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DIGITAL TWINS AND CIRCULAR ECONOMY AS DRIVERS OF SUSTAINABLE REGIONAL INDUSTRIAL DEVELOPMENT

Azimova Maxfuza Rashidovna
Lecturer at the Department of Green Economy and Agribusiness,
Bukhara State University;
Anvarova Sevinch Akmalovna
Student at Bukhara State University, E-mail: maxfuzaazimova791@gmail.com

Abstract: This article examines how digital twins and circular economy principles can be integrated to accelerate sustainable regional industrial development. The study treats a digital twin as a dynamic virtual representation of industrial assets, processes and material flows, while circular economy is interpreted as a system that reduces virgin resource use, extends product life and recovers value from waste. Using an IMRAD structure, the research combines literature analysis, process mapping, indicator grouping, a five-point maturity assessment and conceptual modelling. A Sustainable Digital-Circular Transformation Index is proposed to evaluate four dimensions: resource efficiency, circularity, social capability and governance transparency. The results show that the greatest value is created when real-time operational data are connected with decisions on energy use, predictive maintenance, reverse logistics, industrial symbiosis and sustainability disclosure. The article presents three tables and three analytical diagrams that can be adapted by regional industrial enterprises and public authorities. The proposed framework supports cost reduction, resilience, decent work, climate action and transparent management, while also identifying risks related to data quality, cybersecurity, workforce skills and investment capacity.1
Keywords: sustainable development, digital twin, circular economy, regional industry, industrial symbiosis, resource efficiency, ESG, smart manufacturing, resilience.

1. Introduction

Sustainable development requires simultaneous progress in economic productivity, environmental protection and social well-being. For industrial regions, this challenge is particularly important because manufacturing creates employment and export capacity but also consumes large volumes of energy, water and materials. The United Nations 2030 Agenda therefore links industrialization, decent work, responsible production, climate action and partnerships within one integrated development framework. Recent global assessments also indicate that progress toward many Sustainable Development Goals remains insufficient, which increases the importance of practical transformation mechanisms at enterprise and regional levels.2

1The study framework is grounded in the United Nations 2030 Agenda, the GRI impact perspective, and the sustainable industrial transformation literature.
2See United Nations (2015), The Sustainable Development Goals Report 2024, and UNIDO Industrial Development Report 2024.

Two concepts have become especially relevant to this transformation. The first is the digital twin: a continuously updated virtual model of a physical asset, production line or supply network. The second is the circular economy: an approach that seeks to retain the value of products, components and materials for as long as possible through reduction, reuse, repair, remanufacturing and recycling. Individually, each concept can improve performance. Together, they create a stronger management architecture because digital data reveal where losses occur, while circular principles determine how those losses can be prevented or converted into value.

At regional level, the integration of digital twins and circular economy can strengthen industrial symbiosis. Waste heat, secondary raw materials, reusable packaging, transport capacity and technical expertise can be exchanged among neighboring enterprises. However, this requires interoperable data, clear governance, trusted indicators and coordinated investment. Therefore, sustainable transformation should not be treated as a collection of isolated ecological projects, but as a redesign of interconnected business processes.

The aim of this study is to develop a scientific and practical framework for integrating digital twins and circular economy principles into regional industrial management. The research objectives are: (1) to identify the main mechanisms of digital-circular integration; (2) to propose an indicator and maturity system; (3) to explain expected environmental, social, governance and economic effects; and (4) to formulate a staged implementation roadmap.

2. Materials and Methods

The study applies a mixed conceptual methodology consisting of systematic literature review, comparative analysis, process mapping, indicator grouping, expert-oriented scoring and conceptual modelling. International sustainable development, reporting and resource-efficiency frameworks were used to define the analytical boundaries. GRI Standards support impact-oriented reporting on the economy, environment and people, while IFRS S1 and IFRS S2 focus on decision-useful information about sustainability-related and climate-related risks and opportunities. OECD work on resource efficiency and circular economy was used to structure material-flow and circular business model indicators.3

The methodological sequence includes five stages. First, the main regional industrial processes are mapped, including procurement, production, maintenance, logistics, sales, reverse flows, human resources and governance. Second, data points are identified for energy, water, material inputs, emissions, equipment conditions, worker safety and supplier performance. Third, a digital twin is used conceptually to connect physical processes with a virtual monitoring and scenario-analysis layer. Fourth, circular interventions are selected. Fifth, results are assessed using a Sustainable Digital-Circular Transformation Index (SDCTI).

3GRI Universal Standards support impact reporting; IFRS S1 and IFRS S2 provide requirements for sustainability-related and climate-related financial disclosures; OECD frameworks inform resource-efficiency and circular-economy measurement.

Table 1. Methodological framework for sustainable digital-circular transformation

Stage	Analytical focus	Main method	Expected output
1	Process diagnosis	Material-flow mapping and document review	Baseline of resource losses and operational risks
2	Data architecture	IoT/data inventory and quality assessment	List of measurable variables and data gaps
3	Digital-twin modelling	Scenario modelling and process simulation	Virtual representation of critical processes
4	Circular redesign	R-strategies, reverse logistics and industrial symbiosis	Portfolio of circular interventions
5	Performance assessment	0–5 maturity scoring and integrated index	Prioritized roadmap and monitoring dashboard

The SDCTI is calculated as: SDCTI = 0.30RE + 0.25CI + 0.20SC + 0.25GT, where RE is resource efficiency, CI is circular integration, SC is social capability and GT is governance and transparency. Each block is scored from 0 to 5. The weighting gives priority to physical resource performance and governance because digital-circular projects fail when either operational impacts or accountability mechanisms are weak. The weights are proposed for general regional industrial assessment and may be adjusted according to sectoral characteristics.[4]

Figure 1. Integrated digital-circular model for sustainable regional industry

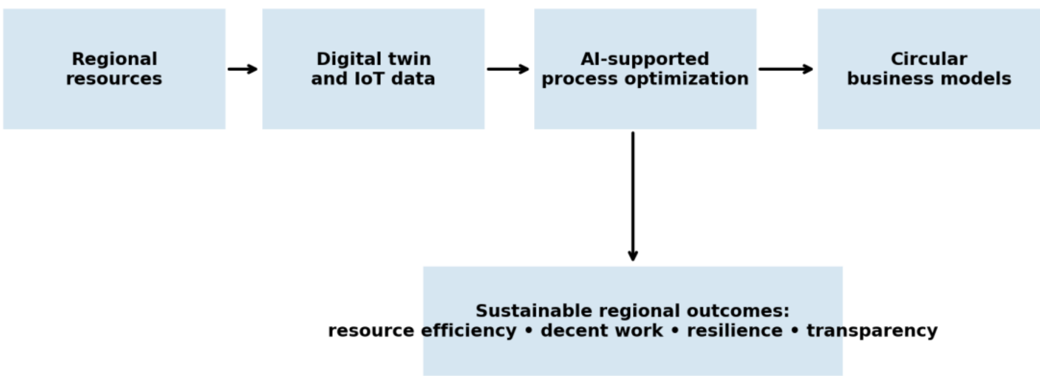


Figure 1 demonstrates that sustainable outcomes are produced through a connected chain. Regional resources and industrial assets generate data; digital twins convert the data into operational insight; artificial intelligence and scenario analysis support optimization; and circular business models transform avoided losses into economic and environmental

[4] The SDCTI weighting structure and five-point maturity scale are proposed by the author and should be calibrated for specific industries and regional conditions.

value. The feedback loop enables continuous improvement rather than one-time modernization.

3. Results

The analysis identifies six priority areas in which digital twins and circular economy reinforce each other: energy management, predictive maintenance, material circularity, reverse logistics, workforce capability and transparent governance. Digital twins can detect abnormal energy consumption, predict equipment failure and compare alternative production schedules. Circular economy principles ensure that these insights lead to lower material demand, longer asset life and higher recovery of by-products.

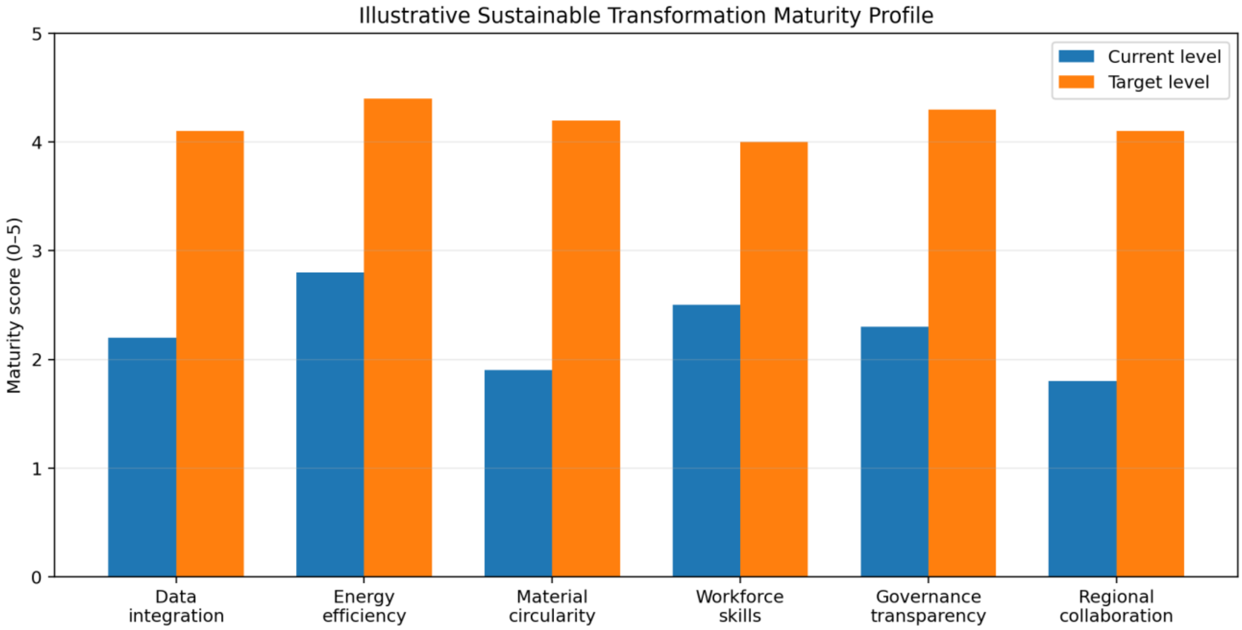
A central result is that technology alone does not guarantee sustainability. Enterprises may install sensors and software without changing procurement criteria, maintenance rules or waste contracts. Therefore, digital maturity and circular maturity must advance together. A high-performing system links each data signal to a defined managerial response, responsible unit and measurable target.

Table 2. Core indicators of sustainable digital-circular performance

Dimension	Indicator	Unit	Management meaning	Primary data source
Resource efficiency	Energy intensity	kWh per unit	Efficiency of production and equipment	Meters, production records
Resource efficiency	Water intensity	m^3 per unit	Pressure on regional water resources	Meters, utility reports
Circular integration	Secondary material share	Percent	Reduction of virgin material dependency	Procurement and inventory data
Circular integration	Product/material recovery rate	Percent	Effectiveness of reverse flows	Waste and logistics records
Social capability	Digital-green training	Hours per employee	Workforce readiness for transformation	HR and training systems
Social capability	Safety incident frequency	Rate per hours worked	Quality of preventive management	Safety records
Governance	Data completeness	Percent	Reliability of digital-twin decisions	Data governance register
Governance	Sustainability disclosure maturity	0–5 score	Transparency and stakeholder trust	Annual/ESG reports

Table 2 combines quantitative and qualitative indicators. This is necessary because sustainable transformation includes measurable physical outcomes and institutional capabilities. For example, energy intensity can decline even when governance is weak, but the improvement may not be durable if data ownership, audit trails and employee responsibilities are unclear. Similarly, a sophisticated disclosure system has limited value when physical resource performance does not improve.

Figure 2. Illustrative sustainable transformation maturity profile



The illustrative profile in Figure 2 compares a current and target situation. The largest gaps appear in material circularity and regional collaboration. This pattern is common when enterprises first digitalize internal operations but do not yet establish reverse logistics or cross-enterprise material exchanges. The profile helps managers distinguish technology gaps from organizational and ecosystem gaps.

Table 3. Maturity levels for digital-circular sustainable development

Level	Score	Main characteristics	Priority action
Initial	0.0–1.0	Fragmented data; sustainability actions are isolated	Create baseline and assign responsibilities
Connected	1.1–2.0	Critical assets are monitored; limited circular practices	Improve data quality and pilot recovery flows
Integrated	2.1–3.0	Digital twin supports selected decisions; circular KPIs exist	Connect procurement, production and reverse logistics
Optimized	3.1–4.0	Scenario analysis guides resource and maintenance decisions	Scale industrial symbiosis and automated control
Regenerative	4.1–5.0	Continuous closed-loop optimization with transparent reporting	Innovate business models and regional partnerships

The maturity model shows that enterprises should not attempt to reach advanced transformation through a single large technology purchase. A staged approach reduces financial and operational risk. At the connected level, the purpose is reliable visibility. At the integrated level, the purpose is coordinated decision-making. At optimized and regenerative levels, the purpose is continuous redesign of products, processes and inter-enterprise relationships.

Figure 3. Roadmap for implementing sustainable digital-circular transformation

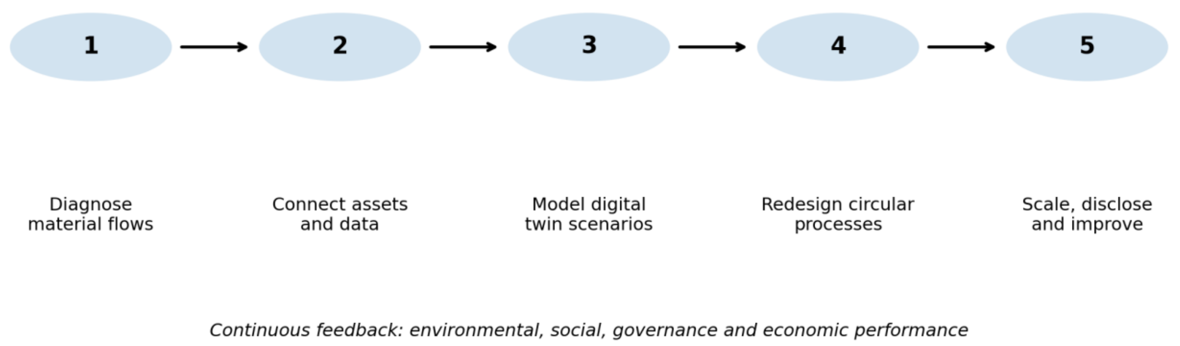


Figure 3 presents a five-stage roadmap. Diagnosis prevents enterprises from digitalizing inefficient processes without redesign. Data connection creates the evidence base. Digital-twin scenarios test interventions before capital is committed. Circular redesign changes material and value flows. Finally, scaling and disclosure institutionalize results and support access to finance, partnerships and public trust.

4. Discussion

The proposed framework contributes to sustainable development research by connecting three levels that are often studied separately: enterprise operations, circular business models and regional coordination. At enterprise level, digital twins increase visibility and reduce uncertainty. At business-model level, circular strategies convert avoided waste and extended asset life into economic value. At regional level, industrial symbiosis and shared infrastructure create benefits that a single enterprise cannot achieve independently.

The environmental implications include lower energy and water intensity, reduced material extraction, fewer emissions and higher recovery rates. Social implications include safer maintenance, new digital-green skills and more resilient employment. Governance implications include traceable data, clearer accountability and stronger sustainability disclosure. IFRS sustainability standards emphasize decision-useful information on risks and opportunities, while GRI emphasizes significant impacts on the economy, environment and people. Using both perspectives can improve the balance between investor information and broader stakeholder accountability.5

5This dual perspective reflects the distinction between impact materiality in GRI and investor-focused sustainability-related financial information in IFRS S1 and IFRS S2.

Several limitations must be recognized. First, digital twins depend on reliable and interoperable data. Poor sensor calibration or incomplete records can create false confidence. Second, connected industrial systems introduce cybersecurity and privacy risks. Third, small and medium-sized enterprises may face financial and skills constraints. Fourth, circularity can shift impacts rather than reduce them if transport distances, energy requirements or product quality are ignored. Therefore, life-cycle thinking and independent verification remain necessary.

The framework is conceptual and should be tested with enterprise-level datasets. Future empirical research may estimate sector-specific weights, compare industrial regions and quantify the relationship between digital-circular maturity and productivity, emissions, employment quality and access to finance.

5. Conclusion

The study concludes that digital twins and circular economy principles can form a powerful integrated mechanism for sustainable regional industrial development. Digital twins provide timely visibility, simulation and predictive capability; circular economy provides the strategic direction for reducing resource dependence, extending asset life and recovering value. The combination transforms sustainability from a reporting exercise into a continuous management process.

The proposed SDCTI, indicator system, maturity model and implementation roadmap can support enterprises, investors and regional authorities. Practical priorities include establishing a reliable data baseline, selecting material sustainability issues, connecting critical assets, piloting circular interventions, training employees, strengthening data governance and progressively aligning disclosure with recognized international standards.

For regional policy, the most important recommendation is to create enabling ecosystems rather than isolated projects. Shared data platforms, industrial symbiosis exchanges, green finance, training centers and common measurement rules can reduce the cost of transformation. Such coordinated action contributes directly to responsible production, climate resilience, decent work, innovation and long-term regional competitiveness.6

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6The recommendations are aligned with SDGs 8, 9, 12, 13 and 17, and with OECD work on resource efficiency, circular economy and the green-digital twin transition.

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