *J Health Care and Research*, vol. 1, no. 3, pp. 135–143, 2020. DOI: 10.36502/2020/hcr.6171

[21] *F. A. Irany, A. Iyer, A. Mikler, and R. B. Flores, “The Multi-phase spatial meta-heuristic algorithm for public health emergency transportation,” International Journal of Scientific Research & Engineering Trends, vol. 7, no. 4, p. 10, Jul. 2021,* [Online]. Available: https://hal.science/hal-04553633.

[22] K. R. Haapala *et al.*, “A review of engineering research in sustainable manufacturing,” *J. Manuf. Sci. Eng.*, vol. 135, no. 4, p. 041013, 2013.

[23] M. Garetti and M. Taisch, “Sustainable manufacturing: trends and research challenges,” *Prod. Plan. Control*, vol. 23, no. 2–3, pp. 83–104, 2012.

[24] A. D. Jayal, F. Badurdeen, O. W. Dillon Jr, and I. S. Jawahir, “Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels,” *CIRP J. Manuf. Sci. Technol.*, vol. 2, no. 3, pp. 144–152, 2010.

[25] M. Fathi and M. Ghobakhloo, “Enabling mass customization and manufacturing sustainability in Industry 4.0 context: A novel heuristic algorithm for in-plant material supply optimization,” *Sustainability*, vol. 12, no. 16, p. 6669, 2020.

[26] B. Kuys, C. Koch, and G. Renda, “The priority given to sustainability by industrial designers within an Industry 4.0 paradigm,” *Sustainability*, vol. 14, no. 1, p. 76, 2021.

[27] B. N. Pasi, S. K. Mahajan, and S. B. Rane, “The current sustainability scenario of Industry 4.0 enabling technologies in Indian manufacturing industries,” *Int. J. Product. Perform. Manag.*, vol. 70, no. 5, pp. 1017–1048, 2021.

[28] L. D. Xu, E. L. Xu, and L. Li, “Industry 4.0: state of the art and future trends,” *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, 2018.

[29] A. B. Lopes de Sousa Jabbour, C. J. C. Jabbour, M. Godinho Filho, and D. Roubaud, “Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations,” *Ann. Oper. Res.*, vol. 270, no. 1–2, pp. 273–286, 2018.

[30] A. B. De Sousa Jabbour, C. J. C. Lopes, C. Jabbour, and M. G. Foropon, “When titans meet-Can industry 4.0 revolutionise the environmentally sustainable manufacturing wave? The role of critical success factors,” *Technological Forecasting and Social Change*, vol. 132, pp. 18–25, 2018.

[31] T. Masood and P. Sonntag, “Industry 4.0: Adoption challenges and benefits for SMEs,” *Comput. Ind.*, vol. 121, no. 103261, p. 103261, 2020.

[32] M. A. Sameer, D. Khan, and T. Romero, “A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs),” *Journal of manufacturing systems*, vol. 49, pp. 194–214, 2018.

[33] A. Raj, G. Dwivedi, and A. Sharma, “Ana Beatriz Lopes de Sousa Jabbour, and Sonu Rajak. “Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective,” *International Journal of Production Economics*, vol. 224, 2020.

[34] L. Donaldson, *The contingency theory of organizations*. Thousand Oaks, CA: SAGE Publications, 2001.

[35] R. Sousa and C. A. Voss, “Contingency research in operations management practices,” *J. Oper. Manage.*, vol. 26, no. 6, pp. 697–713, 2008.

[36] C. Y. Wong, S. Boon-itt, and C. W. Y. Wong, “The contingency effects of environmental uncertainty on the relationship between supply chain integration and operational performance,” *J. Oper. Manage.*, vol. 29, no. 6, pp. 604–615, 2011.

[37] B. B. Flynn and B. Saladin, “Relevance of Baldrige constructs in an international context: A study of national culture,” *J. Oper. Manage.*, vol. 24, no. 5, pp. 583–603, 2006.

[38] M. Tripsas, “Customer preference discontinuities: a trigger for radical technological change,” *MDE Manage. Decis. Econ.*, vol. 29, no. 2–3, pp. 79–97, 2008.

[39] B. Yalabik and R. J. Fairchild, “Customer, regulatory, and competitive pressure as drivers of environmental innovation,” *Int. J. Prod. Econ.*, vol. 131, no. 2, pp. 519–527, 2011.

[40] D. I. Prajogo, “The strategic fit between innovation strategies and business environment in delivering business performance,” *Int. J. Prod. Econ.*, vol. 171, pp. 241–249, 2016.

[41] C. J. C. Jabbour *et al.*, “Barriers to the adoption of green operational practices at Brazilian companies: effects on green and operational performance,” *Int. J. Prod. Res.*, vol. 54, no. 10, pp. 3042–3058, 2016.

[42] L. Varela, A. Araújo, P. Ávila, H. Castro, and G. Putnik, “Evaluation of the relation between Lean Manufacturing, Industry 4.0, and sustainability,” *Sustainability*, vol. 11, no. 5, p. 1439, 2019.

[43] D. Schmidt, J. Villalba Diez, J. Ordieres-Meré, R. Gevers, J. Schwiep, and M. Molina, “Industry 4.0 lean shopfloor management characterization using EEG sensors and deep learning,” *Sensors (Basel)*, vol. 20, no. 10, p. 2860, 2020.

[44] D. Cica, B. Sredanovic, S. Tesic, and D. Kramar, “Predictive modeling of turning operations under different cooling/lubricating conditions for sustainable manufacturing with machine learning techniques,” *Appl. Comput. Inform.*, vol. ahead-of-print, no. ahead-of-print, 2020.

[45] P.-E. Dossou, P. Torregrossa, and T. Martinez, “Industry 4.0 concepts and lean manufacturing implementation for optimizing a company logistics flows,” *Procedia Comput. Sci.*, vol. 200, pp. 358–367, 2022.

[46] A. Jamwal, R. Agrawal, M. Sharma, V. Kumar, and S. Kumar, “Developing A sustainability framework for Industry 4.0,” *Procedia CIRP*, vol. 98, pp. 430–435, 2021.

[47] G. Yadav, A. Kumar, S. Luthra, J. A. Garza-Reyes, V. Kumar, and L. Batista, “A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies’ enablers,” *Comput. Ind.*, vol. 122, no. 103280, p. 103280, 2020.

[48] N. Bhanot, P. V. Rao, and S. G. Deshmukh, “Enablers and barriers of sustainable manufacturing: Results from a survey of researchers and industry professionals,” *Procedia CIRP*, vol. 29, pp. 562–567, 2015.

[49] S. Luthra, A. Kumar, E. K. Zavadskas, S. K. Mangla, and J. A. Garza-Reyes, “Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy,” *Int. J. Prod. Res.*, vol. 58, no. 5, pp. 1505–1521, 2020.

[50] V. K. Manupati, T. Schoenherr, M. Ramkumar, S. M. Wagner, S. K. Pabba, and R. Inder Raj Singh, “A blockchain-based approach for a multi-echelon sustainable supply chain,” *Int. J. Prod. Res.*, vol. 58, no. 7, pp. 2222–2241, 2020.

[51] A. Surajit and S. Jh Ch Pretorius, “Industry 4.0 and supply chain sustainability: framework and future research directions,” *An International Journal*, vol. 28, no. 5, pp. 1410–1450, 2021.

[52] J.-P. Belaud, N. Prioux, C. Vialle, and C. Sablayrolles, “Big data for agri-food 4.0: Application to sustainability management for by-products supply chain,” *Comput. Ind.*, vol. 111, pp. 41–50, 2019.