Localising digital manufacturing in Sub-Saharan Africa: challenges and strategic pathways for industrial competitiveness

MEZGEBE, Tsegay Tesfay, GEBRESLASSIE, Mulualem Gebregiorgis <http://orcid.org/0000-0002-5509-5866> and MITTAL, Vikas

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Localising digital manufacturing in Sub-Saharan Africa: challenges and strategic pathways for industrial competitiveness

Tsegay Tesfay Mezgebe[1*], Mulualem G. Gebreslassie[2] and Vikas Mittal[3]

*Correspondence:
Tsegay Tesfay Mezgebe
tsegay.tesfay@mu.edu.et
[1]Manufacturing Engineering Chair, Ethiopian Institute of Technology-Mekelle, Mekelle University, Main Campus, P.O. Box 231, Mekelle, Ethiopia
[2]Materials and Engineering Research Institute, Sheffield Hallam University, Howard St, Sheffield S1 1WB, UK
[3]Department of Electronics and Communication Engineering, Chandigarh University, Mohali, Punjab 140413, India

Abstract
Globally, manufacturers are under increasing pressure to line up their products and processes with the evolving market demand. This underscores the importance of embracing nascent manufacturing technologies, with digitalisation being a critical enabler for productivity and competitiveness. However, many low-income countries in the Sub-Saharan Africa region are lagging behind; limiting them from enhancing their productivity and competitiveness. This paper is therefore organized to examine manufacturing digitalisation localising pathways supported with implementation digitalisation index. A thematic survey-based SWOT analysis and TOWS matrix, identifying transformative areas of action, and synthesising various digitalisation variables have substantiated the evolved digitalisation index. It also offers key challenges that need attention during the localisation while defining strategies and policy approaches including perceiving knowledge towards digital transformation, describing benefits from digital success stories, focusing on localised innovation ecosystem, and enriching the process of digital transformation through capacity building. The study then synthesised findings, solely sourced from secondary data, to verify the long-term resilience and benefits of localising the manufacturing digitalisation. The cutting-edge implication of the study in the cased region is finally shown in fostering cross-organisational synergy of the manufacturing industry through boosted productivity, enhanced competitiveness, enriched value addition, and through focused sustainability ecosystem.

Highlights

- Manufacturers are under increasing pressure to adapt their products and processes to meet the evolving market demands.
- Manufacturing digitalisation is key enabler for innovation, productivity, and competitiveness of manufacturing industries.
- It is substantial for Sub-Saharan Africa stakeholders to localise digital technologies in their manufacturing industry.

Keywords Digitalisation index, Enabling pathways, Manufacturing industry, Productivity, Competitiveness, Sub-Saharan Africa

1 Introduction

Prior to the COVID-19 pandemic, several economies in the Sub-Saharan Africa (SSA) have experienced their fastest growth since independence [1]. The manufacturing sector has been emerged as one of the key drivers, contributing approximately 13% to the region's gross domestic product [2]. It has increasingly forged connections with the global economy [3] capitalising on opportunities such as the African Growth and Opportunity Act [4] and the African Continental Free Trade Area [5]. Africa's youthful population [6] on the other hand has been offering significant potential for catalysing changes and innovations in the continent [7].

Despite those capabilities, the sector has not yet been transformed in localising digital technologies in SSA in general in Central, East, and West Africa in particular. Significant number of countries in the region still lack holistic manufacturing digitalisation policies. It is in its infancy of development and has yet to align with Industry 4.0 standardized manufacturing in order to convey substantial economic impact in the region [8–10]. Several challenges [11–13] could be listed including:

1. Lack of cohesion, cooperation, and harmonisation among regional digitalisation actors. There are problems of formulating regional digital strategies and delivering the strategies on the ground through specific intervention guidelines,
2. Insufficient supervisory capacity to identify and mitigate risks exacerbated by digital technologies. High levels of digital literacy and knowledge gap to mitigate risks raising from the digitalisation such as cyberattacks, fraud, and excessive debt which are yet again hindering the manufacturing industry's ability to embrace innovation and emerging technologies,
3. A growing divide between those who can afford the latest technologies and those who cannot. This could be either because of governments' policy for the localisation or because of economic weakness of nations to implement the localisation,
4. Feeble monitoring and evaluating digital strategy implementation.

On the other hand, the economic potential of digital manufacturing is becoming increasingly evident both in terms of industrial development and the broader business environment [14, 15]. The COVID-19 pandemic has further underscored the urgency for adapting digitalised manufacturing processes in the SSA [16]. This implies, the existing competitive market is urging manufacturers in the region to integrate digital manufacturing into their production systems [17]. It is subsequently critical for manufacturers, policy makers, digital technology regulators, academics, and other responsible entities across Africa to strategically collaborate for localising the digital technologies in their manufacturing industry. The collaboration strategies and policies [18–20] that stimulate the localisation include but not limited to knowledge towards digital transformation; good communication and description of benefits from digital success stories; innovative agreements with research centres and innovation agencies; and long-term digital transformation. The responsible entities meanwhile have to define a regulatory framework constructed with virtual safety, data setting, data availability, etc. For this purpose, the different topics of regulation [21] (including localising digital technologies to foster circular economy, establishing e-government for promoting optimization, digitization and modernization of public administration and judiciary experienced in the high-income countries), have to be counterfeit into the African manufacturing ground.

This paper is therefore organized to provide policymakers, government officials, and manufacturers—in the Sub-Saharan Africa particularly in Central, East, and West Africa—with strategies for transitioning their manufacturing sectors towards digitalised production processes. A digitalisation index is framed to show 'enhanced collaboration across stakeholders can foster manufacturing digitization in the region'. The ultimate goal is promoting and ensuring sustainable industrial growth, integrating more effectively with high-income economies, and advancing the continent's Sustainable Development Goals.

2 Review of literature

Manufacturing is a continuously evolving process, from concept development to use of complex methods and tools [22]. One of the key advancements in this evolution is an IT supported manufacturing digitalisation, which has particularly become integral to economic activities in the high-income countries. The evolution involved embedding computer technologies into business processes, and making digitalisation essential for modern manufacturing [23]. As a result, manufacturing digitalisation, often described as part of the Industry 4.0 movement, is playing a significant role in enhancing the artefacts of the manufacturing industry by integrating digital technologies into their manufacturing processes [24]. Plenty of studies have verified its substantial benefits in the high-income countries. Manufacturing costs, production downtime, product design and development cycles, energy conservation, integrating manufacturing components, etc. are among the parameters considered for the benefit verifications.

[25, 26] for instance have validated its promising solution for integrating systems, machines, sensors, employees, and end-users in a manufacturing system. [27] have likewise highlighted that manufacturing digitalisation is potential in reducing manufacturing costs and downtime while [28] showed it can improve energy by achieving optimal energy usage and reducing industrial air pollution. [29] additionally have found that digitalisation lowers production costs in automobile manufacturing. [30] on the other hand have emphasized how digitalisation reduces production downtime and maintenance time, noticing the importance of integrating digital technologies with Total Productive Maintenance for creating effective maintenance pathways and smart manufacturing.

Manufacturing digitalisation is also recognised as product quality enhancing framework [31]. In this manner, [32] have demonstrated 'integrating sensor technologies and digital models significantly improves product quality while also reducing production costs in steel plants by combining quality assurance with production planning and control systems'. Advancements in information and communication technologies [33], the Industrial Internet of Things (IIoT) [34], computational power [35], smart manufacturing [36], and virtual manufacturing systems [37] are some of the key digital technologies accelerating the product quality enhanced benefits.

Besides, the advancement of digital technologies has been crucial in accelerating product development cycles and enabling swift responses to production and product delivery demands. The IIoT is an example of such a transformative technology. Its applications include Radio Frequency Identification [38], Wireless Sensor Networks [39], big data analytics [40], virtual manufacturing [41], and smart sensors [42]. These technologies are considered vital enablers for smart manufacturing, allowing manufacturers to optimise production processes through real-time data. [41] have for instance acknowledged the impact of virtual manufacturing noticing its potential for optimising production through real-time data. Additive manufacturing has furthermore introduced new technologies that have stimulated the development of novel materials, influenced product design, and enabled applications such as bio manufacturing [43].

Table 1 is likewise framed to illustrate additional emerging technologies, theoretical concepts, and their implementation techniques in the effective deployment of manufacturing digitalisation. The theoretical concepts, that integrate technology adoption, innovation system, and digitalisation localisation model, are detailed to highlight 'digitalising manufacturing industry holds transformative and real-time influence for boosting productivity and enhancing competitiveness'. The concepts additionally show that manufacturing digitalisation is a strategic move to stay efficient and resilient in the fast-moving global market.

To sum up, the above-listed studies substantiate the wider benefit rage of digitalised manufacturing in the high-income countries. The triangulated benefit variables for example have a positive relationship to each other to witness implementing digitalised manufacturing is exponentially imperative. However, there are barriers preventing manufacturers from adapting it and that need attention during its implementation everywhere. Some of the barriers include integration complexity, process challenges, workforce adaptation, interoperability challenges, leadership challenges (fear for data loss control, fear for transparency), environmental challenges (lack of standard, lack of regulatory laws), etc. [44, 45]. Addressing these hurdles then demands robust investment in skills development, collaborative policy frame-working, and standardising protocols to ensure the seamless adaptation.

Table 1 Characterization of state-of-the-art manufacturing digitalisation technologies and key theoretical concepts

Technologies	Enabling pathways	Implementation techniques	Functionality aspects	Applicability examples	Prior works
ICT	Institutional policy	Vertical, horizontal, and end-to-end integrations	ICT positively associates with firm's productivity	Electrical and Electronic Goods Manufacturing SMEs in Tunisia	[46–48]
IIoT	Wireless networks, smart sensors, big data analytics	Customization, intelligent monitoring	Cost effective in smart manufacturing	Siemens' electronics manufacturing plant in Amberg, Germany	[34, 49]
Cloud Computing	Web Services, Virtualizations	Artificial Neural Network	Reduces initial investment costs and maintenance works	Netsuite, Microsoft, Amazon	[50, 51]
Cloud Manufacturing	Automation, flexibility	Collaboration, innovation	Sustainable process manufacturing route	Quirky development process	[52, 53]
Digital Twin	Visualization, interfacing, simulation	Product-centric Control Method	Adaptability	The Royal Canadian Air Force (RCAF)	[54–56]
Smart Manufacturing	Sensors, actuators, multi-agent systems	Tracking, tracing, predictive analytics, big data	Cost-effective manufacturing resources	The Intelligent Manufacturing Systems Group affiliated with IFAC committee	[57–59]
Virtual Manufacturing	Collaborative robots, human–machine interfaces	Simulation, interfacing, virtual-real interactions	Operation-ability	Thumb tool for BMW	[41, 60]
Sustainable Manufacturing	Industry 4.0, Augmentation, big data	Value networks, industrial ecosystem	Influences all organizational aspects of human life	Ministry of Enterprize and Innovation in Sweden	[61–63]

2.1 Contextual survey on digitalisation of manufacturing in the SSA

Digitalisation has already made a considerable impact across various other development and administrative sectors in Africa. Small business supply chains [64], urban development addressing climate change [65], sustainable agri-food systems [66], digital marketing and tourism [67], and e-governance [68] to list some applicability impacts. These case studies illustrate the prevalent success and practicality of digitalisation in the service industry though the manufacturing digitalisation yet remains relatively immature. This comparative fact is relative to the development pattern of manufacturing industry in the Sub-Saharan Africa which dates back to the 1980s [69]. Since then, it has played a significant role in generating jobs, particularly for the less-educated workforce. However, despite its emergence, the sector has not advanced to higher levels of technology adaptation and subsequently to productivity performance [17]. The growth patterns of the industry, when viewed from the perspective of comparative development trends such as digitalisation, have been notably inconsistent [1].

Yet, there are a few achievements in digitalising manufacturing processes with variety among the different regions in the continent. Research by [70] for instance highlighted the positive impact of digital technologies on innovation in South Africa, showing that these technologies have increased labour productivity in small manufacturing enterprises. [71] have meanwhile emphasized the role of digital technologies for improving the performance of manufacturing firms, particularly in South Africa. [72] have also framed the use of intelligent manufacturing systems to address the challenges posed by the COVID-19 pandemic. Additionally, [73] have laid the groundwork for digital strategies and conducted a comparative analysis of advancements in digital transformation within the manufacturing sector, focusing on South Africa.

Despite these insights, the interaction between digitalisation localisation framework and technology acceptance model remains underexplored. Many low-income countries in SSA region are still lagging behind the digitalised manufacturing process [74]. Countries in East Africa, Central Africa, and West Africa are among the countries facing challenges and slowly progressing in localising the industry 4.0 standardised digitalisation framework. This slow progress may be due to lack of deep exploration of challenges that are hindering the localisation and lack of multiple scientific studies that prioritize digital manufacturing localisation models. This localisation of digital manufacturing technologies in the SSA region is therefore organized to intersect with a range of theoretical digitalisation localisation models such as shown in Fig. 1. This is due to the fact that localising manufacturing digitalisation requires enthusiastic understanding of regional contexts, and understanding of technological adoption, development, and innovation grounded in socio-technical and institutional baselines in the region.

3 Methods

The paper involved reviewing thematic materials and discussions to create a digitalisation index, which outlines pathways for digital action, policy needs, and collaborative approaches to enhance the digitalisation efforts. Four key methodological components are employed for this purpose as shown in the Scientific Procedures and Rationales for Systematic Literature Review (SPAR-4-SLR) protocol presented in Fig. 2 and narrated in the upcoming sub sections.

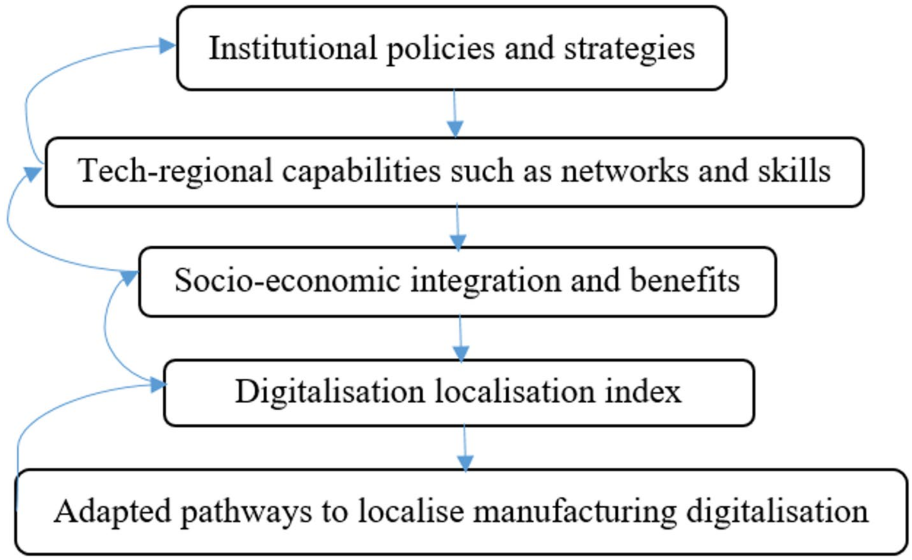

Fig. 1 Digitalisation localisation model

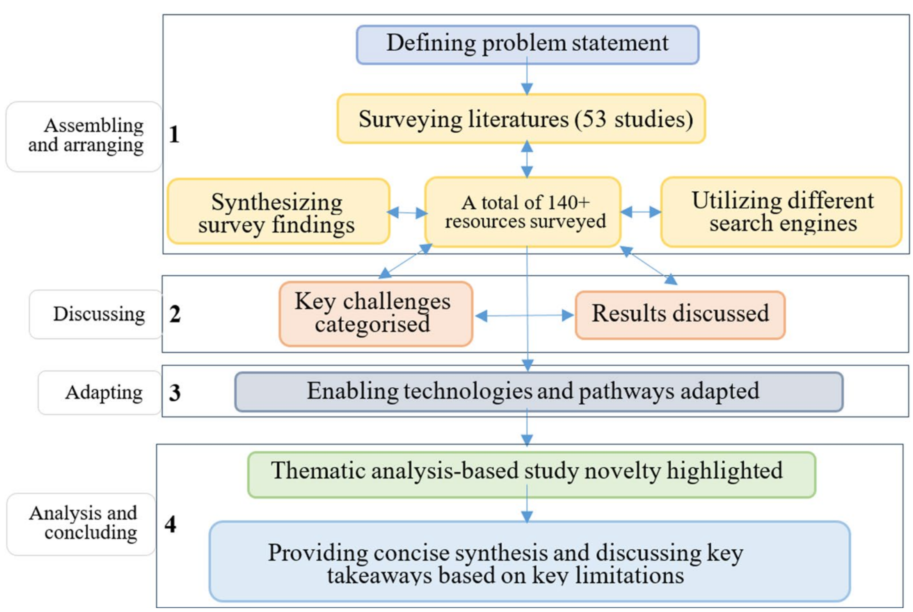

Fig. 2 (SPAR-4-SLR) protocol

3.1 Identification and acquisition of materials

The primary component involved systematically assembling and arranging relevant materials to assess the impact of digitalised manufacturing both in the high-income regions and the SSA region. For this purpose, 68 previously published studies and titles were retrieved though 53 qualitative studies (which include peer-reviewed journal articles, conference papers, books, and online reports) have been finally identified and selected by excluding ~ 22% from the total retrieved.

3.2 Purification and organization

Methodology change, non-peer-reviewed sources, repetitive review, and suggestions from other stakeholders such as academic partners were the purifying approaches while databases such as Google Scholar, Science Direct, SCOPUS, Research Gate, etc. have been utilised to trace and organize the identified resources within a search period between February 2024 and April 2025. Digital manufacturing, technology localisation, manufacturing competitiveness and productivity enhancement, technological adoption challenges, infrastructure development, and digital skills development remained among the specific search keywords in these databases. The solely secondary data sourced review findings were then synthesised in order to validate data from the existing theoretical base by using state-of-the-art digital technologies and implementation techniques as key criteria.

3.3 Comparative assessment

The subsequent task has focused on assessing the current state of manufacturing digitalisation using SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) and TOWS matrix (Threats, Opportunities, Weaknesses, and Strengths) to substantiate the evolved manufacturing digitalisation and to explore implementation challenges by triangulating all the SWOT factors. TOWS is selected over PESTEL because it does not fully concentrate on external factors that PESTEL (Political, Economic, Social, Technological, Legal, and Environmental) do [75].

3.4 Benchmarking and reporting

Benchmarked digital documents, analysis, and presentations were adapted as existing artefacts to apply the digital localisation within context of manufacturing industry in the region. To support the adaptation, a framed manufacturing digitalisation index was developed by identifying transformative areas of action and synthesizing various digitalisation variables. Policy perspectives and recursive collaboration framework then methodologically framed to verify its practicability. Finally, the results were thematically analysed to report the novelty of the study by triangulating various digitalisation trends, tendencies, and implications and to present some limitations for takeaways.

4 Results and discussion

In the first two sections, important topics, research gaps, and emerging trends of digital localisation were studied in a systematic and qualitative ways. This section is organized to objectively report findings and to interpret and explain them why they matter. Policies and implication analysis then followed to ensure the applicability of the proposition.

4.1 The TOWS analysis

Studies such as [76] have verified that it is beneficial for manufacturing industries, which are transforming from legacy business models to adapting digital strategies, to analyze Threats, Opportunities, Weaknesses, and Strengths of emerging technologies in their production systems. Two strategic analyzing procedures namely the SWOT [77] and the TOWS [78] are most commonly in use to identify and examine internal factors (strengths, weaknesses) and external factors (opportunities, threats) and consequently to develop strategic options by matching the internal and external factors respectively. This is due to the fact that both metrics are being considered as elements of strategic application management in manufacturing companies [79]. In line with this, an extensive and thematic survey-based SWOT analysis and TOWS interaction matrix are discussed

Table 2 Strengthening (S_{i-n}) factors for localising the digital manufacturing

Strengths		Descriptions
S_1	Increased efficiency	Digital transformation enables manufacturers to streamline production processes, resulting in increased operational efficiency and reduced production lead times, lowered costs, etc. [80, 81]
S_2	Data-driven decision-making	This supports improved accuracy, faster insights, predictive capabilities, and cost reductions [82, 83]. It also increases quality of manufacturing companies
S_3	Increased agility	Cloud computing, information technology, and the IIoT has led to streamlining of companies' operational performances through faster processing of big data and exchange of information in real-time across their production supply chain [84–86]
S_4	Quality assurance	Studies such as [87, 88] have validated that smart manufacturing pulls inspection and digital quality assurance processes
S_5	Customization	The existing digital channels of manufacturers involves offering personalized products, services, and experiences and gathering feedback and insights to drive product innovation [70–80, 89]
S_6	Continuous improvement	Digitalisation improves process stability whilst increasing employees' competencies at the same time [90, 91]. This is realized by integrating continuous improvement strategies with the framework of digital manufacturing

Table 3 Weaknesses (W_{i-n}) that need to be considered while digital localisation

Weaknesses		Descriptions
W_1	Dependence on technology	This could be problematic when something fails down during production operation such as power outage
W_2	Struggle for flexibility	This could, for example, be adaptability problem to time-oriented dynamism of customer demands
W_3	Potential for cybersecurity	When digitalisation is in action, unless it is fully protected, it has high vulnerability to malware and other security threats

in this sub-section to substantiate the evolved manufacturing digitalisation index in sub-Sect. 0.

4.1.1 The SWOT analysis

As highlighted earlier, manufacturing digitalisation localisation is a strategic integration of digital technologies with localised production processes and operations aimed to improve local reactivity. This digitalisation framework then has its own strengths and weaknesses as offered in the imminent tables (Tables 2, 3, 4).

Opportunity factors: are detailed in Table 5.

4.1.2 The TOWS interaction matrix

An action is now required to come up with fruitful ideas of how to best use information based on the SWOT factors identified. A TOWS interaction matrix, shown in Table 6, is hence developed here to triangulate the four strategic options (SO, ST, WO, WT) of the localisation. The goal is to promote and create an optimal localisation scenario, and to develop strategic options by navigating the strengths, removing the weaknesses, taking advantages of the opportunities, and by reducing the threats.

4.1.3 Findings of the SWOT analysis and the TOWS interaction matrix

From using the SWOT analysis and TOWS interaction matrix on the localisation of manufacturing digitalisation process, it was found that the process is a socio-economic transformation requiring strong strategic collaboration and workforce evaluation and addressing the different threats including skill gaps, barriers, and security issues. It was also found that the TOWS matrix helps to go beyond actionable strategies by prioritizing

Table 4 Threatening ($T_{i\text{-}n}$) factors to localise the digital manufacturing

Threats		Descriptions
T_1	Unemployment [92]	Digitalisation carries a high risk of workforce displacement, either through unemployment or through the relocation of employees' roles. The threat lies in addressing employees' reluctance to acquire new digital skills and preparing them mentally for the impending transformation. This issue represents a significant hurdle in the region's manufacturing sector [93]
T_2	Digital Literacy [74, 94]	A substantial knowledge gap in the region, where high levels of digital literacy is available, hinders the industry's ability to embrace innovation and implement emerging technologies [94]
T_3	Insufficient Scholarly Engagements [95]	The lack of robust academics and research and development institutions, coupled with challenges in fostering innovation and technology development [96], exacerbates the slow adaptation of digital technologies
T_4	E-Services including E-Governance [97]	Effective manufacturing digitalisation necessitates strong ICT and transparent governance [98]. However, both remain in their infancy across much of the SSA, hindering ability to fully support digitalisation efforts
T_5	Financial Constraints [94, 99]	The high costs associated with implementing advanced technologies is limiting their adaptation in many low-income countries. Without adequate financial support, scientific innovations and prototypes are at risk of stagnation
T_6	Privacy and Security Concerns [100]	The increasing generation of data, coupled with the evolution of new technologies within business environments, raises significant privacy and security risks. These concerns might then pose [101] localisation in the region
T_7	Policy constraints [102]	Most of the time, policies on emerging technologies demand financial support, political commitment, academic engagement, data privacy safeguarding, etc. These variables might therefore be difficult to easily access in emerging economies

the WT strategies for de-risking the transformation. The actionable strategies and policies should therefore be efficiently shaped while mitigating the potential threats for enhancing the regional manufacturing industry's resilience.

4.2 Africa led enabling pathways to localise digital manufacturing technologies

The TOWS analysis in sub-Sect. 4.1 validates that though it has its own implementation threats and weakness, digital manufacturing mostly wires its strength for transformative changes of latecomer economies [115]. It involves choosing digital technologies, evaluating them, implementing local policies, and carrying out structural reforms. By examining the current level of manufacturing digitalisation in the SSA, a framed digitalisation index is developed in this paper, Fig. 3. The key drivers for localising the digitalisation are presented in Fig. 3(a), while the need for Industry 4.0 to penetrate all factory operations to ensure automation of processes in Fig. 3(b). To ensure the implement-ability of the index, identifying digitalisation index variables, proposing policy perspectives, and framing a recursive collaboration approach were necessary. Ultimately, by measuring the level of digital adaptation and integration in its environment or system, the goal is to digitally transform the manufacturing industry in the region.c

4.2.1 Variables and areas of action to develop the manufacturing digitalisation index

To measure the level of adapting the manufacturing digitalisation and integration in the digitalisation environment, technology, processes and management practices, and employee qualification are identified as decisive and complementary variables as shown in Fig. 4. [118–120] are cited to define those variables. Three of the variables are made to have their own parameters complementary to each other such that one has relative impact on the value of the other.

Table 5 Opportunity ($O_{i\text{-}n}$) factors to localise digital manufacturing technologies

Opportunities		**Descriptions**
O_1	Assertive space to install inclusive ICT	The SSA has increasingly positioned itself as a key beneficiary in establishing inclusive and sustainable ICT [103]. This effort aims to bridge the digital divide with high-income countries globally [94]. The convergence of wireless applications offers promising opportunities for consolidating ICT-enabled solutions in resource-constrained African countries [104]
O_2	Established Continental Coordination Framework	There is a need of international recognition to enhance the effectiveness of law-making bodies and regulatory agencies through capacity-building initiatives aimed at digital transformation [12]. There is meanwhile a potential for regional harmonization to facilitate trade and the identification and verification of digital transactions
O_3	Increased Digital Momentum in Africa	"The Digital Economy for Africa Initiative" [105], launched in 2018, is one of the significant drivers of digital momentum. The initiative aims to ensure that by 2030, every individual, business, and government in Africa will be digitally enabled, supporting the African Union's "Digital Transformation Strategy for Africa (2020–2030)" [12]. It is organized to achieve objectives such as harnessing digital technologies and innovation to transform African societies and economies; promoting integration across the continent; generating inclusive economic growth; bridging a digital divide; etc
O_4	Industry 4.0 Deployed Smart Manufacturing Framework	Both SSA and the global manufacturing sector must transition from traditional control systems to more agile systems [106]. Industry 4.0 [13] provides a smart manufacturing framework crucial for organizing an entire manufacturing value chain. The Sub-Saharan African community should therefore leverage these opportunities without the need for benefit validation
O_5	Availability of Digitally Leading Countries in Africa	Several countries within the SSA have made significant strides in the digital economy. South Africa, in particular, stands out as a leader in digital manufacturing [107, 108]. Low-income countries in SSA should henceforth collaborate with these more digitally advanced nations to ensure the effective digitalisation of manufacturing across the region
O_6	Availability of Regional Economic Communities (RECs)	The Common Market for Eastern and Southern Africa [109], the Economic Community of West African States [110], and the Intergovernmental Authority on Development in Eastern Africa [111] to mention some. These RECs, in partnership with international stakeholders, play a vital role in the socio-economic development of low-income countries and have a unique opportunity to facilitate cross-border digital transformation. They also significantly contribute to bridging the digital divide [94] between high-income countries and African nations, as well as among member states
O_7	Capacity for Renewable Power Generation	Digitalised manufacturing requires a stable and sufficient power supply [112]. SSA, particularly low-income countries in the region, has significant potential for renewable energy generation, especially hydro-power [113]. The Nile River basin, spanning 11 countries in the region and serving over 238 million people [114], represents a major opportunity for powering digital manufacturing and facilitating their localisation within the region

Table 6 TOWS factors interaction matrix (adapted from [78]); where $i = 1$ up to n is the number of SWOT factors

TOWS		**Internal factors**	
		Strengths ($S_{i\text{–}n}$)	**Weaknesses ($W_{i\text{-}n}$)**
External factors	Opportunities ($O_{i\text{-}n}$)	*SO*: Leverage existing strengths to capitalize digital opportunities. E.g., Build strong ICT infrastructure	*WO*: Minimize weaknesses to take advantage of digital opportunities. E.g., Devote in digital skills
	Threats ($T_{i\text{-}n}$)	*ST*: Leverage existing strengths to mitigate digitalisation threats. E.g., Trust in new digital product	*WT*: Address weaknesses to reduce the impact of digitalisation threats. E.g., Ensure robust cybersecurity

The infrastructural technology provides open interfaces for the free scalable use of resources such as machines which enable operating sequences in short set-up times [118]. Similarly, while the reliability guarantees the right data, the adaptability capability adjusts new information for flexibility purpose. Processes and management practices are also identified as necessary variables because tasks are not solvable alone due to complexity [118]. Mapping digitalisation plan, conducting performance review, and

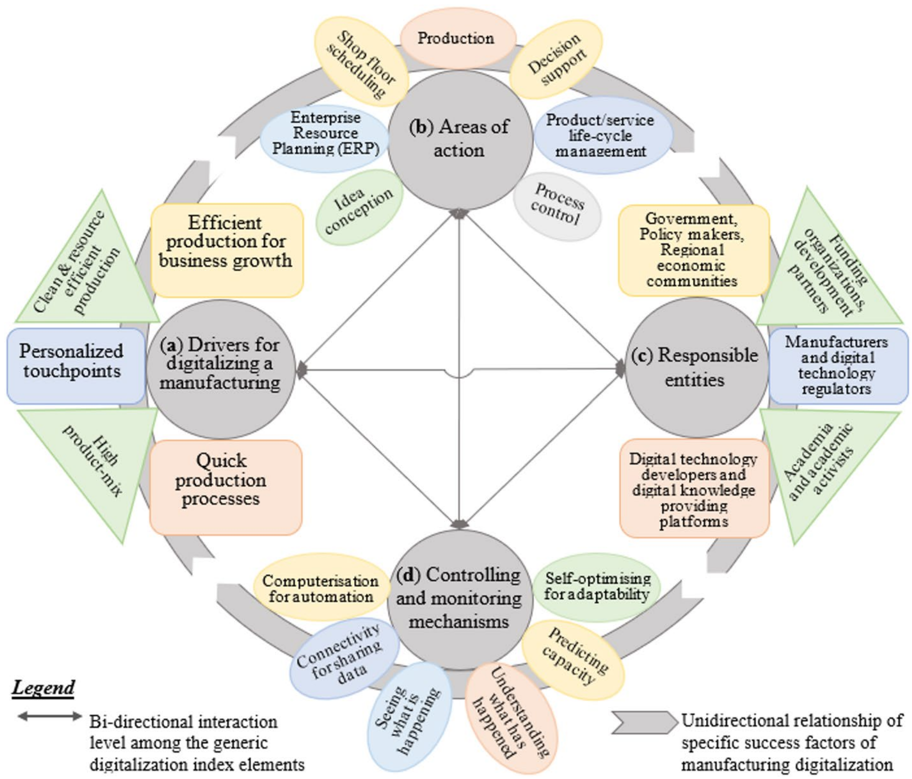

Fig. 3 Manufacturing digitalisation index (adapted from [116, 117])

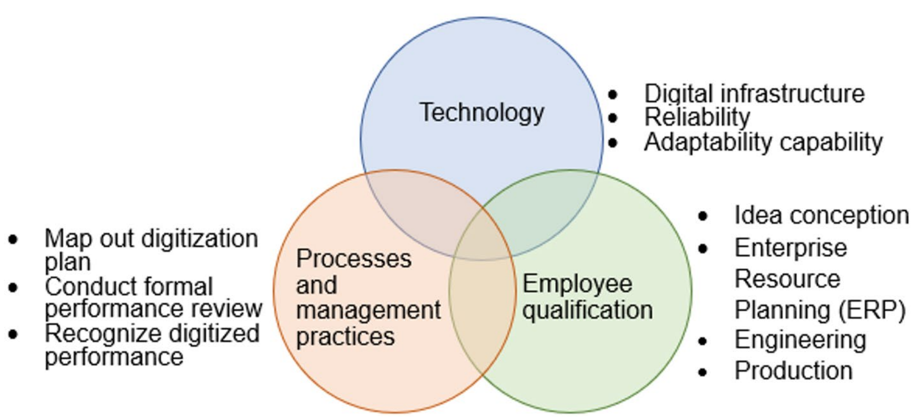

Fig. 4 Complementarity of digitalisation index variables

recognizing best performing could be mentioned among the potential management practices. Collaborative transformation in those processes, capabilities, and offerings within industrial firms and their associated ecosystems progressively creates, delivers, and captures increased service value [121, 122]. This verifies applying process-centric digitalisation of operations in manufacturing companies increases productivity and competitiveness. Workers at all levels of digitizing companies should on the other hand get sufficient skills training compendium. This supports operating new technologies within the framework of organisational innovations [120]. Employees and manufacturing companies need to keep up with new knowledge, on idea conception, ERP, engineering, production, recycling, etc., as changes due to new knowledge intense work [118].

4.2.2 Policy approaches

After identifying the digitalisation drivers and areas of implementation actions, the next step is to establish clear policy approaches and implementation strategies. Well-defined policies can drive economic growth across various sectors. The following ten policies, with their responsible private and public responsible entities in Fig. 3(c), are therefore discussed to fully localise the digital manufacturing in the region defined. They are selected based on the modern industrial policy perspectives of latecomer economies and based on their capability to be customized to nations' policy and political economy in the SSA region. Studies such as [115, 123] have also supported their implications for digital economy and digital industrial policy.

Policy 1—Define manufacturing digitalisation challenges

It focuses on identifying and addressing challenges and/or threats that hinder the envisioned localisation. It serves as a foundation for accelerating the development of digital services. Academia, technology developers, and policymakers are among the key responsible entities to implement this policy.

Policy 2—Develop inclusive digital economy

Developing an inclusive digital economy requires sustained and coordinated efforts from digitalisation stakeholders as a robust digital economy fosters Industry 4.0 oriented culture [124, 125]. National policy frameworks and international agreements must therefore prioritize financial inclusion, innovation, and growth while also protecting people and the environment, ensuring fair competition, and maintaining a sustainable tax base. For this purpose, governments, policymakers, and digital technology regulators have to collaboratively focus on endorsing digital literacy, ensuring impartial digital access, transitioning digital divide, and on fostering a supportive digital business ecosystem.1

Policy 3—Create next-generation scholars and operating models

The African Union has identified human development as one of the core pillars for a digital Africa [12]. Integrating locally available resources with international digital knowledge platforms is a key action. Promoting the training of digital specialists, establishing knowledge hubs, updating curricula to meet evolving digitalisation needs, and providing consultancy services are key aspects of this policy [23]. Governments, policymakers, academia, digital technology developers, and knowledge-providing platforms are among the implementing entities of it.

Policy 4—Invest in digital technology innovations

Stakeholders in the digital sector must invest in the local development of digital technologies to reduce dependency on imported devices and tools. This investment could include expanding telecom networks, promote the local manufacturing of ICT and networking devices, and organize international conferences to introduce digital technologies to manufacturers. For this purpose, governments, development partners, regional economic communities, telecom companies, and manufacturers should work cooperatively.

Policy 5—Tax reduction for digital technology investors

To stimulate an inclusive digital economy, organizations that invest in digital technologies should receive tax reductions. This is because tax reduction incentive policy can promote extent of organization's` digitalisation [126] through implementing financial effect test and through triangulating self-resilience for digitalisation. Governments, policymakers, and digital technology regulators are responsible for executing this policy.

Policy 6—Strengthen intra-Africa collaborations

Developing partnerships focused on the localisation of digital technologies within the intra-Africa alliances can provide governments and policymakers with options to attract private investors, accelerate manufacturing processes, and ensure industrial growth. Governments, policymakers, regional economic communities, development partners, and manufacturers should therefore work together for its implementation.

Policy 7—Implement simultaneous digital readiness assessments

Key assessment variables include scope of the digital strategy [127], customer requirement identification, market competitiveness, employee readiness to adapt digital culture, and the digital maturity of organizations [128]. Academia, policymakers, and digital technology developers should hence engage to evaluate those assessment variables.

Policy 8—Fully utilize different opportunities at hand and leveraged by digital promotors

It is required to avoid and/or minimize shelving of digitization documents and platforms adapted from high-income countries. Digital technology regulators, policy makers, and technology developers in charge of implementing this policy.

Policy 9—Promote control and monitoring

The progress of localising digital technology should regularly be monitored and evaluated by digital economy regulators [129]. This ensures the goals of digital localisation are being met and challenges encountered during the implementation process are addressed effectively, Fig. 3(d). Governments, digital technology regulators, and manufacturers are the responsible entities for this policy.

Policy 10—Ensure sustainability

Digital manufacturing must be safeguarded within the framework of green manufacturing systems [61, 62]. To achieve this, SSA should increase investments in renewable power generation and encourage manufacturers to adapt eco-friendly production systems in their factories. Governments, environmental management authorities, academia, and digital knowledge platforms are the key responsible bodies.

4.2.3 Recursive collaboration framework

As knowledge of new technologies often exists outside the boundaries of industry, it is essential for research institutions and centers of excellence to collaborate on significant projects [130]. The aim is to expand the benefits of digital technologies. A recursive collaboration approach, involving key entities and digital stakeholders as shown in Fig. 5, is consequently contexed in this paper. The goal is to utilize the opportunities and strengths described in Sect. 4.1.1 and efficiently implement the policies outlined.

A recursive collaboration framework is an iterative, feedback-driven approach to collaboration where decision entities—human or artificial—engage in cycles of reflection, adaptation, and refinement [131]. In order to therefore implement the recursive framework in Fig. 5, the collaborating entities are grouped into three clusters (C_s) using a recursive kernel. Recursive kernel is selected because it is a Viable System Model (VSM) to show recursiveness of decision entities that enable real-time monitoring, fault detection, and adaptive control of manufacturing processes [132]. It is employed to demonstrate the structural alignment of the proposition, illustrating the hierarchical relationship of decision-making entities from top to bottom, with that of the governing structure of nations in the region. That is, the recursion process continues inside

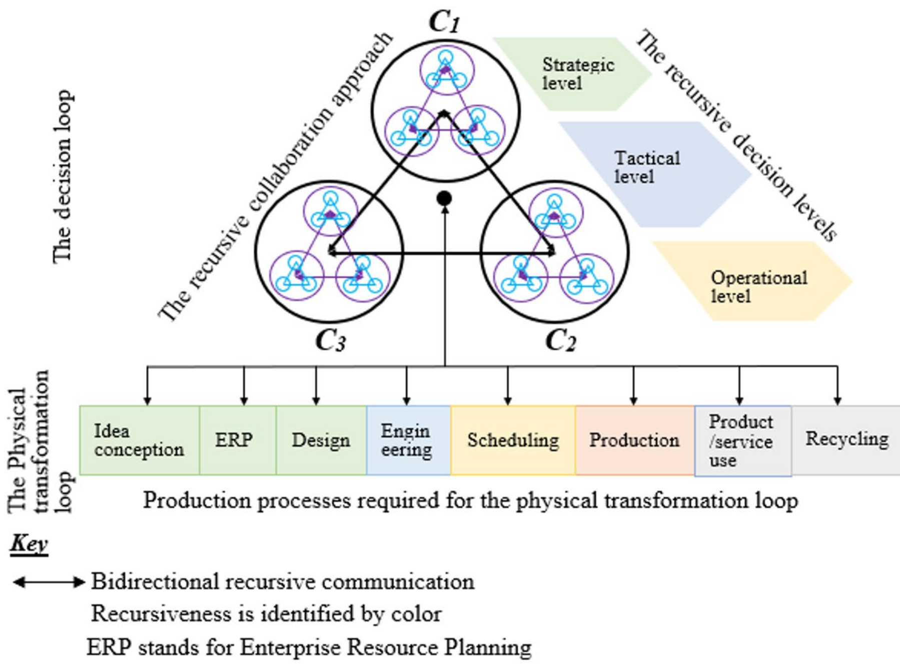

Fig. 5 Recursive collaboration framework

an operating unit, same configuration exists with local management, and all decisional entities decide at their own level by designing iterative processes, fostering open communication, integrate adaptive tools, and by monitoring and reflecting until the required level of detail ends.

1. C_1: Government, policymakers, Regional Economic Communities, digital technology regulators, and environmental management authorities,
2. C_2: Development partners and funding organizations,
3. C_3: Academia, digital technology developers, digital knowledge platforms, telecom companies, and manufacturers.

Members of C_1 are placed at the top of the recursive loop to indicate their responsibility for strategic-level decisions normally aligned with the governance structure (whatever the administrative governance structure is) of nations in the region. They are tasked with defining the purpose, mission, and vision of localising digital manufacturing. Furthermore, they are placed there to determine the technologies to be used for localising digital manufacturing and strategically analyse the return on investment for digitalisation efforts.

Members of C_2 and C_3 in the figure are positioned below C_1 to represent their role in tactical and operational decisions. These clusters are placed parallel to each other, signifying that their contribution is of similar importance. Key collaborative cooperation variables between C_2 and C_3 include:

1. Deciding the starting point of digital transformation,
2. Understanding digital capabilities of the five production *Ms* (machines, man, materials, money, and methods) within a factory,
3. Defining technology partners to systematically demonstrate the business value of the digital manufacturing journey.

The responsible entities, organized into three clusters, must therefore be allocated according to the recursive governmental structure of Sub-Saharan African member states. This ensures a comprehensive, interoperable, scalable, upgradable, functionally, and profitable digital localisation process. On the other hand, the recursive framework is made to incorporate the concept of Cyber-Physical Systems (CPS) in the digital localisation for transformative manufacturing [133]. To effectively localise the digital manufacturing, there must be a strong link between the physical transformation loop and the virtual decision loop. Possible linking variables between the cyber system and the physical transformation system could include production processes such as evolution, design, implementation, evaluation, and ramp-up processes [134].

4.3 Discussing the localisation implications

The paper aims to propose Africa led pathways, policies, and a recursive collaborative approach for digitizing manufacturing in the SSA. The pathway acknowledges digitalisation as a key driver for innovative, inclusive, and sustainable economic growth. This part is consequently organised to show the novelty of the study by analysing the theoretical contributions, economic implications, and sustainability considerations of the proposition.

4.3.1 Theoretical contributions

Our paper contributes to the relevant literature in various ways. Initially, it explores how manufacturing digitalisation can be applied in industries in order to improve organizational performance. Second, this paper sets Africa led digitalisation path ways, areas of action, policy approaches, and collaboration framework for implementing the emerging thematic area. The goal is to offer policymakers, government officials, researchers, and manufacturers strategies for transitioning the manufacturing industry to digital production processes. The authors therefore argue that the findings on digital localisation provides a unique development patterns compared to existing theoretical contributions.

4.3.2 Economic implications

Recent studies, particularly those published after the outbreak of COVID-19 pandemic, show that initiating digital manufacturing is becoming one of the solutions for a resilient future [135]. [136] for instance confirm that the effective adaptation of digital technologies can reduce costs and improve the flexibility of manufacturing systems. [137] have outlined the following four economic benefits of digital manufacturing in production workloads:

1. Higher revenue through faster time-to-market,
2. Lower bill of materials cost,
3. Reduced internal procurement expenses,
4. Lower inventory investment.

Localising digital manufacturing, with a focus on a circular economy, is therefore expected to play a significant role in creating jobs, increasing productivity and competitiveness, driving GDP growth, and in improving society in SSA. The authors believe that implementing policy recommendations based on this approach will accelerate economic development in the region.

4.3.3 Sustainability implications

Current manufacturers are facing growing demands to adapt their products and processes to meet sustainability standards [52]. This involves improving sustainable industrial practices and performance assessment, which are increasingly important in discussions [138]. Smart manufacturing [139], cloud manufacturing [140], and digitalised sustainable manufacturing [141] are among the key focal points, enabling intelligent decision-making to achieve the most sustainable manufacturing processes.

Digital stakeholders in SSA must therefore remain focused on explaining and ensuring the importance of transitioning to digital manufacturing. In promoting policy and sustainability implications, the following factors should be considered:

1. Determining the current competitive market,
2. Identifying customized customer requirements,
3. Assessing the capacity of employees and companies to transition to a digital culture,
4. Evaluating the impact of digitalisation on unemployment.

5 Conclusion and future works

In conclusion, this paper has examined diverse perspectives on manufacturing digitalisation through thematically surveying a range of studies. The purpose is to provide a comprehensive overview of the existing significance of digitalisation and to highlight the way forward for future researchers on gaps that this paper hasn't addressed. The findings consequently reveal a universal consent on three key aspects of the digitalisation. First, it analyses how digitalisation is driving economic transformation in high-income countries by focusing on cutting-edge technologies and implementation methods in manufacturing industry. Cognizant of this, it was known that manufacturing digitalisation fundamentally alters production landscapes through technologies such as IoT, digital twins, AI, etc. These innovations drive unprecedented efficiency, customization, and sustainability of manufacturing industry positioning Industry 4.0 as a cornerstone of modern industrial progress. Next, it has discussed the current level of manufacturing digitalisation within the SSA region, highlighting the challenges it faces using SWOT analysis and TOWS interaction matrix. Adapting a policy-oriented manufacturing digitalisation index that outlines the drivers for digitalisation, key areas of action, responsible parties, and monitoring measures were the third aspect that come into examination with plenty of studies supporting the adaptation. At this level, various technological trends are synthesized by considering technology, processes and management practices, and employee qualification as decisive variables to measure the level of adaptation and to ensure its long-term resilience and benefits. The goal is to play a crucial role in guiding, measuring, and filtering the digitalisation enabling pathways discussed.

The digitalisation index on the other hand was supported with exploring digitization variables, policy approaches, and with recursive collaboration framework to ensure the relevance of the adaptation. Modern industrial policy and strategy perspectives and regulatory frameworks practiced in the high-income economies have been consulted during the exploration. It is because addressing the digitalisation challenges demands robust investment in skills development, collaborative policy frameworks, and standardized protocols to ensure the seamless adaptation. A recursive kernel has also been discussed to show the collaborative cooperation is key to build the SSA people are aspiring to be. By integrating circular economy practices, innovative technologies, and business strategies, the kernel has assured digital manufacturing can be enhanced, and the recycling of waste materials can be effectively promoted in the region. Finally, the paper has analysed the theoretical contribution, economic implications, and sustainability aspects of the policy-oriented proposition.

However, there are notable divergences that this paper has not yet touched particularly focusing on the validation of the proposition in a real industrial setting. Future researchers should therefore address the topic we haven't included, in this study, by exploring the following key takeaways:

1. Government agencies, policymakers, and digital regulators aiming to foster cross-organisational synergies in the industry need create space for open fertilization of ideas on digitization. They need to design impact indicators for the implementation by avoiding and/or minimizing shelving of digitization documents and platforms adapted from the high-income countries. This is for the reason that the future of manufacturing lies in its ability to evolve as a connected, intelligent enterprise, poised to meet global demands while fostering innovation and inclusivity.
2. Revitalizing the region's academic sector to provide need-based training and education on digital manufacturing. This includes establishment of incubation centres and science and technology parks;
3. Empirical testing of the digitalisation index: the use of statistical methods to analyse how well the index reflects the actual level of digitalisation in a manufacturing industry in the SSA and how it relates to other relevant factors. This activity helps to validate the index's usefulness as a measurement tool and provides insights into the drivers and impacts of digitalisation.

These takeaways will not only deepen the knowledge on manufacturing digitalisation but also have potential implications for transforming the manufacturing processes in the region.

5.1 Study limitations

Though this paper provides enabling insights to localize digital manufacturing in the Sub-Saharan Africa, there are some limitations that need to be acknowledged. Fully relying on secondary data rather than employing primarily empirical data, political and socio-economic uncertainties in the region to mention among many other limitations.

Acknowledgements
The authors gratefully acknowledge Mekelle University for providing network and administrative contribution to apprehend this paper. The contribution of authors is also part of the acknowledgement. The first author was engaged to framework the conception, interpretation of relevant data, and to write the substantial sections of the manuscript. The second author was engaged in substantially revising and rewriting of the manuscript for rigourness and coherence purposes. Meanwhile, for the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version of this paper arising from this submission.

Author contributions
First author conceived the study, defined the review scope, led the writing of the original manuscript draft, and developed figures and tables followed by detail narration. The second author has contributed in refining the research framework through revising the discussion and conclusion sections and methodology part. He meanwhile conducted a detailed critical analysis of the reviewed studies. The third author then provided critical revisions and editorial oversight throughout manuscript development

Funding
No specific grant was given to this research by and any funding organization in the public, private, or nonprofit sectors.

Declarations

Ethics and Consent to Participate
Not applicable

Consent to Publish
Not applicable

Competing Interest
Not applicable.

Received: 18 January 2025 / Accepted: 6 November 2025
Published online: 02 December 2025

References

1. Diao, X., Ellis, M., McMillan, M. S., Rodrik, D., 2021. Africa's Manufacturing Puzzle: Evidence from Tanzanian and Ethiopian Firms (No. w28344). *NBER WORKING PAPER SERIES, National Bureau of Economic Research*.
2. Dinh HT, Clarke GR. Performance of manufacturing firms in Africa: an empirical analysis. World Bank Publications; 2012.
3. Mshomba, R. E., 2017. Africa and the global economy. In *Routledge Handbook of African Politics* (pp. 361–374). Routledge.
4. Abebe, R., 2007. Opportunities and Challenges of Development for Africa in the global Arena. In AGOA: The Case of Ethiopian Textile Sub-Sector. *African Economic Conference, Addis Ababa*, Ethiopia
5. African Union., 2019. African Continental Free Trade Area, AfCFTA: Creating One African Market. Retrieved from https://au-afcfta.org (Date accessed: March 2024)
6. Pillay NK, Maharaj P. Population ageing in Africa. In: Aging and health in Africa. Boston: Springer; 2012. p. 11–51.
7. Wagner T, Compton RA. Creating innovators: the making of young people who will change the world. Simon and Schuster; 2012.
8. Metu AG, Madichie CV, Kalu CU, Nzeribe GE. The fourth industrial revolution and employment in Sub-Saharan Africa: the role of education. J Afr Dev. 2020;21(1):116–37. https://doi.org/10.5325/jafrideve.21.1.0116.
9. Maisiri W, van Dyk L, Coeztee R. Factors that inhibit sustainable adoption of Industry 4.0 in the South African manufacturing industry. Sustainability. 2021;13(3):1013. https://doi.org/10.3390/su13031013.
10. Peter O, Pradhan A, Mbohwa C. Industry 4.0 concepts within the sub–Saharan African SME manufacturing sector. Procedia Comput Sci. 2023;217:846–55. https://doi.org/10.1016/j.procs.2022.12.281.
11. Jones MD, Hutcheson S, Camba JD. Past, present, and future barriers to digital transformation in manufacturing: a review. J Manuf Syst. 2021;60:936–48. https://doi.org/10.1016/j.jmsy.2021.03.006.
12. African Union., 2020. The Digital Transformation Strategy for Africa (2020–30). Retrieved from https://au.int. Accessed, February 2024
13. Lasi H, Fettke P, Kemper HG, Feld T, Hoffmann M. Industry 4.0. Bus Inf Syst Eng. 2014;6:239–42. https://doi.org/10.1007/s12599-014-0334-4.
14. Rashid A, Rasheed R, Ngah AH. Achieving sustainability through multifaceted green functions in manufacturing. J Glob Oper Strateg Sourc. 2024;17(2):402–28.
15. Rashid A, Rasheed R, Ngah AH, Amirah NA. Unleashing the power of cloud adoption and artificial intelligence in optimizing resilience and sustainable manufacturing supply chain in the USA. J Manuf Technol Manage. 2024. https://doi.org/10.1108/JMTM-02-2024-0080. (**(ahead-of-print)**).
16. Motau V, Obadire O. Digitalization and Government response to COVID-19 in post-pandemic in Africa. Journal of Sustainable Development Law and Policy (The). 2025;16(1):68–85.
17. Banga, K., te Velde, D. W., 2018. *Digitalisation and the Future of Manufacturing in Africa*. London, UK: ODI.
18. Björkdahl J. Strategies for digitalization in manufacturing firms. Calif Manage Rev. 2020;62(4):17–36.
19. Zangiacomi A, Pessot E, Fornasiero R, Bertetti M, Sacco M. Moving towards digitalization: a multiple case study in manufacturing. Prod Plan Control. 2020;31(2–3):143–57.
20. Teixeira JE, Tavares-Lehmann ATC. Industry 4.0 in the European union: policies and national strategies. Technol Forecast Soc Change. 2022;180:121664.
21. Senna PP, Roca JB, Barros AC. Overcoming barriers to manufacturing digitalization: policies across EU countries. Technol Forecast Soc Change. 2023;196:122822. https://doi.org/10.1016/j.techfore.2023.122822.
22. Esmaeilian B, Behdad S, Wang B. The evolution and future of manufacturing: a review. J Manuf Syst. 2016;39:79–100. https://doi.org/10.1016/j.jmsy.2016.03.001.
23. Tolkachev SA, Bykov AA, Morkovkin DE, Borisov OI, Gavrilin AV. Digitalisation of manufacturing in Russia, Belarus and the European Union. IOP Conferen Ser Earth Environ Sci. 2020;421(3):032041.
24. Herterich, M. M., Buehnen, T., Uebernickel, F., Brenner, W., 2016. A taxonomy of industrial service systems enabled by digital product innovation. In *2016 49th Hawaii International Conference on System Sciences (pp. 1236–1245)*. IEEE.
25. Lievano-Martínez FA, Fernández-Ledesma JD, Burgos D, Branch-Bedoya JW, Jimenez-Builes JA. Intelligent process automation: an application in manufacturing industry. Sustainability. 2022;14(14):8804. https://doi.org/10.3390/su14148804.
26. Rinderle-Ma, S., Mangler, J., 2021. Process automation and process mining in manufacturing. In *International conference on business process management*, 3–14.
27. Qamsane Y, Phillips JR, Savaglio C, Warner D, James SC, Barton K. Open process automation-and digital twin-based performance monitoring of a process manufacturing system. IEEE Access. 2022;10:60823–35. https://doi.org/10.1109/ACCESS.2022.3179982.
28. Shinkevich MV, Vertakova YV, Galimulina FF. Synergy of digitalisation within the framework of increasing energy efficiency in manufacturing industry. Int J Energy Econ Policy. 2020;10(3):456–64. https://doi.org/10.32479/ijeep.9397.
29. Shivajee V, Singh RK, Rastogi S. Manufacturing conversion cost reduction using quality control tools and digitisation of real-time data. J Clean Prod. 2019;237:117678. https://doi.org/10.1016/j.jclepro.2019.117678.

30. Tortorella GL, Saurin TA, Fogliatto FS, Tlapa Mendoza D, Moyano-Fuentes J, Gaiardelli P, et al. Digitalisation of maintenance: exploratory study on the adoption of Industry 4.0 technologies and total productive maintenance practices. Prod Plan Control. 2024;35(4):352–72. https://doi.org/10.1080/09537287.2022.2083996.
31. Chryssolouris G, Mavrikios D, Papakostas N, Mourtzis D, Michalos G, Georgoulias K. Digital manufacturing: history, perspectives, and outlook. Proc Inst Mech Eng B J Eng Manuf. 2009;223(5):451–62. https://doi.org/10.1243/09544054JEM1241.
32. Herzog K, Winter G, Kurka G, Ankermann K, Binder R, Ringhofer M, et al. The digitalisation of steel production. BHM Berg-Huttenmann Monatsh. 2017;162(11):504–13. https://doi.org/10.1007/s00501-017-0673-9.
33. Ilchenko M, Uryvsky L, Globa L. Advances in information and communication technologies: processing and control in information and communication systems, vol. 560. Springer; 2019.
34. Badarinath, R., Prabhu, V. V., 2017. Advances in internet of things (IoT) in manufacturing. In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing: IFIP WG 5.7 International Conference, APMS 2017, Hamburg, Germany, September 3–7, 2017, Proceedings, Part I, Springer International Publishing*, 111–118.
35. Wang J, Kusiak A. Computational intelligence in manufacturing handbook. CRC Press; 2000.
36. Kusiak A. Smart manufacturing. Int J Prod Res. 2018;56(1–2):508–17. https://doi.org/10.1080/00207543.2017.1351644.
37. Iwata K, Onosato M, Teramoto K, Osaki S. A modelling and simulation architecture for virtual manufacturing systems. CIRP Ann. 1995;44(1):399–402. https://doi.org/10.1016/S0007-8506(07)62350-6.
38. Roberts CM. Radio frequency identification (RFID). Comput Secur. 2006;25(1):18–26. https://doi.org/10.1016/j.cose.2005.12.003.
39. Akyildiz IF, Vuran MC. Wireless sensor networks. Wiley; 2010.
40. Rashid A, Baloch N, Rasheed R, Ngah AH. Big data analytics-artificial intelligence and sustainable performance through green supply chain practices in manufacturing firms of a developing country. J Sci Technol Policy Manag. 2025;16(1):42–67.
41. Soori M, Arezoo B, Dastres R. Virtual manufacturing in industry 40: A review. Data Sci Manage. 2023. https://doi.org/10.1016/j.dsm.2023.10.006.
42. Konyha J, Bányai T. Sensor networks for smart manufacturing processes. Solid State Phenom. 2017;261:456–62. https://doi.org/10.4028/www.scientific.net/SSP.261.456.
43. Sala D, Richert M. Perspectives of additive manufacturing in 5.0 industry. Materials. 2025;18(2):429.
44. Bag S, Sahu AK, Kilbourn P, Pisa N, Dhamija P, Sahu AK. Modeling barriers of digital manufacturing in a circular economy for enhancing sustainability. Int J Prod Perform Manag. 2022;71(3):833–69.
45. Vogelsang, K., Liere-Netheler, K., Packmohr, S., Hoppe, U., 2019. *Barriers to digital transformation in manufacturing: development of a research agenda*.
46. Piget P, Kossaï M. The relationship between information and communication technology use and firm performance in developing countries: a case study of electrical and electronic goods manufacturing SME s in Tunisia. Afr Dev Rev. 2013;25(3):330–43. https://doi.org/10.1111/j.1467-8268.2013.12032.x.
47. Wollschlaeger M, Sauter T, Jasperneite J. The future of industrial communication: automation networks in the era of the internet of things and Industry 4.0. IEEE Ind Electron Mag. 2017;11(1):17–27. https://doi.org/10.1109/MIE.2017.2649104.
48. Zhu C, Guo X, Zou S. Impact of information and communications technology alignment on supply chain performance in the industry 4.0 era: mediation effect of supply chain integration. J Ind Prod Eng. 2022;39(7):505–20. https://doi.org/10.1080/21681015.2022.2099472.
49. Khan WZ, Rehman MH, Zangoti HM, Afzal MK, Armi N, Salah K. Industrial internet of things: recent advances, enabling technologies and open challenges. Comput Electr Eng. 2020;81:106522. https://doi.org/10.1016/j.compeleceng.2019.106522.
50. Khorshed MT, Ali AS, Wasimi SA. A survey on gaps, threat remediation challenges and some thoughts for proactive attack detection in cloud computing. Future Gener Comput Syst. 2012;28(6):833–51. https://doi.org/10.1016/j.future.2012.01.006.
51. Ooi KB, Lee VH, Tan GWH, Hew TS, Hew JJ. Cloud computing in manufacturing: the next industrial revolution in Malaysia? Expert Syst Appl. 2018;93:376–94. https://doi.org/10.1016/j.eswa.2017.10.009.
52. Fisher O, Watson N, Porcu L, Bacon D, Rigley M, Gomes RL. Cloud manufacturing as a sustainable process manufacturing route. J Manuf Syst. 2018;47:53–68. https://doi.org/10.1016/j.jmsy.2018.03.005.
53. Wu D, Greer MJ, Rosen DW, Schaefer D. Cloud manufacturing: strategic vision and state-of-the-art. J Manuf Syst. 2013;32(4):564–79. https://doi.org/10.1016/j.jmsy.2013.04.008.
54. Liao M, Renaud G, Bombardier Y. Airframe digital twin technology adaptability assessment and technology demonstration. Eng Fract Mech. 2020;225:106793. https://doi.org/10.1016/j.engfracmech.2019.106793.
55. Lu Y, Liu C, Wang KI-K, Huang H, Xu X. Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues. Robot Comput Integr Manuf. 2020;61:101837. https://doi.org/10.1016/j.rcim.2019.101837.
56. Qi Q, Tao F, Hu T, Anwer N, Liu A, Wei Y, et al. Enabling technologies and tools for digital twin. J Manuf Syst. 2021;58:3–21. https://doi.org/10.1016/j.jmsy.2019.10.001.
57. Barari A, Tsuzuki MSG. Smart Manufacturing and Industry 4.0. Appl Sci. 2023;13(3):1545. https://doi.org/10.3390/app13031545.
58. Estrada-Jimenez, L. A., Pulikottil, T. B., Nikghadam-Hojjati, S., Barata, J., 2023. *Self-organisation in Smart Manufacturing-Background, Systematic Review, Challenges and Outlook*. IEEE Access.
59. Lu Y, Xu X, Wang L. Smart manufacturing process and system automation–a critical review of the standards and envisioned scenarios. J Manuf Syst. 2020;56:312–25. https://doi.org/10.1016/j.jmsy.2020.06.010.
60. Mourtzis D, Angelopoulos J, Panopoulos N. Operator 5.0: a survey on enabling technologies and a framework for digital manufacturing based on extended reality. J Mach Eng. 2022. https://doi.org/10.36897/jme/147160.
61. Chen X, Despeisse M, Johansson B. Environmental sustainability of digitalisation in manufacturing: a review. Sustainability. 2020;12(24):10298. https://doi.org/10.3390/su122410298.
62. Rashid A, Rasheed R, Altay N. Greening manufacturing: the role of institutional pressure and collaboration in operational performance. J Manuf Technol Manage. 2025;36(2):455–78.
63. Machado CG, Winroth MP, da Ribeiro Silva EHD. Sustainable manufacturing in industry 4.0: an emerging research agenda. Int J Prod Res. 2020;58(5):1462–84. https://doi.org/10.1080/00207543.2019.1652777.
64. Mazwane S, Maya O, Makhura MN. Digitalization and small businesses supply chain financing: Evidence from sub-Saharan Africa. Afr J Sci Technol Innov Dev. 2024;16(4):1–11. https://doi.org/10.1080/20421338.2023.2296201.

65. Balogun AL, Adebisi N, Abubakar IR, Dano UL, Tella A. Digitalisation for transformative urbanisation, climate change adaptation, and sustainable farming in Africa: trend, opportunities, and challenges. J Integr Environ Sci. 2022;19(1):17–37. https://doi.org/10.1080/1943815X.2022.2033791.
66. Bahn RA, Yehya AAK, Zurayk R. Digitalisation for sustainable agri-food systems: potential, status, and risks for the MENA region. Sustainability. 2021;13(6):3223. https://doi.org/10.3390/su13063223.
67. Mkwizu KH. Digital marketing and tourism: opportunities for Africa. Int Hosp Rev. 2019;34(1):5–12. https://doi.org/10.1108/IHR-09-2019-0015.
68. Froehlich, A., Ringas, N., Wilson, J., 2020. E-Governance in Africa and the World. *Space Supporting Africa: Volume 3: Security, Peace, and Development through Efficient Governance Supported by Space Applications*, 53–124. https://doi.org/10.1007/978-3-030-52260-5_2
69. Signé, L., 2018. *The potential of manufacturing and industrialization in Africa: Trends, opportunities, and strategies. Africa Growth Initiative*
70. Gaglio C, Kraemer-Mbula E, Lorenz E. The effects of digital transformation on innovation and productivity: firm-level evidence of South African manufacturing micro and small enterprises. Technol Forecast Soc Change. 2022;182:121785. https://doi.org/10.1016/j.techfore.2022.121785.
71. Avenyo, E. K., Bell, J. F., 2022. Digital Technology Adoption and Performance in South African Manufacturing Firms: Early Evidence for Policy. Retrieved from https://publication.aercafricalibrary.org/items/65942713-555a-41a2-8df2-97e5971f0cdc Aaccessed, May 2024
72. Mezgebe TT, Gebreslassie MG, Sibhato H, Bahta ST. Intelligent manufacturing ecosystem: a post COVID-19 recovery and growth opportunity for manufacturing industry in sub-Saharan countries. Sci Afr. 2023;19:e01547. https://doi.org/10.1016/j.sciaf.2023.e01547.
73. Gaffley, G., Pelser, T. G., 2021a. Digital transformation in the manufacturing sectors of South Africa. In *Proceedings of the 14th International Business Conference (Virtual)*, 20, 21.
74. Wentrup R, Ström P, Nakamura HR. Digital oases and digital deserts in Sub-Saharan Africa. J Sci Technol Policy Manag. 2016;7(1):77–100. https://doi.org/10.1108/JSTPM-03-2015-0013.
75. Bathla, D., Awasthi, S., Ahuja, R., 2022. PESTEL Analysis of the Automotive Industry. In *Applying Metalytics to Measure Customer Experience in the Metaverse* (pp. 143–160). IGI Global.
76. Khalil, A., November 2021. *Digital swot/tows analysis of the automotive industry*. Technical Report
77. Wheelen TL, Hunger JD, Hoffman AN, Bamford CE, Kansal P. Strategic management and business policy: globalization, innovation and sustainability, by Pearson. Pearson Education India; 2002.
78. Mihajlović I, Perišić M, Spasojević Brkić V, Milošević I, Milijić N. Digitalization of strategic decision-making in manufacturing SMEs: a quantitative SWOT-TOWS analysis. Precision Mech Dig Fabric. 2024;1(3):176–88. https://doi.org/10.56578/pmdf010305.
79. Skotnicka-Zasadzień, B., Zasadzień, M., Grebski, W., 2023. Application of TOWS/SWOT Analysis as an Element of Strategic Management on the Example of a Manufacturing Company. *Scientific Papers of Silesian University of Technology. Organization & Management/Zeszyty Naukowe Politechniki Slaskiej. Seria Organizacji i Zarzadzanie*, 189.
80. Cox, M., April 2024. Digital Transformation in Manufacturing: Benefits, Key Challenges, and Solutions. Retrieved from https://blog.kainexus.com/digital-transformation-in-manufacturing (date accessed, March 01, 2025)
81. Dassanayake DRI, Buddhika MK, Maduranga IDK, Seneviratne JA, Kumarage WGC. Revolutionizing manufacturing: the role of robotics in the 21st century. J Desk Res Rev Anal. 2024. https://doi.org/10.4038/jdrra.v2i1.30.
82. Selvarajan G. Leveraging AI-enhanced analytics for industry-specific optimization: a strategic approach to transforming data-driven decision-making. Int J Enhan Res Sci Technol Eng. 2021;10:78–84.
83. Ghasemaghaei M, Ebrahimi S, Hassanein K. Data analytics competency for improving firm decision making performance. J Strateg Inf Syst. 2018;27(1):101–13.
84. Dave DM. Advancing resilience and agility in manufacturing through Industry 5.0: a review of digitization, automation, and advanced analytics. Int J New Technol Res(IJNTR). 2023;9:5–12.
85. Choudhury A, Behl A, Sheorey PA, Pal A. Digital supply chain to unlock new agility: a TISM approach. Benchmarking Int J. 2021;28(6):2075–109.
86. Rashid A, Rasheed R, Amirah NA. Information technology and people involvement in organizational performance through supply chain collaboration. J Sci Technol Policy Manag. 2023. https://doi.org/10.1108/JSTPM-12-2022-0217. (**(ahead-of-print)**).
87. Galindo-Salcedo M, Pertúz-Moreno A, Guzmán-Castillo S, Gómez-Charris Y, Romero-Conrado AR. Smart manufacturing applications for inspection and quality assurance processes. Procedia Comput Sci. 2022;198:536–41.
88. Wojtusik, B. J., 2023. *Digital quality assurance technologies: evaluation and potential use cases* (Doctoral dissertation, Technische Hochschule Ingolstadt).
89. Castro, H., Câmara, F., Câmara, E., Ávila, P., June 2023. Digital Factory for Product Customization: A Proposal for a Decentralized Production System. In *International Conference on Flexible Automation and Intelligent Manufacturing (pp. 879–886)*. Cham: Springer Nature Switzerland.
90. Vinodh S, Antony J, Agrawal R, Douglas JA. Integration of continuous improvement strategies with Industry 4.0: a systematic review and agenda for further research. TQM J. 2021;33(2):441–72.
91. Hambach J, Kümmel K, Metternich J. Development of a digital continuous improvement system for production. Procedia CIRP. 2017;63:330–5.
92. Pradhan, A., Agwa-Ejon, J., 2018. Opportunities and challenges of embracing smart factory in South Africa. In *2018 Portland International Conference on Management of Engineering and Technology (PICMET)*, 1–8
93. Ramshankar, C. S., 2020. How Digital Is Your Manufacturing. Retrieved from https://maxbyte.co/how-digital-is-your-manufacturing/. Accessed, June 2024
94. Mutula SM. Digital divide and economic development: case study of sub-Saharan Africa. Electron Libr. 2008;26(4):468–89. https://doi.org/10.1108/02640470810893738.
95. Langthaler, M., Bazafkan, H., 2020. Digitalisation, education and skills development in the Global South: an assessment of the debate with a focus on Sub-Saharan Africa. *ÖFSE Briefing Paper*, 28. https://doi.org/10.60637/2020-bp28
96. Mwelwa J, Boulton G, Wafula JM, Loucoubar C. Developing open science in Africa: barriers, solutions and opportunities. Data Sci J. 2020;19:31–31. https://doi.org/10.5334/dsj-2020-031.

97. Mutula SM. E-government implementation strategies and best practices: implications for Sub-Saharan Africa. Mousaion. 2012;30(2):5–23.
98. Ndubuisi G, Otioma C, Tetteh GK. Digital infrastructure and employment in services: evidence from Sub-Saharan African countries. Telecomm Policy. 2021;45(8):102153. https://doi.org/10.1016/j.telpol.2021.102153.
99. Aker, J., Cariolle, J., 2022. The use of digital for public service provision in sub-Saharan Africa. *FERDI Notes brèves/Policy briefs*, hal-03003899v2
100. Gamundani, A. M., 2023. Unmasking the Potential of Usable Security and Privacy Technologies in Empowering African Digital Landscapes. In *Proceedings of the 4th African Human Computer Interaction Conference (pp. 201–207)*.
101. Díaz A, Guerra L, Díaz E. Digital transformation impact in security and privacy. Dev Adv Defence Secur Proc MICRADS. 2022;2021:61–70.
102. Shao, G., Kibira, D., 2018. Digital manufacturing: Requirements and challenges for implementing digital surrogates. In *2018 Winter Simulation Conference (WSC)* (pp. 1226–1237). IEEE.
103. Gyamerah S, He Z, Gyamerah EED, Asante D, Ahia BNK, Ampaw EM. Implementation of the belt and road initiative in Africa: a firm-level study of sub-saharan African SMEs. J Chin Polit Sci. 2022;27(4):719–45. https://doi.org/10.1007/s11366-021-09749-0.
104. Bwalya KJ, Chris R, Mandla N. Convergence of wireless technologies in consolidating e-government applications in Sub-Saharan Africa. Int J ICT Res Dev Africa (IJICTRDA). 2010;1(4):15–30. https://doi.org/10.4018/978-1-60960-042-6.ch004.
105. World Bank Group., 2019. Digital Economy for Africa Initiative. TICAD Seminar Series. Retrieved from https://www.worldbank.org/en/programs/all-africa-digital-transformation. Accessed, March 2024
106. Sanchez LM, Nagi R. A review of agile manufacturing systems. Int J Prod Res. 2001;39(16):3561–600. https://doi.org/10.1080/00207540110068790.
107. Al-Dahdah, E., Appaya, M. S., Butcher, N., Derner, C., Egejeru, C., Eliasz, T. K., Zanza, A. D., 2020. South Africa-Digital Economy Diagnostic. Retrieved from https://documents.worldbank.org/en/publication/documents-reports/documentdetail/464421589343923215/south-africa-digital-economy-diagnostic (date accessed, February 2024)
108. Gaffley G, Pelser TG. Developing a digital transformation model to enhance the strategy development process for leadership in the South African manufacturing sector. S Afr J Bus Manage. 2021;52(1):12. https://doi.org/10.4102/sajbm.v52i1.2357.
109. Dirar L. Common market for eastern and southern African countries: multiplicity of membership issues and choices. Afr J Int Comp Law. 2010;18(2):217–32. https://doi.org/10.3366/ajicl.2010.0005.
110. Okolo JE. Integrative and cooperative regionalism: the economic community of West African states. Int Organ. 1985;39(1):121–53. https://doi.org/10.1017/S0020818300004884.
111. Magu, S. M., 2023. The Intergovernmental Authority on Development (IGAD). In *Towards Pan-Africanism: Africa's Cooperation through Regional Economic Communities (RECs), Ubuntu and Communitarianism*. 101–123.
112. Zhang Q, Wang Q. Digitalisation, electricity consumption and carbon emissions-evidence from manufacturing industries in China. Int J Environ Res Public Health. 2023;20(5):3938. https://doi.org/10.3390/ijerph20053938.
113. Hathaway, T., Pottinger, L., 2008. The great hydro-rush: The privatisation of Africa's rivers. Electric capitalism: Recolonising Africa on the power grid, 149–79. https://doi.org/10.4324/9781849771061-5/great-hydro-rush-terri-hathaway-lori-pottinger. Accessed, June 2024
114. Melesse AM, Abtew W, Setegn SG. Nile River basin. Cham: Springer; 2011.
115. Foster C, Azmeh S. Latecomer economies and national digital policy: an industrial policy perspective. J Dev Stud. 2020;56(7):1247–62.
116. DEMANDDYNAMICS, 2021. Unlocking the Potential: 5 Ways Digitalisation Can Boost Manufacturing. Retrieved from https://demanddynamics.com/5-ways-your-manufacturing-business-can-benefit-from-digitalisation/. Accessed, July 2024
117. Cámara, N., Tuesta, D., 2017. DiGiX: the digitisation index. *BBVA Bank, Economic Research Department*, 17(03).
118. Vogelsang K, Liere-Netheler K, Packmohr S, Hoppe U. Success factors for fostering a digital transformation in manufacturing companies. J Enterp Transform. 2018;8(1–2):121–42.
119. Baier MS, Lockl J, Röglinger M, Weidlich R. Success factors of process digitalization projects–insights from an exploratory study. Bus Process Manag J. 2022;28(2):325–47. https://doi.org/10.1108/BPMJ-07-2021-0484.
120. Burdín, G., 2022. *Digitalization, productivity and employment: elements to think about vocational training in Latin America*. ILO
121. Rossini M, Ahmadi A, Staudacher AP. Applying a process-centric approach to the digitalization of operations in manufacturing companies: a case study. Procedia Comput Sci. 2024;232:1141–50. https://doi.org/10.1016/j.procs.2024.01.112.
122. Sjödin D, Parida V, Visnjic I. How can large manufacturers digitalize their business models? A framework for orchestrating industrial ecosystems. Calif Manage Rev. 2022;64(3):49–77.
123. Aiginger K, Rodrik D. Rebirth of industrial policy and an agenda for the twenty-first century. J Ind Compet Trade. 2020;20:189–207.
124. Javaid M, Haleem A, Singh RP, Sinha AK. Digital economy to improve the culture of industry 4.0: a study on features, implementation and challenges. Green Technol Sustain. 2024. https://doi.org/10.1016/j.grets.2024.100083.
125. Ch, R. K., 2016. *Stimulating digital innovation for growth and inclusiveness. The role of policies for the successful diffusion of ICT. OECDpublishing*
126. Ding Q, He W, Deng Y. Can tax reduction incentive policy promote corporate digital and intelligent transformation? Int Rev Financ Anal. 2025. https://doi.org/10.1016/j.irfa.2025.103932.
127. Kittelberger, D., Allramseder, L. S., 2019. The digital strategy: The guide to systematic digitisation of the company. *Performance Management in Retail and the Consumer Goods Industry: Best Practices and Case Studies*, 123–136. https://doi.org/10.1007/978-3-030-12730-5_8
128. Aslanova, I. V., Kulichkina, A. I., 2020. Digital maturity: Definition and model. In *2nd International Scientific and Practical Conference "Modern Management Trends and the Digital Economy: from Regional Development to Global Economic Growth" (MTDE 2020) (pp. 443–449)*. Atlantis Press.
129. Beaumier G, Kalomeni K, Campbell-Verduyn M, Lenglet M, Natile S, Papin M, et al. Global regulations for a digital economy: between new and old challenges. Glob Policy. 2020;11(4):515–22. https://doi.org/10.1111/1758-5899.12823.
130. Lorenz R, Benninghaus C, Friedli T, Netland TH. Digitization of manufacturing: the role of external search. Int J Oper Prod Manag. 2020;40(7/8):1129–52. https://doi.org/10.1108/IJOPM-06-2019-0498.

131. Trukovich JJ. From reactions to reflection: a recursive framework for the evolution of cognition and complexity. Biosystems. 2025;250:105408.
132. Beer S. The viable system model: its provenance, development, methodology and pathology. J Oper Res Soc. 1984;35(1):7–25.
133. Lee J, Bagheri B, Kao H-A. A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. Manuf Lett. 2015;3:18–23. https://doi.org/10.1016/j.mfglet.2014.12.001.
134. Leitão P, Colombo AW, Karnouskos S. Industrial automation based on cyber-physical systems technologies: prototype implementations and challenges. Comput Ind. 2016;81:11–25. https://doi.org/10.1016/j.compind.2015.08.004.
135. Camarinha-Matos LM, Rocha AD, Graça P. Collaborative approaches in sustainable and resilient manufacturing. J Intell Manuf. 2024;35(2):499–519. https://doi.org/10.1007/s10845-022-02060-6.
136. Demartini M, Evans S, Tonelli F. Digitalisation technologies for industrial sustainability. Procedia Manuf. 2019;33:264–71. https://doi.org/10.1016/j.promfg.2019.04.032.
137. Evans, D., Timme, S., 2024. The Economic Impact of a Digital Manufacturing Partner for Production Workloads. Retrieved from https://www.fictiv.com/ebooks/the-economic-impact-of-a-digital-manufacturing-partner-for-production-workloads#:~:text=These%20benefits%20include%3A,Lower%20inventory%20investment (date accessed, June 2024)
138. Cagno E, Neri A, Howard M, Brenna G, Trianni A. Industrial sustainability performance measurement systems: a novel framework. J Clean Prod. 2019;230:1354–75. https://doi.org/10.1016/j.jclepro.2019.05.021.
139. Phuyal S, Bista D, Bista R. Challenges, opportunities and future directions of smart manufacturing: a state of art review. Sustain Futu. 2020;2:100023. https://doi.org/10.1016/j.sftr.2020.100023.
140. Zhang L, Luo Y, Tao F, Li BH, Ren L, Zhang X, et al. Cloud manufacturing: a new manufacturing paradigm. Ent Inf Syst. 2014;8(2):167–87. https://doi.org/10.1080/17517575.2012.683812.
141. Despeisse M, Chari A, González Chávez CA, Monteiro H, Machado CG, Johansson B. A systematic review of empirical studies on green manufacturing: eight propositions and a research framework for digitalized sustainable manufacturing. Prod Manufact Res. 2022;10(1):727–59. https://doi.org/10.1080/21693277.2022.2127428.

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