Society of Production Engineering

ICPES 2025

40. INTERNATIONAL CONFERENCE ON PRODUCTION ENGINEERING - SERBIA 2025

DOI: 10.46793/ICPES25.529K

University of Nis
Faculty of Mechanical Engineering

Nis, Serbia, 18 - 19. September 2025

ROADMAP FOR SUSTAINABLE MANUFACTURING IN THE INDUSTRY 4.0 AND 5.0 ERA: CONCEPTS, METRICS, AND OPPORTUNITIES FOR SMES

Ana KITIĆ[1]*, Mladen RADIŠIĆ[2], Milan GROZDANOVIĆ[3], Ivana JANKOVIĆ[4]
Orcid: 0000-0001-6465-3471; **Orcid:** 0000-0002-6689-7717; **Orcid:** 0000-0002-5618-9274
[1]University of Niš, Faculty of Mechanical Engineering, Niš, Serbia
[2]University of Novi Sad, Faculty of Technical Science, Novi Sad, Serbia
[3] University of Belgrade, Technical Faculty in Bor, Bor, Serbia
[4]University of Niš, Faculty of Mechanical Engineering, Niš, Serbia
*Corresponding author: ana.kitic@masfak.ni.ac.rs

Abstract: *This paper discusses about how Industry 4.0 and the new Industry 5.0 paradigm make it possible for small and medium-sized businesses (SMEs) to make things in a way that is good for the environment. We put together a taxonomy of technology, sustainability lever, KPI by combining the economic, environmental, and social streams of the literature (PLM/LCA, lean–green practices, sustainable supply chains, RMS/modularity, and digitalization/AI/IoT) into a structured narrative review. Based on this synthesis, we suggest a SME-friendly metric set and a useful roadmap that puts human-machine collaboration, green and circular technologies, data-driven operations, flexible and resilient production, smart workplaces, ethical governance, and ecosystem support in the right order. The roadmap makes it clear how digital skills can lead to triple-bottom-line results and where policy and funding can speed up adoption. The paper gives SME managers and policymakers a clear framework and useful metrics to help them plan and assess digitally enabled sustainability transitions.*

Keywords: *sustainable manufacturing, Industry 4.0, Industry 5.0, SMEs, digital twin/IoT/AI, circular economy, KPIs, roadmap*

1. INTRODUCTION

The need for a new model of production and consumption that considers its effects on society and the environment is becoming more widely recognised. Stakeholders are putting more pressure on the industry to report openly about these effects. In this sense, sustainable manufacturing means reducing damage to the environment and energy and natural resource consumption while being both socially and financially responsible. As a result, organisations and the research community, especially in the industrial sector, are paying more attention to the idea of sustainable manufacturing.[1]

Social sustainability and ecosystem degradation have emerged as major concerns in the business world in recent decades. However, most corporate social responsibility research focusses on large corporations, frequently ignoring the unique characteristics of small and medium-sized businesses (SMEs). [2]

When the effects of SMEs are considered collectively, it becomes easier to understand the crucial role that they play in global sustainability. [3]

Although small and medium-sized enterprises are widespread, it is not easy for them to adapt to the requirements of Industry 5.0 while also adhering to sustainability principles. In this paper, we present a clear framework and a metric that can help SMEs more easily align with the requirements of Industry 5.0.

2. INDUSTRY 4.0 AND SUSTAINABILITY

Authors argue that the surge of expectations surrounding Industry 4.0's contribution to sustainable development is accompanied by a lack of clear understanding of how digital technologies actually deliver economic, environmental, and social benefits in manufacturing. Drawing on a systematic literature review, the authors distill 15 "sustainability functions" (e.g., energy-consumption optimization via IoT sensors, digital twins for waste reduction, predictive maintenance for higher reliability) and use Interpretive Structural Modeling (ISM) to map their interdependencies and implementation sequence. The outcome is a visual roadmap that shows the steps companies can follow to leverage Industry 4.0 technologies for strengthening all three pillars of sustainability, economic, environmental, and social thus providing managers and scholars with a practical guide for planning digitally driven, triple-bottom-line transformations.[4]

Digital transformation of Industry 4.0 technologies helps small and medium-sized businesses (SMEs) make their manufacturing more sustainable by making it more efficient, optimising resources, doing business in an ethical way, and being more competitive. Using sensor-based IoT devices to keep an eye on how machines are being used, how much energy they use, and the skills of the workers makes it possible to make decisions based on real-time data that cut down on waste and make the best use of resources.

By combining cyber-physical systems, AI, big data analytics, and automated quality control tools that cut down on defects, energy use, and operational costs, you can make production more efficient and sustainable.

Allow for flexibility and quick response to changing market needs and the need for customisation, which is very important for small and medium-sized businesses that have to deal with complicated customer needs.

Help small and medium-sized businesses move from linear to sustainable manufacturing models by using fewer resources and making less waste.

Even though there are problems with cost, skills, and adoption, better communication, information flow, and collaboration across supply chains can help businesses become more ethical and sustainable.[5–7]

2.1 Industry 5.0, sustainability and SMEs

Industry 5.0 is an improvement on Industry 4.0 that focusses more on people, the environment, and resilience. This makes it very useful for small and medium-sized businesses in sustainable manufacturing. Industry 4.0 was all about automation and efficiency. In contrast, Industry 5.0 uses collaborative robotics (cobots), renewable energy, circular economy principles, and digital technologies to support production models that are sustainable, customised, and adaptable.[8]

3. INDUSTRY 5.0 ENHANCE SUSTAINABILITY IN SME MANUFACTURING PRACTICES

Industry 5.0 utilises the small and medium-sized enterprises (SMEs) more sustainable by combining human-centered design, advanced technology, and circular economy ideas to make a production system that is more durable, eco-friendly, and socially responsible. Industry 5.0 prioritizes eco-friendly manufacturing by incorporating green technologies, renewable energy sources (like bioenergy), and energy-efficient production systems. It promotes material reuse, waste minimization, and closed-loop production models that reduce

environmental impact and resource consumption. IoT and big data analytics allow real-time monitoring for better resource efficiency and waste reduction. AI and machine learning optimize production quality and energy use. These technologies support predictive maintenance and flexible manufacturing, increasing adaptability and reducing downtime. Industry 5.0 uses AI, IoT, and blockchain to enhance supply chain transparency and responsiveness, helping SMEs quickly adjust to disruptions such as supply delays or market changes without compromising operational efficiency. By combining human creativity with machine precision, SMEs can offer personalized products at scale, which aligns with customer demand and enhances competitiveness while maintaining sustainability [8].

4. METRICS OF SUSTAINABLE MANUFACTURING

The most effective KPIs (Key Performance Indicators) for measuring SME sustainability in manufacturing focus on economic, environmental, and social dimensions, enabling SMEs to track and improve their sustainability performance comprehensively.

The Triple Bottom Line (TBL) is a fundamental metric framework utilized to assess sustainable manufacturing by analyzing performance across three equally significant dimensions: economic, environmental, and social. For SMEs in manufacturing, TBL facilitates the equilibrium of profitability (economic), environmental stewardship (planet), and social responsibility (people) to attain comprehensive sustainability.[9, 10]

4.1 Economic sustainability

The literature shows that manufacturing companies can improve economic sustainability through life-cycle thinking (PLM/LCA) to spread costs and value across product-process-system levels; logistics and supply-chain optimisation; and digitalization / global integration (e-products, mass customisation, digital manufacturing, integration of design management with ERP, STEP-NC) that boost productivity and decision-making. A lot of work has been done on reconfigurable manufacturing systems (RMS), which include modular, scalable machines, feasibility models, reconfiguration policies, and indices for measuring reconfigurability. These systems are more flexible, can respond to changes in the market or product faster, have better CAPEX/OPEX profiles, and are more competitive. The corpus also emphasises the need for disciplined energy cost management, the flexibility to adapt to crises, and choosing suppliers who are aware of sustainability (for example, AHP+QFD) to lower the total cost of ownership and risk. When you put them all together, principles like eco-design, reuse/repair/recycling, lean operations, and sustainable supply chains help businesses become more efficient, keep their margins steady, and stay in business for a long time.

4.2 Environmental sustainability

In manufacturing shows that recycling, waste reduction, pollution prevention, and ISO 14000 certification boost plant efficiency. Supply chains adopt “green” techniques and performance metrics due to regulatory, market, and reputational constraints. Environmental cost accounting (e.g., extended activity-based costing) promotes waste reduction for productivity and sustainability. Lean techniques and environmental management increase business outcomes, while reduced raw-material consumption, redesign products for environmental performance, and solid-waste recycling lower production costs and improve product quality [11].

4.3 Social sustainability

An analysis of **social sustainability** in manufacturing focusses on the larger value generation for society, transparency and

disclosure, and the conditions and well-being of workers. It appears at the social effects of designing a logistics network and uses criteria that cover internal human resources, external populations, macro-level social performance, and stakeholder participation. Impact assessments often look at things from a life-cycle point of view, separating effects on workers, local communities, and society.

7. INDUSTRY 5.0 OPPORTUNITIES FOR SUSTAINABLE MANUFACTURING IN SMES

Industry 5.0 differs from Industry 4.0 in several key respects. Industry 5.0 is a human-centered, sustainable, and resilient approach to business. Implementing 5.0 reduces operating costs, makes operations "greener," and improves product quality. Small and medium enterprises need to adopt advanced technologies like AI, IoT and robots to improve productivity and stay ahead of the competition [12].

In Industry 5.0, people and machines work together (for example, with cobots and AR interfaces) to make things more accurate, efficient, and safe while still allowing people to do meaningful work.

SMEs can make sustainability a key competitive advantage by using green and circular technologies like renewables, zero-waste processes, and digital material passports.

AI/ML and IoT analytics make it possible to optimise resources in real time, predict when maintenance will be needed, forecast demand, and reduce scrap, which lowers both costs and carbon.

Flexible, reconfigurable production and blockchain-enabled supply-chain visibility make it easy to adapt quickly to changes in the market, disruptions, and mass customisation.

Smart building and EHS technologies (BMS, sensors, wearables) make workplaces safer, more comfortable, and more energy-efficient. They also help social sustainability.

Combining human creativity with digital twins and additive manufacturing lets small and medium-sized businesses make products that are unique to each customer and help speed up the process of coming up with new ideas.

Digital operations and supplier relationships that are ethical and responsible include social responsibility, human-centered design, and open governance.

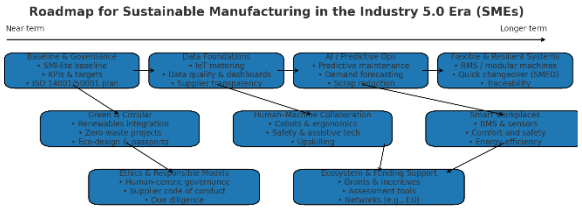

Figure 1. Roadmap for Sustainable Manufacturing in the Industry 5.0 Era (SMEs). Sequence is indicative; tracks may run in parallel. Progress should be monitored with SMI-lite KPIs.

Ecosystem programs and funding, like EU SURE5.0, give small and medium-sized businesses (SMEs) the money, tools for evaluation, and networks they need to make the switch to sustainable Industry 5.0 faster and with less risk [13].

Figure 2 shows a way to put the literature synthesis into action by linking industry 4.0/5.0 technologies to sustainability levers and example kpis that are important for small and medium-sized businesses. The taxonomy puts seven technology groups (iot/sensors, ai/ml, digital twins, rms/modular automation, additive manufacturing, blockchain traceability, and smart building/ehs) against five levers: energy and resource efficiency, circularity and waste, safety and well-being, transparency and compliance, and resilience and flexibility. It also links each lever to practical kpis, such as energy intensity and renewables share, waste-to-landfill and recycled content, trir and training coverage, suppli the figure doesn't tell smes what to do; it helps them choose a set of kpis that works for their industry and level of maturity.

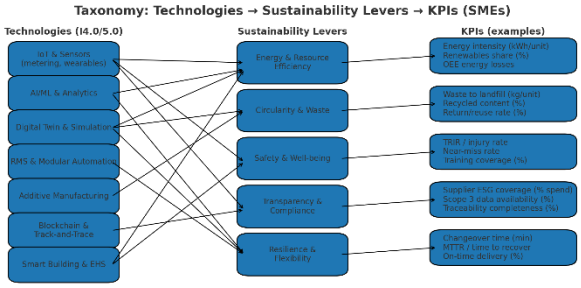

Figure 2. Taxonomy linking Industry 4.0/5.0 technologies to sustainability levers and example KPIs for SMEs. Links are indicative; KPIs should be adapted to sector context.

8. CONLCULISON

The review shows that Industry 4.0 capabilities, which are made even better in Industry 5.0 by principles that focus on people and resilience, can help businesses do well on all three bottom lines when they are put in the right order and measured with the right KPIs. For small and medium-sized businesses (SMEs), short-term wins come from being more efficient with energy and materials, being able to predict when maintenance will be needed, and having a clear view of the supply chain. Medium-term gains come from using circular design, reconfigurable systems, and training the workforce. The suggested roadmap and taxonomy make measurement and governance work, which helps companies connect projects to results and lets policymakers focus their support. Because this is a desk review, future work should test the roadmap in the real world (through case studies and surveys in different sectors) and measure the effect sizes of the most important interventions.

REFERENCES

[11] Sartal, A., Bellas, R., Mejías, A.M., García-Collado, A.: The Sustainable Manufacturing Concept, Evolution And Opportunities Within Industry 4.0: A Literature Review. Advances In Mechanical Engineering. 12, (2020).

[12] Jansson, J., Nilsson, J., Modig, F., Hed Vall, G.: Commitment To Sustainability In Small And Medium-Sized Enterprises: The Influence Of Strategic Orientations And Management Values. Bus Strategy Environ. 26, 69–83 (2017).

[13] Ayyagari Asli Demirguc-Kunt Vojislav Maksimovic The World Bank, M.: Small Vs. Young Firms Across The World Contribution To Employment, Job Creation, And Growth. (2011)

[14] Ching, N.T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., Asadi, S.: Industry 4.0 Applications For Sustainable Manufacturing: A Systematic Literature Review And A Roadmap To Sustainable Development. J Clean Prod. 334, 130133 (2022).

[15] Jamwal, A., Palit, N., Kumari, S., Agrawal, R., Sharma, M.: A Decision Framework For Smes To Address Sustainability Issues With Industry 4.0 Technologies. Ann Oper Res. (2025).

[16] Santos, A. De M., Sant'anna, Â.M.O.: Industry 4.0 Technologies For Sustainability Within Small And Medium Enterprises: A Systematic Literature Review And Future Directions. J Clean Prod. 467, 143023 (2024).

[17] Kumar, R., Singh, R.Kr., Dwivedi, Y.Kr.: Application Of Industry 4.0 Technologies In Smes For Ethical And Sustainable Operations: Analysis Of Challenges. J Clean Prod. 275, 124063 (2020).

[18] Shabur, M.A., Shahriar, A., Ara, M.A.: From Automation To Collaboration: Exploring The Impact Of Industry 5.0 On Sustainable Manufacturing, (2025)

[19] Vasconcelos, A.F., González, I.A.R., Fernández, M.A., Santiago, A.Z., Romage, G.R.: Applying A Delphi Method To Assess The Sustainability In Smes: An Approach Of Triple Bottom Line. Revista De Gestão Social E Ambiental. 18, E09690 (2024).

[20] Sethi, R., Rajesh, M.: 444-464; 2022 For The Manufacturing Industries. (2022)

[21] Garbie, I.H.: An Analytical Technique To Model And Assess Sustainable Development Index In Manufacturing Enterprises. Int J Prod Res. 52, 4876–4915 (2014).

[22] Takawira, B., Pooe, D.: Sme Readiness For Industry 5.0: A Systematic Literature Review. Southern African Journal Of Entrepreneurship And Small Business Management. 17, 1–14 (2025).

[23] Aviable at: https://www.eitmanufacturing.eu/news-events/activities/sure5-0/ 20.05.2025