Industry 4.0 and Smart Data

Subjects: Engineering, Manufacturing | Computer Science, Interdisciplinary Applications
Contributor: Davide Settembre-Blundo

The digital transformation of manufacturing firms, in addition to making operations more efficient, offers important opportunities both to promote the transition to a circular economy and to experiment with new techniques for designing smarter and greener products.

Keywords: Industry 4.0 ; circular eco-design ; re-engineering ; sustainable manufacturing ; smart data ; raw material ; ceramic tiles

1. Introduction

The manufacturing world has now taken up the challenge of the fourth industrial revolution, or Industry 4.0 [1], which is based on two foundations: automation [2] and data [3]. The new manufacturing paradigm of smart factories [4] is able to create environments that can adapt processes in real time to current needs through the elaboration of information based on the digital technologies of the Internet of Things [5]. Industry 4.0 pushes manufacturing industries to make their processes minimize waste: this transition to efficiency links Industry 4.0 with the goals of the circular economy [6]. This relationship becomes increasingly evident as companies define new strategies to achieve more ambitious environmental sustainability goals [7]. In fact, Industry 4.0 has a high potential to promote environmental sustainability because, unlike previous industrial revolutions, it is not accompanied by increased emissions or waste generation [8], but rather by increased operational efficiency [9] and organizational resilience [10]. To ensure successful optimization of manufacturing operations and improve production efficiency, an integrated MES (Manufacturing Execution System), ERP (Enterprise Resource Planning), and PLC (programmable logic controller) system was implemented. Thanks to these digital systems, it is possible to manage, monitor, and coordinate the execution of real-time physical processes providing feedback on process performance. In addition, to follow the environmental aspects into product and process development, the insertion of intelligent and interconnected sensors and PLCs in the production lines enables automated data collection for dynamic life cycle assessment (LCA) analysis [11]. The integration of simulation modelling with LCA increases predictive capacity in terms of environmental sustainability and circular eco-design, drastically reducing the reaction time of the company and its operational efficiency. Environmental impact assessment can also be combined with economic [12], social [13], or technological [14] impact assessment for a more complete view of the degree of sustainability. Alternatively, LCA, LCC, and S-LCA can be integrated with each other in a holistic methodological approach called Life Cycle Sustainability Assessment (LCSA) [15].

This efficiency can not only be determined in real time, but thanks to simulation environments where the physical and virtual worlds come together, it is possible to predict the behavior of production systems by anticipating errors and improving decision-making processes [16]. Thus, the simulation environment can improve efficiency in the exploitation of natural resources, energy, and other inputs, as well as in the development of closed-loop processes within the supply chain [17]. From an organizational point of view, Industry 4.0 leads to the transformation of the traditional factory into an effective smart factory [18] that, due to its intrinsic characteristics, is more efficient and therefore potentially more sustainable and able to implement the characteristic aspects of the circular economy [19], i.e., the so-called 6Rs: reduce, reuse, recycle, recover, redesign, and remanufacture [20]. To implement this change in corporate culture, however, it is necessary to innovate not only technologies, but also organizational paradigms and, therefore, business models [21]. Among these, circular business models [22] involve the development of products as service models [23], for which servitization becomes the way to extend their life cycle [24]. Extending the life cycle of products means keeping their value, and the resources used to manufacture them as long as possible within the economic loop [25]. Therefore, the impact level on the environment, economy, and society will be lower.

In a technologically advanced production framework, as smart factories are [26], the efficient use of production factors is already a given. Implementing at least four of the six R actions (reduce, reuse, recycle, recover) that characterize the circular economy is, therefore, easier. The real challenge for manufacturing companies is instead the redesign of products

[27] and, therefore, of the entire value chain [28]. Eco-design [29], a methodology for product design in which sustainability issues (environmental, but also socio-economic) are considered during the product development process as an additional factor to those traditionally used for decision-making, can help manufacturing companies [30]. Eco-design simultaneously considers all the fundamental elements that make a product marketable, from its aesthetic characteristics to its functional performance, also evaluating all the phases of its production and distribution chain, in addition to the socio-economic and commercial factors [31][32]. In this life cycle approach (understood as the set of stages in the useful life of a product up to the final management of its waste), the product is not the final destination but a temporary state of matter and energy that can provide the consumer with a use and service benefit [33]. Therefore, from a circular economy perspective, eco-design is one of the main ways to re-engineer products so that they are high quality as well as ecological and socially responsible.

As previously pointed out, the literature evidences the benefits that manufacturing firms can reap from the synergistic relationship between digital technologies and the re-engineering of products [34], processes [35], and entire supply chains [36] in a circular economy perspective [37]. However, having the right technologies is not always a sufficient and necessary condition to change the operational paradigm. In this regard, Zheng et al. [38] point out that there is still a lack of comprehensive research on the applications of Industry 4.0 enabling technologies in manufacturing life cycle processes. The digital transformation of industrial sectors also leads companies to address a new reality in which physical and virtual resources are integrated into a single production system. Among virtual resources, data are an important raw material able to produce organizational knowledge if manufacturing firms can turn Big Data (collected in an Industry 4.0 environment) into Smart Data (able to generate value). Lacam and Salvetat [39] argue that Smart Data cannot replace Big Data, but both domains work in a synergistic relationship through a virtuous cycle of data exploitation. These authors also emphasize that it is not necessary to mine a large amount of data to extract value from it. Even how to capture and exploit a smaller volume of useful data for a specific purpose has not yet been adequately explored in the literature. The latest literature explores the barriers to the circular economy and sustainability implementation in an Industry 4.0 environment [40]. However, empirical studies with quantitative approaches are lacking, and most studies are conceptual or qualitative [41].

2. Industry 4.0 and Smart Data as Enablers of the Circular Economy in Manufacturing: Product Re-Engineering with Circular Eco-Design in Ceramic Industry

The circular economy represents a new organizational paradigm for manufacturing systems that drives companies to re-engineer activities and processes to make them sustainable, thanks to a conscious and efficient use of resources and production factors. The transition to the circular economy can be enabled by the development of digital technologies related to Industry 4.0, as they facilitate process and product innovation thanks to their high potential for tracking resource consumption and emissions.

2.1. Implications for Scholars

It has shown that the digital technologies of the Industry 4.0 environment really can help companies embark on a path toward circularity, not only based on the increased operational efficiency implicit in smart manufacturing but also by promoting a trajectory of organizational innovation. It is based on integrating two categories of production factors: tangible resources (materials and machinery) and intangible resources (data). Therefore, the enabling factor of circularity and, more generally, of sustainability becomes the ability of the manufacturing firm that is already efficient from an operational point of view to analyze the raw information intelligently collected by the equipment, i.e., to transform data from a simple accumulation of records (Big Data) into high-value assets (Smart Data).

From the large availability of Big Data, helpful information was selected to conduct a predictive assessment of environmental impacts corresponding to different procurement scenarios. This allowed the selection of the best solution from an environmental and technological point of view and, therefore, the re-engineering of the ceramic product. This predictive approach, based on Life Cycle Assessment and microstructural analysis of materials, has been called circular eco-design precisely because it responds to the fifth of the 6Rs of the circular economy: redesign.

Therefore, this empirical validation of the theoretical hypotheses that emerged from the literature fills the knowledge gaps highlighted in the introduction paragraph: the enabling potential of digital technologies for the circular economy and the transformation of Big Data into Smart Data to create value.

2.2. Implications for Industry Practitioners

Smart Data has made it possible to highlight new circular opportunities, exploiting the full potential of Industry 4.0 to achieve significant environmental benefits. Circular eco-design has highlighted how distances between the source of supply of raw materials and the factory and the type of transport are together key factors for the environmental sustainability of the finished product. Through a life cycle approach and the use of technological characterization techniques of materials, this research has shown how it can change the paradigm of product design. In the case of ceramic materials, the industrial practice has always seen technologists formulating body compositions whose sodium/potassium ratio was strongly unbalanced in favor of sodium. This conviction has led companies to oversaturate with extra-EU sodium feldspar to maintain a high level of sintering of the ceramic body to obtain low porosity. Eco-design and empirical testing in laboratory and pilot environments have challenged this assumption, also demonstrating that with a strong reduction in imported sodium feldspar to the advantage of domestic potassium feldspar, it is possible to obtain a fully sintered and technologically performing ceramic body. With the same logic, the quantity of Ukrainian clay in the composition of the ceramic bodies was progressively reduced in favor of the German clay supplied to the factory by train and of a national clay. Both raw materials benefit from a transport system with low environmental impact.

From the point of view of industry practitioners, a virtuous circle of circular innovation has thus been created:

- Digital technologies have enabled the smart exploitation of Big Data;
- Smart Data has enabled circular eco-design that has led to product innovation;
- Product innovation has favored the re-engineering of the raw material sourcing system;
- The company moved a further step toward transitioning to the circular economy.

References

1. Khanzode, A.G.; Sarma, P.R.S.; Mangla, S.K.; Yuan, H. Modeling the Industry 4.0 adoption for sustainable production in Micro, Small & Medium Enterprises. J. Clean. Prod. 2021, 279, 123489.
2. Thomson, L.; Kamalaldin, A.; Sjödin, D.; Parida, V. A maturity framework for autonomous solutions in manufacturing firms: The interplay of technology, ecosystem, and business model. Int. Entrep. Manag. J. 2021, 1–28.
3. Zambetti, M.; Adrodegari, F.; Pezzotta, G.; Pinto, R.; Rapaccini, M.; Barbieri, C. From data to value: Conceptualising data-driven product service system. Prod. Plan. Control 2021, 1–17.
4. Horick, C. Industry 4.0 production networks: Cyber-physical system-based smart factories, real-time big data analytics, and sustainable product lifecycle management. J. Self-Gov. Manag. Econ. 2020, 8, 107–113.
5. Ghouri, A.M.; Mani, V.; Jiao, Z.; Venkatesh, V.G.; Shi, Y.; Kamble, S.S. An empirical study of real-time information-receiving using industry 4.0 technologies in downstream operations. Technol. Forecast. Soc. Chang. 2021, 165, 120551.
6. Romero, C.A.T.; Castro, D.F.; Ortiz, J.H.; Khalaf, O.I.; Vargas, M.A. Synergy between circular economy and industry 4.0: A literature review. Sustainability 2021, 13, 4331.
7. Sharma, N.K.; Govindan, K.; Lai, K.K.; Chen, W.K.; Kumar, V. The transition from linear economy to circular economy for sustainability among SMEs: A study on prospects, impediments, and prerequisites. Bus. Strateg. Environ. 2021, 30, 1803–1822.
8. D'Adamo, I.; Ferella, F.; Gastaldi, M.; Maggiore, F.; Rosa, P.; Terzi, S. Towards sustainable recycling processes: Wasted printed circuit boards as a source of economic opportunities. Resour. Conserv. Recycl. 2019, 149, 455–467.
9. Santana, A.; Afonso, P.; Zanin, A.; Wernke, R. Costing models for capacity optimization in Industry 4.0: Trade-off between used capacity and operational efficiency. Procedia Manuf. 2017, 13, 1183–1190.
10. D'Adamo, I.; Rosa, P. How do you see infrastructure? Green energy to provide economic growth after COVID-19. Sustainability 2020, 12, 4738.
11. Ferrari, A.M.; Volpi, L.; Pini, M.; Siligardi, C.; García-Muiña, F.E.; Settembre-Blundo, D. Building a sustainability benchmarking framework of ceramic tiles based on life cycle sustainability assessment (LCSA). Resources 2019, 8, 11.
12. Marzouk, M.; Azab, S. Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. Resour. Conserv. Recycl. 2014, 82, 41–49.

13. Khorassani, S.M.; Ferrari, A.M.; Pini, M.; Blundo, D.S.; Muiña, F.E.G.; García, J.F. Environmental and social impact assessment of cultural heritage restoration and its application to the Uncastillo Fortress. Int. J. Life Cycle Assess. 2019, 24, 1297–1318.
14. Vacchi, M.; Siligardi, C.; Demaria, F.; Cedillo-González, E.I.; González-Sánchez, R.; Settembre-Blundo, D. Technological Sustainability or Sustainable Technology? A Multidimensional Vision of Sustainability in Manufacturing. Sustainability 2021, 13, 9942.
15. Mahbub, N.; Oyedun, A.O.; Zhang, H.; Kumar, A.; Poganietz, W.R. A life cycle sustainability assessment (LCSA) of oxymethylene ether as a diesel additive produced from forest biomass. Int. J. Life Cycle Assess. 2019, 24, 881–899.
16. Azarmipour, M.; Elfaham, H.; Gries, C.; Kleinert, T.; Epple, U. A Service-based Architecture for the Interaction of Control and MES Systems in Industry 4.0 Environment. In Proceedings of the 2020 IEEE 18th International Conference on Industrial Informatics (INDIN), Warwick, UK, 20–23 July 2020; pp. 217–222.
17. Bressanelli, G.; Perona, M.; Saccani, N. Challenges in supply chain redesign for the Circular Economy: A literature review and a multiple case study. Int. J. Prod. Res. 2019, 57, 7395–7422.
18. Resman, M.; Turk, M.; Herakovic, N. Methodology for planning smart factory. Procedia CIRP 2020, 97, 401–406.
19. Agrawal, R.; Wankhede, V.A.; Kumar, A.; Upadhyay, A.; Garza-Reyes, J.A. Nexus of circular economy and sustainable business performance in the era of digitalization. Int. J. Product. Perform. Manag. 2021. ahead-of-print.
20. Spaltini, M.; Poletti, A.; Acerbi, F.; Taisch, M. A quantitative framework for Industry 4.0 enabled Circular Economy. Procedia CIRP 2021, 98, 115–120.
21. Pieroni, M.P.P.; McAloone, T.C.; Pigosso, D.C.A. Developing a process model for circular economy business model innovation within manufacturing companies. J. Clean. Prod. 2021, 299, 126785.
22. D'Adamo, I.; Gastaldi, M.; Rosa, P. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. Technol. Forecast. Soc. Chang. 2020, 152, 119887.
23. Bressanelli, G.; Saccani, N.; Perona, M.; Baccanelli, I. Towards circular economy in the household appliance industry: An overview of cases. Resources 2020, 9, 128.
24. Han, J.; Heshmati, A.; Rashidghalam, M. Circular economy business models with a focus on servitization. Sustainability 2020, 12, 8799.
25. Hapuwatte, B.M.; Jawahir, I.S. Closed-loop sustainable product design for circular economy. J. Ind. Ecol. 2021.
26. Waibel, M.W.; Steenkamp, L.P.; Moloko, N.; Oosthuizen, G.A. Investigating the Effects of Smart Production Systems on Sustainability Elements. Procedia Manuf. 2017, 8, 731–737.
27. García-Quevedo, J.; Jové-Llopis, E.; Martínez-Ros, E. Barriers to the circular economy in European small and medium-sized firms. Bus. Strateg. Environ. 2020, 29, 2450–2464.
28. Jørgensen, M.S.; Remmen, A. A Methodological Approach to Development of Circular Economy Options in Businesses. Procedia CIRP 2018, 69, 816–821.
29. Pazoki, M.; Samarghandi, H. Take-back regulation: Remanufacturing or Eco-design? Int. J. Prod. Econ. 2020, 227, 107674.
30. Rajput, S.; Singh, S.P. Industry 4.0—Challenges to implement circular economy. Benchmarking 2019, 28, 1717–1739.
31. Maccioni, L.; Borgianni, Y.; Pigosso, D.C.A. Can the choice of eco-design principles affect products' success? Des. Sci. 2019, 5, e25.
32. Barbosa, A.J.D.; de Paiva Santos, V.H.; de Araújo, P.C.; de Medeiros, F.L.; da Silva Otaviano, L.Y. Eco product development combining eco design and life cycle assessment. Benchmarking 2021, 28, 502–516.
33. da Luz, L.M.; de Francisco, A.C.; Piekarski, C.M.; Salvador, R. Integrating life cycle assessment in the product development process: A methodological approach. J. Clean. Prod. 2018, 193, 28–42.
34. Dev, N.K.; Shankar, R.; Swami, S. Diffusion of green products in industry 4.0: Reverse logistics issues during design of inventory and production planning system. Int. J. Prod. Econ. 2020, 223, 107519.
35. Patrucco, A.; Ciccullo, F.; Pero, M. Industry 4.0 and supply chain process re-engineering: A coproduction study of materials management in construction. Bus. Process Manag. J. 2020, 26, 1093–1119.
36. Tripathi, S.; Gupta, M. A framework for procurement process re-engineering in Industry 4.0. Bus. Process Manag. J. 2021, 27, 439–458.
37. Brad, E.; Brad, S. Algorithm for designing reconfigurable equipment to enable industry 4.0 and circular economy-driven manufacturing systems. Appl. Sci. 2021, 11, 4446.

38. Zheng, T.; Ardolino, M.; Bacchetti, A.; Perona, M. The applications of Industry 4.0 technologies in manufacturing context: A systematic literature review. Int. J. Prod. Res. 2021, 59, 1922–1954.
39. Lacam, J.-S.; Salvetat, D. Big data and Smart data: Two interdependent and synergistic digital policies within a virtuous data exploitation loop. J. High Technol. Manag. Res. 2021, 32, 100406.
40. Kumar, P.; Singh, R.K.; Kumar, V. Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers. Resour. Conserv. Recycl. 2021, 164, 105215.
41. Beltrami, M.; Orzes, G.; Sarkis, J.; Sartor, M. Industry 4.0 and sustainability: Towards conceptualization and theory. J. Clean. Prod. 2021, 312, 127733.

Retrieved from https://encyclopedia.pub/entry/history/show/33606