

GREEN DIGITAL TRANSFORMATION AND SUSTAINABLE PERFORMANCE IN MANUFACTURING SMES: GREEN INNOVATION CAPABILITY AND REGULATORY PRESSURE

Zeeshan Zaib Khattak¹, Hamza Iftikhar^{*2}

¹NUST Business School, National University of Sciences and Technology (NUST), Islamabad, Pakistan

^{*2}Government and Public Policy, Jinnah School of Public Policy and Leadership, NUST, Islamabad, Pakistan

^{*}hftikhar@jsppl.nust.edu.pk

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Corresponding Author: *

Hamza Iftikhar

Abstract

Despite the assumption that digital transformation and environmental sustainability reinforce each other, digital transformation does not necessarily lead to greener, more sustainable companies. This conceptual review explores the impact of digital transformation on the economic, environmental, and social performance of small and medium-sized enterprises (SMEs) in manufacturing. The resource-based view of the firm and the dynamic capabilities literature are leveraged to develop the conceptualisation of green innovation capability as a major capability through which the positive impact of digital transformation takes place. The credibility and supportive nature of regulatory pressure are identified as a boundary condition that can encourage capability development. Still, they may drive SMEs to comply symbolically with regulations if the former is not credible or compliance costs exceed SMEs' ability to pay. Digital transformation is distinguished from digital adoption, and four capability foundations are identified: data visibility, process integration, intelligent optimisation, and digitally enabled collaboration. Furthermore, potential countereffects of digital transformation are explored, including energy consumption, electronic waste, cybersecurity risks, supplier exclusion, and rebound effects. Five propositions outline the relationship between digital transformation, green innovation capability, top-management environmental commitment, regulatory pressure, and multidimensional sustainable performance. An implementation path and a research design that employ structural equation modelling and configurational analysis are provided. The contribution of the paper lies in exploring the reason for the variation in the sustainability performance of SMEs that invest in the same digital technologies.

1. INTRODUCTION

Small and medium-sized enterprises (SMEs) engaged in manufacturing are subject to multiple pressures to boost efficiency, cut costs, meet customer expectations, and minimise

environmental impacts. Enterprise systems, sensors, cloud computing, analytics, artificial intelligence, additive manufacturing, and digitally enabled supply chains are often cited as means of

achieving these goals. These technologies can make material and energy flows transparent, identify wastages, facilitate preventive maintenance, and promote traceability. At the same time, digitalisation leads to increased electricity consumption, accelerated equipment renewal, the creation of electronic waste, and dependence on technology suppliers (Abbass et al., 2022; Al-barrow et al., 2021; Iqbal et al., 2025a,b).

Therefore, the link between digital transformation and sustainability cannot be considered automatic and positive. Technology adoption includes the purchase or use of certain technologies, while digital transformation involves the alignment of the organisation's strategy, processes, capabilities, structure, and business model. The company may buy sensors but not incorporate the data they provide into production decision-making, or apply the enterprise system to improve financial control, but not to environmental performance. The use of technology to pursue sustainability requires certain organisational capabilities (Ibrahim et al., 2024; Bushra et al., 2022; Iqbal et al., 2020).

There is evidence of a positive correlation among digital transformation, innovation capabilities, and ESG performance. Chen and Wang (2024) found, based on data from manufacturing SMEs, that innovation capabilities and servitization partially mediate the relationship between digital transformation and ESG performance. It has been shown that digital transformation can positively affect environmental performance via green innovation and information-enabled coordination. However, such research usually uses cross-sectional perception data, employs general measures of digitalisation, and treats sustainability as a dependent variable (Iqbal et al., 2024; Khattak et al., 2017).

In this study, NRBV is used to examine the relationship between two constructs. The resource-based view (RBV) has been augmented theoretically by Hart (1995)'s proposition that competitive advantage depends on the natural environment. The prevention of pollution,

product stewardship, and sustainable development need not be mere compliance activities; organisational capabilities can aid them. Digital capabilities could enhance such capabilities, provided the firm can recombine knowledge, processes, and relationships to innovate in environmentally sustainable ways.

The proposed mediator is green innovation capability, which refers to organisations' ability to produce better products from an environmental perspective, innovate their production processes, use less material and energy, and employ sustainable management practices (Khattak et al., 2018a,b). The proposed moderator is regulation, since environmental regulations will set the agenda for priorities and expected benefits. However, regulation might lead to substantial or only symbolic actions, depending on enforcement and other factors.

Research questions include: What roles do digital capabilities play in green innovation within manufacturing SMEs? What roles does green innovation capability play in economic, environmental, and social performance? In what circumstances would digital capabilities bring about substantial, rather than symbolic, sustainability actions?

In this paper, an integrative literature review approach is applied for reviewing the literature on strategic management, information systems, innovation, operations, and environmental management. This kind of review is suitable when evidence spans both theory and empirics, and when the aim is to create a framework rather than estimate a single average effect (Snyder, 2019; Torraco, 2005; Khattak et al., 2019).

In the conceptual search, terms such as "digital transformation," "green digital transformation," "SME sustainability," "green innovation capability," "environmental performance," "ESG performance," "regulatory pressure," and "natural-resource-based view" were included. Peer-reviewed literature on management and sustainability has been prioritised, while seminal theoretical literature has been considered to establish the essential constructs. The sources have been coded

based on digital capability, innovation mechanism, regulation, performance measure, negative effects, and research methods.

The synthesis is conducted on a concept-oriented basis (Webster & Watson, 2002). In the synthesis, converging and diverging propositions are considered, and propositions are developed. However, it cannot be classified as an exhaustive systematic review, nor can it provide a PRISMA flow diagram and meta-analytical results.

3. Theoretical Foundation: The Natural-Resource-Based View

Hart (1995) argues that an organisation's engagement with the natural environment determines its resource and capabilities for competitive advantage. Waste and emissions reductions occur through pollution prevention capabilities; environmental impact management throughout the product life cycle through product stewardship capabilities; and growth within ecological and social limits through sustainable development capabilities. Hart & Dowell (2011) would later show how such capabilities may interact with dynamic capabilities in addressing modern sustainability challenges.

The Natural Resource-Based View (NRBV) is well-suited to small and medium-sized enterprises (SMEs) in that it focuses on what organisations can do with their resources rather than merely on the possession of technologies. Digital systems cannot be considered valuable, rare, and inimitable. Still, their strategic value can emerge from the routines that link data with environmental information and influence decision-making and stakeholder relationships. Two companies using the same software can produce different results because one introduces environmental indicators into its operations, whereas the other uses the software only for reporting.

Green innovation capability can be described as a process of transformation. It is dynamic, as technologies, regulations, markets and environmental challenges change continuously.

SMEs need to sense, exploit and reconfigure them. According to Chen & Chang (2013), green dynamic capabilities and green transformational leadership foster green creativity and product development performance.

4. Components of Green Digital Transformation

4.1 Data visibility

The adoption of digital sensing technology, such as sensors, meters, and information systems, enables measurement of energy usage, scrap, water usage, emissions, equipment health status, and supplier performance. Improved visibility eliminates informational distance between environmental goals and operational decisions. It enables managers to identify unusual consumption patterns, benchmark production lines, and evaluate improvement programs.

However, improved visibility cannot independently affect the effectiveness of environmental performance management if data are flawed and not used sufficiently by managers. SMEs might have an excess of information that their employees struggle to understand properly. Therefore, data management, definition of common terms, and specialised dashboards become crucial. Environmental performance measures must be associated with operational and financial measures.

4.2 Process integration and optimization

Planning, production, maintenance, inventory, and quality functions can be coordinated through enterprise systems and industrial connectivity. Analytics can help optimise equipment utilisation, prevent defects, predict failures, and coordinate batch sizes. These efforts could lead to savings in material and energy intensity and in costs. However, an efficiency effort focused narrowly on productivity can result in increased production or in shifting environmental impact to other phases or processes.

This is illustrated by the rebound effect, where increased efficiency lowers per-unit costs, but lower costs could motivate greater production.

Thus, for sustainable performance measurement to be effective, both absolute and intensity measurements must be considered.

4.3 Digitally enabled collaboration

Platforms enable collaboration with suppliers, consumers, educational institutions, regulatory bodies, and service providers. SMEs can gain access to technical expertise, track material sources, collaborate on the design of recyclable products, or provide service-oriented solutions. Servitization and innovation capabilities are the mechanisms through which transformation leads to improved ESG outcomes, according to Chen & Wang (2024). Collaboration is especially useful for SMEs that lack internal research capabilities.

Digital collaboration also poses challenges of dependence and exclusion. Small suppliers might fail to satisfy data or interoperability requirements. Platforms tend to centralise negotiating power in lead firms. Therefore, governance must consider issues of access, data ownership, cybersecurity, and cost distribution.

5. Green Innovation Capability as a Mediator

Green innovation includes product, process, and managerial innovation. Product innovation lifecycle reductions are realised through material changes, durability, better repair, and recyclability. Process innovation reduces waste, cuts down on emissions, and saves resources. Managerial innovations include environmental accounting, cross-functional teamwork, supplier criteria, and incentives.

Digital innovation offers information and coordination resources, whereas green innovation capability converts these resources into new products and processes. This dichotomy helps us understand why the results of adopting technology can be limited. Dashboards can reveal problems, but workers need process improvement skills and empowerment to change things. Lifecycle databases can guide design decisions, but engineers and suppliers need collaboration habits to act on them.

Proposition 1: Digital transformation capability will be positively associated with green innovation capability when digital data, processes, and collaboration are integrated with environmental objectives.

Proposition 2: Green innovation capability will mediate the relationship between digital transformation capability and multidimensional sustainable performance.

6. Sustainable Performance as a Multidimensional Outcome

Productivity, cost management, quality, income generation, risk management, and market access are measures of economic performance. Measures of environmental performance include absolute and per-unit reductions in the use of energy, emissions, water, waste, and hazardous substances. Measures of social performance include safety, skill building, decent work, community impacts, and supply chain sustainability.

These outcomes are mutually reinforcing or contradictory. Maintenance may save time and energy and boost safety. Automation will ensure accuracy but may eliminate tasks or increase surveillance. Traceability of suppliers may enhance environmental assurance, but it comes at an expense to small-scale suppliers. An integrated approach that treats sustainability as a single, holistic measure may overlook such contradictions.

This means that the model assumes limited complementarity rather than win-win results. The manager must consider trade-offs. A project that reduces the environmental footprint yet harms employees or poses risks to the organisation's financial stability cannot be called sustainable.

Proposition 3: The positive effect of green innovation capability will vary across economic, environmental, and social performance, and will be stronger when firms use balanced rather than exclusively financial performance systems.

7. Regulatory Pressure as a Boundary Condition

Environmental regulation can alter the cost structure of actions and their acceptability. Valid regulatory standards may reduce ambiguity, establish shared expectations, and inspire investment. Environmental reporting can spur the development of data systems, while emissions standards can increase the value of process innovation. Appropriate policy tools can help SMEs overcome resource constraints through technical expertise, joint infrastructure development, and financing.

Regulation can also generate compliance costs and symbolic behaviour. If the standards are ambiguous, enforcement varies, or the reporting system is decoupled from performance improvements, the firm might concentrate on reporting. Compliance costs for large firms can be passed on to small suppliers. Frequent changes in the standard can hamper long-term investments.

Pressure can only be effective, provided it is credible, consistent, proportional, and supportive. It is assumed that regulatory pressure will enhance the impact on the transformation-innovation link.

Proposition 4: Regulatory pressure will strengthen the positive relationship between digital transformation capability and green innovation capability when regulation is credible, consistent, and accompanied by proportionate support for SMEs.

8. Top-Management Environmental Commitment

In SMEs, strategy is heavily shaped by owners and senior managers. Digital initiatives often compete with immediate operational priorities, while investments in sustainability may not produce yield or immediate returns. Top management commitment, therefore, plays an important role in determining whether environmental objectives are actually incorporated into technology choices, budgets, performance measures, and employee responsibilities.

Such commitment needs to be demonstrated through actions rather than words. It can be seen in the resources leaders provide, the consistency of their priorities, their willingness to allow experimentation, and their openness about areas where performance falls short. Leaders also influence whether digital transformation is introduced simply as a technical project or developed with meaningful employee involvement. Greater employee participation can bring valuable operational knowledge into the transformation process while also reducing resistance to change.

Proposition 5: Top-management environmental commitment will strengthen the indirect relationship between digital transformation and sustainable performance through green innovation capability.

9. Countervailing Environmental and Social Effects

Digital technologies also have their own environmental footprint. Producing hardware requires minerals and energy, data processing consumes electricity, and the rapid replacement of devices contributes to growing amounts of electronic waste. Moving operations to cloud services may shift environmental impacts elsewhere rather than remove them. There are also wider risks to consider. Cybersecurity failures can interrupt production or expose sensitive stakeholder information, while algorithmic optimisation may prioritise measurable efficiency at the expense of employee judgment or community needs.

For this reason, a credible green digital strategy should consider the full life cycle of the technologies being used. This includes responsible procurement, repairing and reusing equipment where possible, using renewable electricity when feasible, minimising unnecessary data collection and storage, and managing electronic waste appropriately. Firms should also consider how digital technologies affect job design and the skills employees need. These safeguards help ensure that businesses do not

claim environmental gains from digitally enabled production while overlooking the environmental and social costs of the digital infrastructure itself.

10. Implementation Pathway for SMEs

The proposed pathway starts with a materiality assessment to identify the environmental and social issues that matter most to the firm. The next step is to examine what data are available and where important decisions are made. From there, the firm can choose small digital initiatives that address specific, measurable problems, such as excessive energy use, material waste, equipment breakdowns, or traceability issues. Cross-functional teams can then test possible changes to products and processes before evaluating the results through financial, environmental, and social measures. When these approaches prove successful, the resulting practices can be standardised and gradually expanded across the organisation and its wider supply network.

Following this sequence helps SMEs avoid investing in technology to adopt it. It also makes the learning process easier to observe and evaluate. Where sophisticated digital infrastructure is too expensive, SMEs can begin with relatively simple tools and build their capabilities over time. In many cases, strong management practices and reliable data may deliver more value than investing in advanced systems before the organisation is ready to use them effectively.

11. Proposed Empirical Research

Testing of the model could take place among manufacturing SMEs in industries such as textiles, food processing, engineering, electronics, automotive components, and chemicals. The respondents should comprise owners, operations managers, sustainability managers, and digital transformation managers who are familiar with the organisation's practices. Multis respondent sampling would increase validity.

The PLS-SEM approach could be used to test a predictive model with higher-order constructs,

provided the measurement choices are theoretically justified. Digital transformation and sustainable performance may not necessarily be considered as reflective constructs; they could be formative constructs. Reliability, convergent validity, discriminant validity, collinearity, predictive relevance, and out-of-sample prediction need to be verified.

A configurational approach, such as fsQCA, could complement the net-effect approach by analysing configurations of digital capabilities, management commitment, regulations, and innovation related to high performance. This takes into account the fact that SMEs may follow multiple routes to sustainability. Cross-sectional data can be interpreted as associations, whereas a longitudinal approach can facilitate causal analysis.

12. Discussion and Implications

To reconcile the heterogeneous outcomes in the paper, it is useful to distinguish between digital resources and green innovation capabilities. Digital technologies provide visibility and coordination, while green innovation capabilities enable organisational change. Such differentiation allows for the resolution of the conflict between the two contradictory claims about the inherent sustainability or detrimental effects of digitalisation.

Managers need to incorporate environmental criteria into business cases related to digital investments from the start. The cases should specify expected operational and sustainability outcomes, baseline measurements, data management needs, cybersecurity impacts, and rebound effects. The workers must be trained not just to work with digital tools but also to solve environmental problems.

Policymakers should avoid imposing one-size-fits-all compliance requirements. Testing facilities, green finance tools, technical extension services, interoperability standards, and e-waste facilities could help achieve real compliance. Indicators used in reporting frameworks need to be

commensurate with SMEs' capacity without sacrificing credibility.

12.1 Capability maturity and sequencing

The suggested framework implies a staged process rather than a transformation of SMEs. In the first visibility stage, the firm gathers baseline data and discovers the environmental impacts that matter. In the second stage of integration, the firm incorporates environmental information into its plans, maintenance, purchases, and design. In the third stage of innovation, employees and partners use data to inform product and process design. Finally, in the fourth stage of the ecosystem, the firm coordinates life-cycle improvement with suppliers and customers. Not having done the early work of data gathering and governance will result in a well-developed tool being fed incorrect information.

Maturity is not a single technological ladder. The resource-constrained SME could develop excellent environmental routines with relatively little technology, while a high-tech firm can stay environmentally reactive. It is necessary to assess the fit among environmental priorities, digital architecture, employee skills, management systems, and partner capabilities to avoid misrepresenting digital intensity.

12.2 Financing and investment appraisal

Small enterprises often have shorter investment periods and more financing constraints than big companies. Traditional valuation approaches tend to place small businesses at a disadvantage by not recognising the gains from sustainability investments in risk reduction, regulatory compliance, reputation management, learning opportunities, and future business opportunities. Managers have to integrate traditional discounted financial metrics with scenario analysis and non-financial metrics. Pilot projects could help overcome uncertainties, yet the pilots must have clear learning goals and a pathway to scaling.

Green financing may reduce financing constraints for SMEs, yet funding initiatives can become bureaucratic and hard for small

organisations to access. Both private investors and public authorities may enhance adoption by using simplified documentation, reliable measuring practices, and technical expertise. Meanwhile, environmental benefit claims must be validated to avoid greenwashing and the misappropriation of funds for regular IT enhancements.

12.3 Workforce implications and just transition

The digital optimisation of work processes entails risks that require a just transition approach. Companies need to assess which work activities will be affected, offer training opportunities, engage employees, and track the intensity and autonomy of work.

Employee engagement helps not only to ensure the legitimacy of sustainability practices but also to increase their innovative potential. Operators can identify sources of waste hidden behind statistical data. Environmental information needs to be interpreted collectively by engineers, maintenance staff, purchasing managers, and shop-floor workers. Incentives should be based on learning and improvement of outcomes.

12.4 Supply-network distribution of costs

Lead firms may require suppliers to provide emissions data, trace materials, or adopt platforms. These requirements can improve stewardship but may shift costs and risks to smaller firms. A relational approach includes shared standards, technical support, reasonable implementation periods, and transparent data-use rules. Without such arrangements, digital sustainability initiatives may consolidate suppliers and exclude otherwise capable SMEs.

Limitations and Future Research

The presented framework is conceptual and needs testing in various industries and contexts. Sustainability metrics are prone to self-report bias. Future research should control for energy, waste, certification, and product data whenever possible. Future research should compare results using intensity measures with those based on

absolute measures and consider potential unintended outcomes of digital transformation.

Construct specification deserves special attention. Digital transformation may be formative, since the four components – strategy, organisation, process integration, and technology adoption – jointly constitute the construct rather than represent a single interchangeable latent factor. Similarly, sustainable performance is multifaceted. Researchers need to determine whether three economic, environmental, and social dimensions can be combined into a single construct or should be considered separately. Poorly specified constructs may yield statistics that are acceptable but misleading.

Future research can complement digital trace data with a qualitative explanation. Machine and resource data can suggest improvements, while interviews may reveal the cause of those improvements – technological innovation, employees' effort, regulations, or market pressure. Using a difference-in-differences or matched longitudinal design, researchers may compare adopters of digital transformation with similar companies that have not yet adopted it. This approach would yield more valid results than retrospective assessments of perceived performance.

Researchers should also analyse the life-cycle effects of digital technologies used by firms. Increased emissions, increased electricity use for cloud computing, shorter machinery lifespans, and disposal challenges may offset any operational gains from digitalisation. Analysis of procurement records, energy use, maintenance, and end-of-life data will help to detect rebound and burden-shifting effects. This kind of research should differentiate between firm-level benefits and environmental advantages gained by shifting impacts outside the firm, such as outsourcing to suppliers and data service providers.

Comparisons between sectors should include industry-specific functional units to avoid misinterpreting gains resulting from changes in product mix, outsourcing production, or reduced

production volume during the observation period.

Longitudinal case studies would help understand the development of capabilities. Comparative research should test the hypothesis that the stimulating role of regulations for innovation versus symbolic compliance depends on different enforcement mechanisms. Digital inclusion in supplier networks and the shifting of costs to smaller suppliers should also be examined.

Industry-specific analysis is inevitable, as impacts and technological options vary widely across sectors. The same sustainability metrics cannot assess energy-intensive production, food processing, electronics assembly, and textile manufacturing. Future research should start with material impact assessment and compare common capability mechanisms. Circular practices such as repair, refurbishment, remanufacturing, and product-life extension entail different digital requirements than traditional efficiency programs. They rely more on the product's history, reverse logistics information, the condition of the components, and the customer's involvement.

Conclusion

The digital transformation could lead to sustainable performance, but it requires more than just technology. Green innovation capacity turns information, connectivity, and collaboration into changes in products, processes, and management activities. The role of regulation and senior management commitment will decide the seriousness and sustainability of these changes. In addition, green digital transformation needs to consider energy use in the digital space, e-waste, cybersecurity, job design, and the rebound effect.

Declarations

Ethical Considerations and Declarations

This study was reviewed and approved by the Research Committee of the NUST Business School (NBS). This study was conducted in

accordance with the ethical standards of the approving institution.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation and revision of this manuscript, the authors used ChatGPT and Paperpal to support language editing, grammatical correction, and improvements in clarity and readability. These tools were not used to generate or modify research data, conduct statistical analyses, fabricate references, or make substantive research decisions. The authors critically reviewed and verified all AI-assisted content and accept full responsibility for the accuracy, originality, and integrity of the published work.

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