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Barriers and Enablers of Sustainable Smart Manufacturing in Resource-Constrained SMEs

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Abstract

Sustainable Smart Manufacturing (SSM) has emerged as a critical pathway for enhancing productivity, resource efficiency, and environmental performance in modern industry. However, small and medium-sized enterprises (SMEs), particularly in developing economies, face significant challenges in adopting SSM due to resource constraints. This study presents a comprehensive review and conceptual synthesis of the key barriers and enablers influencing SSM adoption in resource-constrained SMEs. Major barriers identified include financial limitations, technological gaps, inadequate infrastructure, workforce skill shortages, organizational resistance, and regulatory uncertainty, which collectively hinder digital transformation.Conversely, the study highlights several enabling factors, including declining costs of digital technologies, supportive government policies, industry collaboration, workforce development initiatives, and the emergence of cloud-based manufacturing platforms. Based on these insights, a five-stage SSM adoption framework is proposed, encompassing readiness assessment, strategic technology selection, pilot implementation, capacity development, and scale-up with sustainability integration.The findings emphasise that SSM adoption is not solely a technological process but a broader socio-economic transformation requiring coordinated stakeholder engagement. The study contributes to both theory and practice by offering a structured, scalable roadmap to support SMEs in achieving sustainable industrial transformation and long-term competitiveness.

Keywords
Sustainable smart manufacturing, small and medium-sized enterprises, Industry 4.0 technologies, digital transformation, sustainability performance

1. Introduction
Global manufacturing industries are experiencing rapid transformation driven by digitalization, automation, artificial intelligence, and sustainability requirements (Jamwal et al. 2021). The increasing pressure to reduce environmental impacts, improve resource efficiency, and maintain global competitiveness has accelerated the transition toward SSM (Chatradhi et al. 2025). SSM integrates smart manufacturing technologies such as industrial Internet of Things (IIoT),

data analytics, cyber-physical systems, and automation with sustainability objectives including energy efficiency, waste minimization, and circular resource utilization (Andronie et al. 2021).

Small and medium-sized enterprises (SMEs) play a critical role in global industrial ecosystems (Cavallo et al. 2021; Zhang at al. 2023). SMEs contribute significantly to employment, industrial output, and economic resilience, particularly in developing and emerging economies (Hasan et al., 2025). However, despite their importance, SMEs face structural limitations that affect their ability to adopt advanced manufacturing technologies (Jamwal at al. 2025; Rojas-Berrio at al. 2022). Resource constraints, including limited financial capital, inadequate technical expertise, infrastructure limitations, and restricted access to innovation networks, often slow technology adoption (Rajiani at al. 2023).

The transition to SSM needs substantial investments in digital infrastructure, workforce development, and process redesign (Ferreira at al. 2023). For many SMEs, especially those operating in resource-constrained environments, these requirements create significant barriers. At the same time, emerging digital technologies are becoming more affordable and accessible, creating new opportunities for SMEs to adopt smart manufacturing solutions.

This study aims to examine the barriers and enablers influencing the adoption of SSM in resource-constrained SMEs and to propose a practical adoption framework that supports application in such environments. The research contributes to the growing body of literature on sustainable manufacturing and digital transformation by focusing specifically on SME implementation challenges and opportunities.

2. Background and Conceptual Foundations

2.1 Sustainable Smart Manufacturing

The SSM represents the convergence of Industry 4.0 technologies and sustainable manufacturing principles. Smart manufacturing focuses on real-time data-driven decision-making, system integration, automation, and process optimisation (Basingab, 2025). Sustainable manufacturing focuses on reducing environmental impact while maintaining economic viability and social responsibility.

The integration of these two paradigms enables manufacturing systems to achieve improved operational efficiency, reduced resource consumption, improved product quality, and improved supply chain transparency. SSM systems typically incorporate:

• Industrial Internet of Things (IIoT)
• Advanced robotics and automation
• Artificial intelligence and machine learning
• Digital twins and simulation technologies
• Cloud-based manufacturing systems
• Real-time energy and resource monitoring

SSM enables manufacturers to optimize production processes dynamically, predict maintenance requirements, reduce waste generation, and improve lifecycle sustainability performance.

2.2 SMEs and Industrial Sustainability

SMEs depict the majority of manufacturing firms globally (Bilali, 2022). Their flexibility, agility, and niche specialization allow them to respond quickly to market changes. However, SMEs often operate with limited financial resources, limited access to advanced technologies, and limited research and development capacity.

In sustainability transitions, SMEs face additional challenges such as compliance costs, sustainability reporting requirements, and supply chain pressure from larger organizations demanding sustainable production practices.
SMEs and Industrial Sustainability: Discussion

Small and medium-sized enterprises (SMEs) are central to industrial sustainability, especially in emerging economies such as South Africa, where they contribute significantly to employment, local value creation, and supply chain resilience. However, a delicate balance between structural constraints and emerging opportunities shapes their transition toward Sustainable Smart Manufacturing (SSM).

At the core, SMEs face systemic barriers that limit their sustainability performance (Alayón et al. 2022). Financial constraints restrict investment in advanced technologies such as IIoT and cyber-physical systems, while limited digital infrastructure and skills shortages slow adoption (Peter at al. 2023). Organizational resistance and regulatory ambiguity further compound these challenges, often leading to incremental rather than transformative change. As a result, many SMEs remain locked in resource-intensive, inefficient production systems that undermine both competitiveness and environmental performance.

Yet, these constraints do not negate the strategic importance of SMEs in driving industrial sustainability. In fact, SMEs offer unique advantages: agility, shorter decision-making cycles, and closer integration with local economies. When supported effectively, they can act as rapid adopters of modular and scalable smart technologies. Declining costs of digital tools, increasing access to cloud-based platforms, and the rise of collaborative innovation ecosystems are lowering traditional entry barriers.

From a sustainability perspective, SSM enables SMEs to simultaneously pursue economic, environmental, and social objectives (Rantanen, 2021). Improved resource efficiency reduces material and energy consumption, while real-time monitoring enhances process optimisation and waste minimisation. These gains translate into lower operational costs and improved environmental compliance. Socially, the transition fosters skills development, supports job creation in emerging digital roles, and can help formalise informal sectors linked to manufacturing value chains.

Policy and institutional support play a decisive role in this transition. Alignment with national strategies such as the National Development Plan 2030 and the National Waste Management Strategy 2020 can create an enabling environment through incentives, infrastructure investment, and regulatory clarity. Public procurement reforms and targeted SME funding mechanisms can further accelerate adoption by reducing financial risk and stimulating demand for sustainable products.

The proposed multi-stage SSM adoption framework is particularly relevant in this context. By emphasising readiness assessment, SMEs can align technological investments with their operational capabilities. Strategic prioritisation ensures that limited resources are directed toward high-impact technologies. Pilot implementation reduces risk, while capacity development addresses skills gaps. Finally, scalable integration embeds sustainability into core business processes, ensuring long-term impact rather than isolated improvements.

2.3 Resource Constraints in SMEs

Resource constraints are a defining characteristic of SMEs, particularly in emerging economies such as South Africa. These limitations directly influence their capacity to adopt SSM and remain competitive in increasingly digital and sustainability-driven markets.

2.3.1 Financial Constraints

Financial restrictions are often the most immediate and restrictive barrier. SMEs typically rely on internal funds or short-term financing, with limited access to long-term, low-interest capital (Sawitri, 2023). High upfront costs associated with smart technologies such as Industrial Internet of Things (IIoT) devices, automation systems, and data analytics platforms can be prohibitive.

Additionally, financial institutions often perceive SMEs as high-risk borrowers due to limited collateral, inconsistent cash flows, and a lack of credit history. This restricts their ability to secure funding for capital-intensive upgrades. As a result, SMEs tend to prioritise short-term operational survival over long-term strategic investments, delaying digital transformation and sustainability initiatives.

2.3.2 Human Resource Constraints

Human capital limitations significantly hinder SME innovation capacity. Many SMEs lack access to highly skilled personnel, particularly in areas such as data analytics, automation engineering, cybersecurity, and digital systems integration (Brandy, 2023).

This skills gap affects not only the implementation of advanced technologies but also their effective utilisation and maintenance. SMEs often depend on generalist employees rather than specialised experts, which limits their ability to manage complex smart manufacturing systems. Furthermore, limited training budgets and weak linkages with higher education institutions exacerbate the problem, resulting in slow technology absorption and low digital maturity.

2.3.3 Technological Constraints
Technological limitations in SMEs are closely tied to financial and skills limitations (Ruiz-Palomo, Fernández-Gámez, and León-Gómez, 2022). Many SMEs operate with outdated or legacy equipment that lacks compatibility with modern digital technologies. This makes integration with smart manufacturing systems difficult and costly.

Limited access to advanced manufacturing tools, such as robotics, additive manufacturing, and real-time monitoring systems, restricts productivity improvements and process optimisation. Moreover, SMEs often lack the technical knowledge required to evaluate, select, and implement appropriate technologies, leading to fragmented or ineffective adoption.

2.3.4 Infrastructure Constraints
Infrastructure challenges are particularly pronounced in developing contexts. Unreliable energy supply, characterised by frequent outages or load shedding, disrupts production schedules, damages equipment, and increases operational costs. In South Africa, energy instability remains a critical issue affecting industrial productivity.

In addition, poor digital connectivity limits the deployment of cloud-based systems, real-time monitoring, and data-driven decision-making. Inadequate industrial infrastructure, including transport and logistics networks, further constrains supply chain efficiency and market access. These factors collectively undermine the feasibility and scalability of smart manufacturing initiatives.

Synthesis and Implications
These resource constraints are interdependent. Financial limitations restrict investment in technology and skills; skills shortages hinder technology adoption; and weak infrastructure reduces the effectiveness of both. This creates a reinforcing cycle that slows SME transformation.

Addressing these challenges requires integrated interventions, including targeted financing mechanisms, skills development programmes, infrastructure investment, and policy support. Without such coordinated efforts, SMEs risk being excluded from the benefits of Sustainable Smart Manufacturing, limiting broader industrial sustainability and economic growth (Alkhodair and Alkhudhayr, 2025).

1.1 Objectives
To investigate the key barriers and enablers influencing the adoption of SSM in resource-constrained small and medium-sized enterprises (SMEs), and to develop a practical adoption framework.

To identify and critically analyse the financial, technological, infrastructural, workforce, organisational, and regulatory barriers affecting SSM adoption in SMEs.

To examine the key enablers, including digital technology advancements, government policies, industry collaboration, and workforce development initiatives that facilitate SSM implementation.

3. Methods
This study adopts a qualitative and conceptual modelling approach to develop a practical and context-relevant SSM adoption framework. A synthesis approach is used to investigate the barriers and enablers influencing the adoption of Sustainable Smart Manufacturing (SSM) in resource-constrained small and medium-sized enterprises (SMEs). The methodology is designed to provide a comprehensive understanding of existing knowledge while developing a context-relevant adoption framework.

3.1 Research Design
The research follows a descriptive and exploratory design, focusing on analysing existing academic literature, industry reports, and policy documents related to smart manufacturing, sustainability, and SME development. This approach

is appropriate given the study's objective of synthesising dispersed knowledge and identifying key patterns, challenges, and opportunities.

3.2 Data Collection

Data were collected through a critical review of secondary sources, including Peer-reviewed journal articles on Industry 4.0 and sustainable manufacturing, conference proceedings, and technical reports

3.3 Limitations of the Methodology

The study is limited by its reliance on secondary data, which may not fully capture firm-specific or region-specific dynamics. Additionally, the absence of primary data collection (e.g., surveys or interviews) limits direct empirical validation. However, the methodology provides a strong conceptual foundation for further applied research.

4. Financial Barriers to Sustainable Smart Manufacturing (SSM) Adoption in SMEs

Financial barriers are among the most decisive constraints limiting the adoption of Sustainable Smart Manufacturing (SSM) in SMEs, particularly in contexts such as South Africa (Gumbi and Twinomurinzi, 2025). The transition to SSM is capital-intensive, requiring substantial upfront investments across multiple domains, which many SMEs are structurally ill-equipped to absorb.

A primary challenge is the high initial investment requirement. SMEs must invest in digital infrastructure (connectivity, cloud systems), smart equipment (sensors, automation, robotics), software platforms (data analytics, ERP systems), and cybersecurity solutions. Beyond hardware and software, significant funding is also needed for workforce training and upskilling, ensuring employees can effectively operate and maintain new technologies. These combined costs create a steep financial entry barrier, particularly for firms with limited retained earnings.

Closely linked is the issue of short-term financial orientation. SMEs often operate under tight cash flow conditions and volatile market environments. As a result, they prioritise immediate operational needs such as wages, raw materials, and energy costs over long-term strategic investments like digital transformation. Since the returns on SSM investments are typically realised over time, this misalignment between investment horizons and survival priorities discourages adoption.

Another critical constraint is limited access to external finance. Financial institutions frequently classify SMEs as high-risk borrowers due to limited collateral, weak credit histories, and uncertain revenue streams. This results in restricted access to loans or financing options, often accompanied by high interest rates and unfavourable lending terms. Consequently, even SMEs willing to invest in SSM may be unable to secure adequate funding.

Furthermore, there is often uncertainty regarding return on investment (ROI). SMEs may lack the analytical tools or expertise to accurately assess the economic benefits of SSM technologies, making such investments appear risky. This perceived uncertainty further reinforces conservative financial decision-making.

In many cases, hidden and indirect costs are underestimated. These include system integration expenses, maintenance, software updates, and downtime during implementation, and cybersecurity management. Such costs can significantly inflate the total cost of ownership, discouraging SMEs from initiating SSM projects.

Overall, financial barriers create a reinforcing cycle: limited capital restricts technology adoption, which in turn limits productivity gains and profitability, further constraining future investment capacity. Addressing these barriers requires targeted interventions such as subsidised financing, tax incentives, public–private partnerships, and innovative funding models (e.g., leasing, pay-as-you-go systems). Without such support mechanisms, widespread SSM adoption among SMEs will remain slow and uneven.

4.1 Technological and Infrastructure Barriers

Technological and infrastructure limitations significantly constrain SSM adoption in SMEs, particularly in South Africa. Many SMEs operate with unreliable digital infrastructure, including unstable internet connectivity and limited access to cloud computing platforms (Idemudia at al. 2023). This restricts the deployment of data-intensive applications such as real-time monitoring and predictive analytics.

A major challenge is the lack of data integration capability. Existing systems are often fragmented, with machines and software operating in isolation. This prevents seamless data flow across production processes, undermining the core principle of smart manufacturing interconnectivity. Similarly, non-interoperable manufacturing systems often have legacy equipment; limit the ability to integrate modern digital tools without costly upgrades or replacements.

Another critical issue is cybersecurity capacity. SMEs frequently lack the expertise and resources to protect digital systems from cyber threats, making them hesitant to adopt connected technologies. In addition, the absence of real-time data acquisition systems limits visibility into operations, reducing opportunities for optimisation.

Infrastructure challenges such as unreliable power supply and load interruptions further disrupt production and damage sensitive equipment, making consistent digital operations difficult. Together, these barriers create a fragile technological foundation that slows or prevents effective SSM implementation.

4.2 Workforce Skills and Competency Barriers

The transition to SSM is fundamentally skills-driven, yet SMEs often face acute human capital deficiencies (Abd Aziz and Yusof, 2026). Smart manufacturing requires multidisciplinary expertise spanning data analytics, automation engineering, mechatronics, cybersecurity, and sustainability performance assessment. However, most SMEs lack access to such specialised talent.

A key issue is the absence of structured training and upskilling programmes. Limited financial resources constrain investment in employee development, while weak collaboration with academic and training institutions reduces opportunities for knowledge transfer. As technologies evolve rapidly, existing employees may become inadequately equipped to manage digital systems.

Furthermore, SMEs struggle to attract and retain skilled professionals, who are often drawn to larger firms offering higher salaries, better career prospects, and more advanced technological environments. This creates a persistent talent gap, limiting SMEs' ability to implement, operate, and sustain SSM systems effectively.

4.3 Organizational and Cultural Barriers

Organizational and cultural dynamics play a critical, though often underrated, role in SSM adoption (Singh, Singh, Chikhale, & Dhir, 2024). SME leadership is frequently risk-averse, largely due to financial vulnerability and uncertain returns on investment. This cautious mindset discourages experimentation with new technologies and delays strategic transformation initiatives.

Resistance to change among employees and management further complicates adoption. Workers may fear job displacement or lack confidence in their ability to adapt to digital systems, leading to low acceptance of new technologies. Without effective change management strategies, even well-funded initiatives can fail.

Additionally, many SMEs lack a clear strategic digital vision. Technology adoption is often reactive rather than proactive, resulting in fragmented or short-term implementations that fail to deliver sustained value. The absence of leadership commitment and long-term planning undermines the transition to fully integrated smart manufacturing systems.

4.4 Regulatory and Policy Barriers
Regulatory and policy environments significantly influence SME adoption of SSM (Liu at al. 2024). In many developing contexts, including South Africa, inconsistent or unclear regulatory frameworks create uncertainty around technology investments, particularly in areas such as data governance, cybersecurity, and environmental compliance. The lack of SME-specific policy incentives, such as tax breaks, grants, or subsidised financing, reduces the economic attractiveness of adopting advanced technologies. Existing policies may be more aligned with large enterprises, leaving SMEs underserved.

5. Enablers of Sustainable Smart Manufacturing (SSM) in SMEs
While barriers are substantial, a set of reinforcing enablers is steadily lowering the threshold for SSM adoption, especially in contexts such as South Africa. These enablers work best in combination, creating momentum for scalable and cost-effective transformation.

5.1 Declining Cost of Digital Technologies
Rapid advances in cloud computing, low-cost IIoT sensors, edge devices, and modular automation have significantly reduced capital requirements. SMEs can now adopt pay-as-you-go models rather than purchasing expensive, monolithic systems.
Modularity is particularly important: firms can start with high-impact use cases such as machine monitoring or energy tracking and scale incrementally. This reduces financial risk, shortens payback periods, and aligns investment with cash flow constraints.

5.2 Government Policies and Incentives
Targeted public support can decisively shift the business case for SSM. Instruments such as tax credits, matching grants, concessional loans, and green financing schemes reduce upfront costs and de-risk investment (Anjanappa, 2024).

Alignment with national strategies such as the National Development Plan 2030 and the National Waste Management Strategy 2020 can also stimulate demand via green public procurement and clearer regulatory guidance. Well-designed SME-specific programmes (simple application processes, faster disbursement) are critical to uptake.

5.3 Industry Collaboration and Innovation Ecosystems
Partnerships with universities, research institutes, technology vendors, and industry clusters accelerate knowledge transfer and lower implementation risk. Through testbeds, pilot projects, and shared facilities, SMEs can validate technologies before full-scale deployment.
Collaborative ecosystems also enable industrial symbiosis (resource sharing, waste-to-resource loops) and access to specialist expertise (integration, cybersecurity, analytics) that would be too costly to build in-house.

5.4 Workforce Development Programs
SSM is skills-intensive; therefore, targeted training and upskilling are pivotal. Short, applied programmes in data analytics, automation, mechatronics, cybersecurity, and sustainability metrics can quickly raise operational readiness. Blended models of industry-led training, TVET partnerships, apprenticeships, and micro-credentials help SMEs close skills gaps without long downtimes. Upskilling existing staff is often more feasible than competing for scarce external talent.

5.5 Digital Manufacturing Platforms
Cloud-based manufacturing platforms (e.g., SaaS ERP/MES, remote monitoring, and digital twins) allow SMEs to access advanced capabilities without heavy infrastructure investment. These platforms support real-time visibility, predictive maintenance, production scheduling, and data-driven decision-making.

Because they are scalable and subscription-based, SMEs can start small, integrate gradually, and avoid vendor lock-in through interoperable, API-driven solutions.

6. Proposed Sustainable Smart Manufacturing (SSM) Adoption Framework for SMEs

The five-stage framework provides a practical, low-risk pathway for SMEs to transition toward Sustainable Smart Manufacturing, especially in resource-constrained contexts such as South Africa. It emphasises sequencing, affordability, and capability building, ensuring that adoption is both scalable and sustainable.

Stage 1: Readiness Assessment

This foundational stage evaluates the SME's current state across three key dimensions: financial capacity, technological infrastructure, and workforce skills.
• Financial readiness: ability to fund pilot projects or access external financing
• Technological readiness: condition of existing equipment, connectivity, and data systems
• Workforce readiness: digital literacy, technical skills, and adaptability
Tools such as digital maturity models, SWOT analysis, and gap assessments are useful here. The outcome is a clear baseline that informs realistic planning and prevents misaligned investments.

Stage 2: Strategic Technology Selection

Rather than adopting complex systems all at once, SMEs should prioritise high-impact, cost-effective technologies aligned with their operational needs.
Typical entry points include:
• IIoT sensors for machine monitoring
• Energy management systems
• Cloud-based ERP/MES platforms
• Basic automation or retrofitting existing equipment
Decision-making should be guided by cost–benefit analysis, ease of integration, scalability, and return on investment (ROI). The focus is on "quick wins" that build confidence and demonstrate value.

Stage 3: Pilot Implementation

Pilot projects are essential for risk mitigation and learning. SMEs implement selected technologies on a limited scale, for example, a single production line or process.
Key objectives:
• Validate technical feasibility
• Measure performance improvements (e.g., OEE, downtime, energy use)
• Identify operational challenges
Pilots provide evidence-based insights, enabling SMEs to refine strategies before committing to larger investments.

Stage 4: Capacity Development

Sustainable adoption depends on building internal capabilities. This stage focuses on:
• Workforce upskilling in data analytics, automation, and system operation
• Developing a digital knowledge base and standard operating procedures
• Strengthening change management and leadership commitment
Partnerships with training institutions, industry bodies, and technology providers can accelerate learning.
Importantly, SMEs should embed a continuous learning culture to keep pace with evolving technologies.

Stage 5: Scale-Up and Sustainability Integration

After successful pilots and capability development, SMEs can scale up SSM across operations. This involves:
• Expanding digital systems to multiple processes or facilities
• Integrating real-time monitoring and data analytics enterprise-wide
• Embedding sustainability metrics (energy efficiency, waste reduction, emissions tracking) into decision-making
At this stage, SSM becomes part of the core business strategy, supporting long-term competitiveness, regulatory compliance, and environmental performance.

7. Discussion

SSM adoption in SMEs extends well beyond a technical upgrade; it represents a systemic transformation that reshapes how firms create value, organise work, and interact with their ecosystems (Alkhodair and Alkhudhayr, 2025). Findings underscore that technology is only one layer successful adoption depends equally on institutional support, organisational readiness, and socio-economic conditions.

At the firm level, SSM requires a shift from reactive, survival-driven operations to data-informed, strategically aligned decision-making. This involves reconfiguring business models, investing in workforce capabilities, and embedding sustainability metrics (e.g., energy intensity, material efficiency) into daily operations. Consequently, adoption is as much about leadership vision, change management, and culture as it is about sensors, software, and automation.

A key insight is the need for coordinated multi-stakeholder engagement. Governments play a catalytic role by providing enabling policies, incentives, and infrastructure. Alignment with national strategies such as the National Development Plan 2030 can stimulate SME participation through funding mechanisms, tax incentives, and public procurement reforms. Industry stakeholders, including large firms and technology providers, contribute through supply chain integration, mentorship, and technology diffusion, while universities and research institutions support skills development, applied research, and pilot experimentation. Without this coordinated ecosystem, SMEs face fragmented support and higher implementation risks.

SMEs in developing economies such as South Africa encounter compounded structural challenges. Infrastructure deficits, particularly unreliable electricity and limited broadband connectivity, directly undermine digital operations. Financial vulnerability further constrains long-term investment, reinforcing a cycle where firms prioritise short-term survival over innovation. In addition, regulatory uncertainty and limited access to technical expertise slow adoption and reduce confidence in digital transformation initiatives.

Despite these constraints, an important countertrend is the democratisation of digital technologies. The declining cost of cloud computing, IIoT devices, and modular automation systems allows SMEs to bypass traditional capital-intensive industrialisation pathways. Rather than following the linear trajectory of large-scale mechanisation, SMEs can adopt incremental, scalable, and platform-based solutions, effectively "leapfrogging" stages of development. For example, cloud-based manufacturing systems enable real-time monitoring and analytics without requiring extensive in-house IT infrastructure, while low-cost sensors provide immediate visibility into machine performance and energy usage.

This leapfrogging potential is particularly significant for sustainability. SMEs can integrate resource-efficient practices from the outset, avoiding legacy inefficiencies associated with older industrial models. In doing so, SSM becomes a vehicle for achieving triple-bottom-line outcomes: improved productivity (economic), reduced environmental impact (environmental), and enhanced skills and job quality (social).

However, realising these opportunities requires addressing persistent capability gaps. Digital tools alone do not guarantee performance improvements; SMEs must develop the absorptive capacity to interpret data, maintain systems, and continuously improve processes. This reinforces the importance of workforce development, knowledge networks, and organisational learning.

In essence, SSM adoption in SMEs should be understood as a transition pathway rather than a one-time intervention. It involves iterative learning, gradual scaling, and alignment with broader industrial and sustainability goals. When supported by coherent policies, collaborative ecosystems, and targeted capacity-building initiatives, SMEs can move from being constrained adopters to active drivers of sustainable industrial transformation in emerging economies

8. Practical Implications

The study's findings translate into actionable guidance across managerial, policy, and research domains. Because SSM adoption in SMEs is resource-sensitive and context-dependent, the emphasis is on phased implementation, targeted support, and evidence-based refinement.

Managerial Implications
For SME managers, the priority is to de-risk adoption while demonstrating early value:
Adopt phased transformation: Start with high-impact, low-cost use cases (e.g., machine monitoring, energy tracking) before scaling. Align each phase with cash flow and clear ROI targets.
Link technology to business goals: Tie SSM investments to measurable KPIs, such as OEE, downtime, scrap rate, energy intensity, rather than adopting tools for their own sake.
Leverage retrofit and modularity: Upgrade existing assets with sensors and edge devices instead of replacing entire lines. Prefer interoperable, API-driven solutions to avoid lock-in.
Build internal capability: Invest in upskilling (data literacy, basic automation) and appoint internal "digital champions" to sustain momentum.
Use partnerships strategically: Collaborate with vendors, universities, and peers for pilots, troubleshooting, and knowledge transfer.
Strengthen change management: Communicate benefits, address job-security concerns, and incentivise adoption to reduce resistance.
Policy Implications
Public policy is pivotal in correcting market failures that SMEs cannot overcome alone, particularly in South Africa:
Design SME-specific incentives: Simplified grants, tax credits, and concessional loans for SSM pilots, with fast approval cycles and minimal administrative burden.
De-risk investment: Support shared testbeds, demonstration centres, and voucher schemes that allow SMEs to trial technologies before full deployment.
Invest in infrastructure: Prioritise reliable electricity and broadband in industrial zones to enable real-time, data-driven operations.
Develop skills pipelines: Co-fund TVET–industry programmes, apprenticeships, and micro-credentials in automation, data analytics, and cybersecurity.
Stimulate demand: Use green public procurement and standards to create markets for sustainably manufactured goods.
Ensure regulatory clarity: Provide clear guidance on data governance, cybersecurity, and environmental compliance to reduce uncertainty.
Alignment with national strategies such as the National Development Plan 2030 can amplify impact through coordinated, cross-departmental action. Research Implications
Future research should move from conceptual models to robust empirical validation:
Longitudinal and quasi-experimental studies: Measure pre/post impacts of SSM adoption on OEE, energy use, emissions, and cost structures.
Context-sensitive comparisons: Examine sectoral differences (e.g., metals, food processing) and regional constraints within emerging economies.
Cost–benefit and ROI modelling: Develop SME-friendly tools that quantify the total cost of ownership and payback under uncertainty.
Adoption pathways and maturity models: Validate staged frameworks and identify critical thresholds for scaling.
Socio-technical dynamics: Study change management, workforce adaptation, and organisational learning as determinants of success.
Ecosystem effects: Assess how clusters, supply chains, and policy instruments jointly influence outcomes.

9. Future Research Directions
Advancing SSM in SMEs now depends on moving from conceptual frameworks to rigorous, context-aware evidence. The following directions outline where research can deliver the greatest practical impact, particularly in emerging economies such as South Africa.

There is a clear need for field-based, longitudinal studies that test proposed SSM frameworks in real SME environments. Future work should:
• Measure pre- and post-impacts on OEE, downtime, energy intensity, scrap rates, and cost.
• Use quasi-experimental designs (matched firms, staggered rollouts) to strengthen causal inference.
• Document implementation pathways, including failures, to refine staged adoption models.
• Produce replicable toolkits (checklists, KPIs, data templates) that SMEs can apply directly.
Sector-Specific SSM Adoption Models
"SME" is not a homogeneous category. Research should develop sector-tailored models that reflect process characteristics and constraints:

• Discrete manufacturing (e.g., machining): focus on machine monitoring, predictive maintenance.
• Process industries (e.g., food, chemicals): emphasis on traceability, quality analytics, compliance.
• Textiles/plastics: energy optimisation, waste reduction, and flexible scheduling.
Outputs should include technology shortlists, ROI benchmarks, and risk profiles per sector.
SME Digital Transformation Maturity Models
Robust, easy-to-use maturity models are needed to guide progression from basic digitisation to fully integrated SSM:
• Define clear levels (e.g., ad hoc → connected → data-driven → autonomous → sustainable).
• Link each level to capabilities, required investments, and expected benefits.
• Incorporate diagnostic tools for self-assessment and prioritisation.
• Validate models across regions to ensure context sensitivity (infrastructure, skills, policy).
Sustainability Performance Measurement Frameworks

A persistent gap is the lack of standardised, SME-friendly sustainability metrics:
• Develop integrated KPI sets covering economic (cost/OEE), environmental (energy, water, emissions, waste), and social (skills, safety) dimensions.
• Enable real-time measurement through IIoT-enabled dashboards.
• Align with international reporting standards while keeping data collection lightweight.
• Establish benchmark datasets to compare performance across firms and sectors.

Integration of Circular Economy (CE) Models into SSM
Future research should explicitly connect SSM with circular economy (CE) principles:
• Design models for industrial symbiosis, where waste streams from one firm become inputs for another.
• Evaluate remanufacturing, reuse, and recycling loops enabled by digital traceability.
• Quantify combined benefits, cost savings, emissions reduction, and resource efficiency.
• Explore policy and market mechanisms that support CE-enabled SSM at cluster and regional levels.

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Conclusion

SSM grants a transformative pathway for enhancing productivity, sustainability performance, and competitiveness within SMEs. As highlighted in the study, SMEs play a critical role in industrial development but face persistent structural constraints that hinder their ability to adopt advanced digital manufacturing technologies. Key barriers include financial limitations, workforce skill shortages, inadequate technological infrastructure, and regulatory uncertainties, all of which collectively slow the pace of digital transformation.

Despite these challenges, the study demonstrates that emerging enablers such as declining costs of digital technologies, supportive government policies, industry collaboration, and workforce development initiatives create significant opportunities for SMEs to transition toward SSM. The proposed five-stage adoption framework provides a practical and structured roadmap, enabling SMEs to implement smart manufacturing in a phased, scalable, and cost-effective manner.

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