Disruptive Technologies and Manufacturing Performance in South Africa: Firm-Level Evidence

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List of abbreviations and acronyms

4IR	Fourth Industrial Revolution
CCRED	Centre for Competition, Regulation and Economic Development
COVID-19	Corona Virus Disease 2019
IDTT	Industrial Development Think Tank
LIML	Limited-Information Maximum Likelihood
OEMs	Original Equipment Manufacturers
SETAs	Sector Education and Training Authorities

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Abstract

The Fourth Industrial Revolution (4IR) is changing while also adding increased complexity to the global manufacturing landscape. The global transformation in manufacturing is offering new prospects for sustained industrial development in developing countries through increases in productivity, value creation, and efficiency gains as well as employment creation avenues. Digitalization and the adoption of disruptive digital technologies are viewed as crucial to these transformations. However, there are limited research into the current state of disruptive technologies' adoption, digital skills, and capabilities in developing countries, particularly South Africa. This paper examines the effect of adoption of disruptive digital technologies on the performance of South African manufacturing firms. Using novel data from the South African digital skills survey and econometric analyses, our results highlight the importance of the adoption of disruptive digital technologies for the performance of manufacturing firms in South Africa. The policy implications of our results are discussed considering national policies on the Fourth Industrial Revolution (4IR).

1.0 Introduction

Digitalization, under the umbrella of the Fourth Industrial Revolution (4IR), is fast-becoming a catalyst for change influencing innovation, production, trade, consumption, and a host of business processes (Andreoni et al., 2021a). Many of the technologies associated with digitalization and the 4IR are disrupting and bringing new impetus for structural change and technological transformation (Davis et al., 2012). In particular, disruptive technologies are transforming where, how, and what is manufactured (Hannibal & Knight, 2018; Bristow & Healy, 2020). The global transformations in production processes and manufacturing, as a whole, offer new prospects for sustained industrial development in developing countries, potentially through increases in productivity, value creation, and efficiency gains as well as employment creation avenues. Digital technologies, for example, are identified as crucial accelerators of improved product quality, customer satisfaction, workforce diversity, and financial performance (Briken et al., 2017).

However, the analysis of the implications of these advanced production technologies on the performance of manufacturing firms in developing countries is obscured in the relatively scant literature. For example, technologies associated with 4IR are shown to positively impact firm productivity (Benassi et al., 2020; Delera et al., 2022). For example, using firm-level data from Ghana, Thailand, and Vietnam, Delera et al. (2022) found that digital technology adoption generates productivity premium. Despite, studies on the relationship between 4IR, smart manufacturing, and small and medium-sized enterprises in Africa remains scant (Gumbi & Twinomurinzi, 2020), thereby limiting our understanding of the readiness of African firms for the new era of manufacturing. Given that anxieties still persist on the economy-wide effect of disruptive industrial technologies in Africa, a lot more research is needed. This paper aims to provide empirical evidence on the effects of advanced disruptive technologies using unique manufacturing firm-level survey data from Africa's most industrialized country.

A key challenge facing South Africa, a middle-income and technological follower country, is developing and modernizing its technological capabilities and infrastructure to more easily usher in and capture emerging opportunities in the 4IR. This drive towards modernization is even more critical as South Africa looks to break from the 'middle-income trap' to create new productive jobs, improve productivity, and diversify the economy's production structure for self-sustaining economic progress (Bell et al., 2021a). With a significant decline in manufacturing output due to deindustrialization and the COVID-19 pandemic, the prospects for disruptive technology-induced manufacturing recovery is emphasized for recovery in South Africa (Bell et al., 2021b).

However, there is little known about the current state of disruptive technologies' adoption and the digital skills and capabilities available in South Africa's manufacturing sectors needed to foster industrial recovery and technological transformation locally. Understanding these technology gaps is crucial given the link between Industry 4.0, the changing nature of work and skills in South Africa, and the importance of a strong manufacturing sector for economic development. Additionally, this is important in the context of South Africa's efforts to develop industrial capacity and propel the economy into the digital age following the National Development Plan and Industrial Policy Action Plans.

The contributions of the paper are three-fold. First, the paper provides one of the first empirical evidence examining the effect of digital technologies on the performance of manufacturing firms, specifically in South Africa. It departs from the anecdotal discussions of the effect of digital technology on firm performance in developing countries by providing an empirical examination of this relationship.[1] Second, the paper employs an innovative firm-level data: digital skills survey data collected from 516 manufacturing enterprises in South Africa. The relationship between technology adoption behaviour of firms and their performance may be bi-directional (Delera et al., 2022). Given the difficulty in finding valid instruments (see Delera et al., 2022), this paper also contributes to the literature by constructing and using an “adoption index” that aggregates adoption behaviours of firms across different groups of manufacturing firms. This approach is common and found to reduce bi-directionality between variables in the micro-econometric literature (see, for example, Avenyo et al., 2021).

Our estimation results reveal that, the adoption of disruptive digital technologies for supplier and production management business functions are positive determinants of manufacturing firms' performance in South Africa. Specifically, we found supplier-related and production management-related disruptive digital technologies enhances firms' ability to innovate and export. These findings are robust across different specifications and may be key in driving evidence-based policy action that promotes and fosters the adoption and diffusion of advanced digital technologies strategy in South Africa.

The remainder of this paper proceeds as follows. Section 2 summarizes the available and related literature, with specific focus on the effect of digital technologies on manufacturing performance. Description of the data and the empirical strategy are discussed in Section 3. Section 4 presents and discusses the estimation results; while the conclusion in Section 5 summarizes our discussions and concludes the study.

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1 This excludes Delera et al. (2022) who used a cross-country survey data to econometrically examine the relationship between digital adoption and productivity in Ghana, Thailand, and Vietnam.

2.0 Overview of the literature: 4IR and Disruptive Technologies

In today's ever-changing and increasingly globalized manufacturing system, numerous emerging technologies are altering where, how, and by whom production is taking place (Hannibal & Knight, 2018). The vast degree of advancements caused by these new technologies are disruptive to businesses, governments, and societies alike (Schuelke-Leech, 2018). Additionally, the opening of a new cycle of productive forces development associated with different eras of technological advancement have been at the forefront of socioeconomic and human development from agrarian societies to industrial and post-industrial societies (Melnyk et al., 2019).

The 4IR and the commensurate digital technologies are leading to the creation of entirely new markets and new jobs while also facilitating a deepening of supply chains and, hence, greater levels of integration into international markets (Monaco et al., 2019). The 4IR wave is establishing a nascent paradigm shift in numerous industries and the new technologies are being implemented across the production and management (Bongomin et al., 2020). These technologies include new data-driven technologies, automation, molecular technologies, and earth-system engineering approaches coupled with requirements for significantly greater data storage and distribution infrastructure (Thomas, 2019). Some of them include cloud computing, big data, artificial intelligence, robotics systems, Internet of things, 3D printing, virtualization, cyber security, sensor technologies, advanced robotics systems, automation, smart sensors, simulation, nanotechnology, drones, and biotechnology (Ulas, 2019; Bongomin et al., 2020; Andreoni et al., 2021a).

The adoption of 4IR and other disruptive technologies encompasses with it a new approach to understanding how value is created. Moreover, the rise of new market segments commensurate with the digital transformation and 4IR is opening a myriad of business opportunities for firms and industries (Amshoff et al., 2015). However, the experiences of different firms, industries, and geographies are not synonymous.

Rather, digitalization and 4IR is being experienced differentially across the globe, and these differences are due to several challenges being faced in specific countries (Andreoni et al., 2021a).

This section presents a discussion of the above issues: (i) review of related literature on the disruptive versus incremental nature of digital technologies; (ii) discussion on some opportunities digital technology adoption offers; and (iii) synthesis and a summary of our review of the literature.

Technology and process-improvements: Disruptive vs incremental

Despite its vastness, there is a robust debate on the true disruptive nature of technologies under the collective term of 4IR. One view suggests that the disruptive potential of a new technical process or advancement is dependent on the degree of new knowledge created by its adoption (Dewar & Dutton, 1986). So, under this hypothesis, disruptive innovations create high degrees of new knowledge whereas incremental innovations create low degrees of new knowledge. Other authors writing on this topic describe disruptive innovations as technologies that were previously new to the world and incremental innovations as being improvements or enhancements in technology performance (Hacklin et al., 2004). The key point is that, the disruptive potential of these new technologies, while having differing impacts on actors at different levels of the value chains, must be implemented on a sliding scale. What this entails is that understanding disruptive technologies can be either complementary (supplementing existing products, processes or business models) or a substitute (displacing existing practices in a sector or value chain) (Krishnan et al., 2020).

However, the degree to which technologies are considered disruptive or incremental may not be the same across time, firms, and industries. Thus, the disruptive potential of technologies and process advancements are also dependent on the respective settings in which they are adopted. For example, a disruptive technology such as additive manufacturing[2] could represent an incremental innovation in one industry while leading to revolutionary industrial changes in another marked by a fundamental shift in the manufacturing ecosystem (Steenhuis & Pretorius, 2017). This logic adheres to the idea of technology convergence, whereby, once combined, several incrementally-defined technologies can lead to highly disruptive changes (Hacklin et al., 2004). This is a pointer to the transversality of many of these technologies, and their relative applicability across and along several industries, production systems, and within the operations of firms (Andreoni et al., 2021a).

Moreover, the relative degree of disruption that encapsulates a given technology or process can also be viewed from the angle of the complexity of the outcomes from the improved system, or even the system or firm operations themselves, rather than

2 Additive manufacturing is defined by a range of technologies that can translate virtual solid model data into physical models (Gibson et al., 2021).

the complexity of the individual technologies being considered (Barnes & Slattery, 2021). In this sense, technologies that disrupt a given firm's operations in such a way as to introduce new forms of business and open avenues for an expansion of their capabilities and capacities. Based on this discussion, in this paper, we employ a definition of disruptive technologies as it relates to improving existing business processes in manufacturing firms and/or offering opportunities for an expansion of these firms' capabilities and complexity of their operations into avenues such as the abilities to export and/or to innovate.

Opportunities from the adoption of disruptive technologies

There is a growing but largely anecdotal literature discussing the opportunities that can be gained from an increased use of disruptive technologies. These technologies are identified to offer numerous benefits for manufacturers and economies, from structural transformation of production and manufacturing systems to moving from low-productivity activities into higher-productivity activities (Salawu et al., 2020; Andreoni et al., 2021c). From the perspective of African economies, the uptake of disruptive technologies can assist in promoting a transformation of their productive structures and accelerate the drive towards increased industrialization (Ayentimi & Burgess, 2019).

The degree of potential that disruptive technologies and 4IR offer African economies begins with significant productivity benefits and extends across a spectrum of sectors with ever-greater linkages developed in the process. For example, innovations in agricultural technology in East Africa have opened the door to innovations in food processing and farming with more significant transparency along the entire value chain (Krishnan et al., 2020). The ‘industrialization of freshness' is one such case study showing how advances in technologies and their adoption have had a positive disruptive effect on the South African fresh-fruit industry by widening market access and enabling firms to adhere to ever-changing quality standards in the face of evermore uncertain climatic conditions (Cramer & Chisoro-Dube, 2021).

Additionally, research into the deepening of the Thai automotive supply chain highlights the benefits gained by Thai automotive component producers through the concerted, and assisted, effort by the state and foreign-owned original equipment manufacturers (OEMs) to improve the competitiveness in the domestic market through advancements in its technological infrastructure ((Monaco et al., 2019). The facilitation of the adoption of advanced technologies provided a positive disruptive shock to the Thai-owned component producers that allowed them to integrate into supply chains of large automotive assemblers more easily and compete in the global automotive value chain. In contrast, the South African automotive sector operates with limited technological adoptions, incremental or disruptive, that have, in part, severed to weaken the ability of the South African component manufacturers to compete globally and effectively integrate into the supply chains of the OEMs.

These examples are testaments to the significant positive effect that adopting disruptive technologies can have on firms, industries, markets, and entire sectors. However, as the example of the South African automotive sector shows, a failure to effectively capture the benefits of disruptive technologies may be due to several factors that can impact the ability and success of a firm (and, by extension, an economy) to structurally transform their production and manufacturing capabilities and, in the process, extracting other potential positive benefits and spillovers.

Summary

Overall, the literature on digital technologies emphasizes the potential opportunities offered by the successful adoption and integration of disruptive digital technologies. However, to properly gauge the impacts of disruptive 4IR-linked technologies and their potential disruptions necessitates greater insight into how new technologies are affecting firms and how firms are preparing their operations for the new era of manufacturing. Understanding disruptive technologies impacts, and the extent of their impact on industrial performance in emerging market economies, is crucial for developing proper governance tools and industrial development policies that seek to yield the greatest benefits for developing economies in terms of their acceleration of industrial development.

Given the specific relevance of digital technologies in facilitating the transformation of production processes in the manufacturing sector, a systematic firm-level analysis of the heterogeneous effects of different types of disruptive technologies on manufacturing and across different manufacturing sectors in South Africa is needed. Our paper fills this gap.

3.0 Methodology

Data

For the analysis, we aim to use the South African digital skills survey data. The digital skills survey is a unique online survey conducted in March 2021, covering 516 South African manufacturing firms. The digital skills survey was part of an ongoing joint project for the Department of Trade, Industry, and Competition between the Centre for Competition, Regulation, and Economic Development (CCRED) together with the South African Research Chair in Industrial Development at the University of Johannesburg and in collaboration with the Sector Education and Training Authorities (SETAs) that govern skills training in manufacturing and engineering services (MerSETA), chemicals (CHIETA), and textiles and fibre processing (FP&M SETA).

In general, the survey sought to understand the current level of and possible future gaps in the adoption of disruptive technologies, skills and technological capabilities in South African manufacturing firms. As a result, responses to specific issues on disruptive technologies adoption and investment, digital skills and capabilities building, firm-level and industry-level characteristics, location, employment, innovation, and export activities of firms between 2017/18 and 2019/20 financial years were collected.

Table 1 reports the descriptive statistics of our main variables of interest. Our raw data suggest that about 44% of sampled manufacturing firms export, while about 51% of them introduced at least a product or a process innovation over the period. Majority of the firms are also micro and small-sized firms.

Table 1: Descriptive statistics of data

Variable	Mean	SD	Minimum	Maximum
Firm performance				
Export	.436		0	1
Innovation	.509		0	1
Digital technologies				
Supplier relations	.049		0	1
MERSETA	.057		0	1
FP&M	.000		0	1
CHIETA	.034		0	1
Production management	.124		0	1
MERSETA	.135		0	1
FP&M	.061		0	1
CHIETA	.16		0	1
Employment	73.177	40.179	1	145
Lack of capital	.894		0	1
Age	57.861	38.729	0	100
Size (%)				
Micro	29.93			
Small	29.93			
Medium	25.66			
Large	14.47			

The adoption of disruptive technologies is low in our data, and in line with related data sets from other contexts such as Brazil (Ferraz et al., 2020) and Ghana, Vietnam, and Thailand (Delera et al., 2022). Our data suggest that only about 5% of sampled firms adopted supplier relations technologies, while about 12% introduced production management disruptive technologies. These suggest that firms easily adopt production management-related technologies easily as compared with supplier relations-related technologies. We observe some heterogeneity across SETAs in terms of adoption of technologies as well. Grouping the adoption of digital technologies by SETAs, our data reveal that a higher proportion of MERSETA firms (about 6%) adopted supplier relations-related disruptive technologies followed by CHIETA (about 4%) and FP&M (0%). In the case of the adoption of production management-related technologies, we observe about 16% of CHIETA, 14% of MERSETA, and 6% of FP&M firm adoption rates in our data. Considering other firm-related characteristics, our data show that sampled firms, on average, employ 73 workers, lack capital (about 89%), and about 58 years old.

Empirical strategy

The adoption of disruptive technologies may not be random, and adopters may differ due both to unobserved characteristics (e.g., managerial ability, risk preference, etc.) and observable characteristics (market power, financial resources, human capital, etc.) leading to observed differences in performance. Given these econometric issues, we follow two main econometric approaches. We begin our analysis by first constructing a SETA-level adoption index that aggregates adoption behaviours of firms across different manufacturing SETAs in our sample. That is, SETA-level adoption index averages responses of firms across SETAs with firms belonging to the same SETA having the same SETA-level adoption indicator. While this aggregates the data, the approach allows for variation across SETAs and help to reduce the possible bi-directional relationship between firm performance and digital technology adoption (see Guiso et al., 2004; Avenyo et al., 2021).

The first stage is done formally by estimation a biprobit model with firm and industry level characteristics for two business functions of interest (supplier and production management). We employ a biprobit model at this first stage of estimation to control for possible correlation or complementarity in the adoption of both types of disruptive technologies. Using the predicted values of the SETA variable in the first stage, we conduct the second stage regression by estimating the effect of SETA-level adoption of disruptive technologies on performance outcomes: export dummy, innovation dummy, and total employment. The SETA-level adoption indicators are expected to yield significant coefficients in the first stage regressions and are considered as valid exclusion restrictions.

Hence, this approach allows us to identify and examine the determinants of disruptive technologies adoption on the one hand, and analyse the effect of disruptive technologies adoption on firm performance on the other.

First-level estimation

As noted, we constructed SETA-level variables to control for possible econometric issues that may persist at the firm-level at the first-level of estimation. In the first stage, we estimate a simple biprobit model (in line with Delera et al., 2022) that estimates the effect of SETAs on adoption of disruptive technologies, controlling for other determinants of adoption. Our estimation equations are formalized as:[3]

$$Supplier\_relations_{iq} = a_0 + X_{iq}\delta_1 + SETA_q\delta_2 + \varepsilon_{iq} \tag{6i}$$

$$Production\_management_{iq} = b_0 + X_{iq}b_1 + SETA_q b_2 + \mu_{iq} \tag{6ii}$$

Where: $Supplier\_relations_{iq}$ and $Production\_management_{iq}$ are binary variables that equal 1 if the firm introduced a supplier relations and production management disruptive technologies in firm i of SETA q, respectively, and 0 otherwise. $SETA_q$ is a vector of SETA level classification of the firm, while X_{iq} refers to all firm-level variables that affect the probability to introduce disruptive technologies, following Delera et al. (2022). Digital skills are closely linked with the adoption of disruptive digital technologies. Firms that possess greater levels of higher skilled workers can more easily extract benefits from the adoption of complex digital

3 See Table A1 (in the appendix) for detailed definition of all variables.

technologies. These technologies are often thought to transform a firm's technological infrastructure. We specifically controlled for lack of human resources in the adoption equation to examine this aspect of the literature. ε_{iq} and μ_{iq} are both multivariate normally distributed error terms with mean 0, variances equal to 1.

Given that firms jointly introduce disruptive technologies, and the fact that different technologies may have complementary effects on firms, we estimated Equation 1 (i and ii) jointly using biprobit model. We then predict the probability of disruptive technology adoption by SETA across each equation. We then normalize the predicted values following Guiso et al. (2004) and Avenyo et al. (2021) as:

$$\text{SETA adoption index}_{jq} = 100 * [\hat{\rho}_{jq} - \min(\hat{\rho}_{jq})] / [\max(\hat{\rho}_{jq}) - \min(\hat{\rho}_{jq})] \quad (2)$$

Where: $\text{SETA adoption index}_{jq}$ is defined as the SETA-level adoption indicator of disruptive technology jj (supplier relations or production management) in SETA q. $\text{Min}(\hat{\rho}_{jq})$ and $\max(\hat{\rho}_{jq})$ captures the minimum and maximum marginal probabilities of technology adoption across SETAs, respectively. Equation 2 converts and normalizes SETA-level adoption indicator to between 0 and 100%, with values close to 0 indicating less probability while values close to 100% indicate higher likelihood to introduce disruptive technologies.

Table 2 reports the summary of our SETA-level adoption indicator across our performance variables: export and innovation. The table shows that there is heterogeneity in the adoption of disruptive technologies across manufacturing firms that engage in exporting and innovating activities and otherwise. On average, our analysis shows that SETA-level adoption of supplier relations technologies indicator (about 67%) is higher than that of product management technologies indicator of about 57%, suggesting that the firms are more likely to adopt supplier relations technologies than product management technologies. Across performance variables, we observe that it is more likely for exporters to adopt supplier relations-related technologies than non-exporters, while non-innovators also tend to have a higher likelihood to adopt supplier relations technologies compared with innovators.

Table 2: Description of SETA-level indicator across exporting and innovation activities

SETA-level adoption indicator	All
Supplier relations indicator	
All	67.272
Exporters (non-exporters)	69.120 (66.871) ***
Innovators (non-innovators)	63.557 (71.360) ***
Production management	
All	57.146
Exporters (non-exporters)	57.726 (55.224) ***
Innovators (non-innovators)	54.991 (60.366) ***

Note: * p < 0.10, ** p < 0.05, *** p < 0.01

These results are statistically significant and also hold when we consider production management technologies, suggesting that engagements in the international markets enhance the likelihood to adopt digital technologies more than innovation activities. This finding remains an empirical question beyond the scope of this paper.

Second-level estimation: Effect of disruptive technologies on firm performance

To examine the effect of our constructed SETA-level adoption indicator on firm performance, we estimated two different types of models based on the nature of the performance variables: probit and ivprobit models for export and innovations; OLS and OLS with instrumental variable models for employment. The baseline probit models are presented as:

$$\text{Export}_{iq} = 1, if\ \text{Export}^*_{iq} = \theta_0 + X_{iq}\theta_1 + Supplier\_relations_{iq}\theta_2 + Production\_management_{iq}\theta_3 + \epsilon_{1iq}$$

>0, and 0=otherwise (3)

$$\text{Innovation}_{iq} = 1, if\ \text{Innovation}^*_{iq} = \sigma_0 + X_{iq}\sigma_1 + Supplier\_relations_{iq}\sigma_2 + Production\_management_{iq}\sigma_3 + \epsilon_{2iq}$$

>0, and 0=otherwise (4)

$$\text{Employment}_{iq} = \vartheta_0 + X_{iq}\vartheta_1 + Supplier\_relations_{iq}\vartheta_2 + Production\_management_{iq}\vartheta_3 + \epsilon_{3iq}$$

(5)

Where: Export_{iq}, Innovation_{iq} and Employment_{iq} are our performance variables across firm i and SETA q. Export_{iq} is a dummy variable that assumes the value 1 if firm i and SETA q is engaged in export activities and 0 if otherwise. That is, when $\text{Export}_{iq}^{*} > 0$ and 0 otherwise. Innovation_{iq} captures if firm i in SETA q has introduced either product or process innovations over the period under consideration, that is, when $\text{Innovation}_{iq}^{*} > 0$. X_{iq} is the vector of all firm level controls that may affect the performance of manufacturing firms, in line with Delera et al. (2022). ϵ_{1iq}, ϵ_{2iq}, and ϵ_{3iq} ϵ_{3iq} are normally distributed error terms.

As noted, the effect of disruptive technologies on performance may be bi-directional. That is, better performing firms may have a higher likelihood to adopt digital technologies. As a result, we formulate first-stage regressions to control for possible econometric issues as:

$$Supplier\_relations_{iq} = \theta_0 + X_{iq}\theta_1 + SETA\_index_q + \epsilon_{1iq} \quad (6i)$$

$$Production\_management_{iq} = \sigma_0 + X_{iq}\sigma_1 + SETA\_index_q\sigma_2 + \epsilon_{2iq} \quad (6ii)$$

Where: $SETA\_index_q$ is our SETA-level disruptive technology indicator in SETA q as constructed in Equation 1.

Estimation

Equation 6 (i and ii) are estimated together with each of equations 4-6 using the flexible and recursive conditional mixed process (cmp) modelling framework in Stata (Roodman, 2011). The model estimates each of equations 4-6 jointly with the reduced form regressions (6) using the limited-information maximum likelihood (LIML) estimator. The joint estimation of the structural and reduced forms as a system of equations generates larger sample size in the estimation process leading to efficiency gains based on the use of the full covariance matrix (Roodman, 2011). The model assumes all error terms are correlated and bi-normally distributed.

In each estimation, the variance-covariance matric is clustered at the SETA-level, with the main explanatory variable of interest being the SETA-level disruptive technology indicator.

4. 0 Results and discussion

This section reports and discusses the estimation results from our empirical analyses of the effect of disruptive technology adoption on the performance of firms in South Africa. We report and discuss the effect of disruptive technologies (supplier relations and production management) on three main firm performance variables (export, innovation, and total employment) using two main models: probit model (no control for endogeneity) in columns (1) and (2); and the conditional mixed process model in LIML in column (4) (control for endogeneity of our disruptive digital technology variables). Table 3 further reports the ivprobit model (assumes wrongly that endogenous variables are continuous) in column (3). As noted, all reported standard errors are heteroscedasticity-robust and clustered at the SETA-level.

Disruptive digital technologies and the likelihood to export

Table 3 reports the estimation results analysing the effect of disruptive digital technologies on the likelihood to export. The results across all specifications suggest that South African manufacturing firms that adopted disruptive digital technologies experienced a higher likelihood to engage in export activities. Specifically, our results suggest that manufacturing firms that adopted supply- and production management-related disruptive technologies tend to have a higher likelihood to export than otherwise (column 4). These results are in line with the current empirical literature (see Delera et al., 2022; Ferraz et al., 2020) that suggest that disruptive technologies generate a performance 'bonus' among manufacturing firms in developing countries.

Other significant determinants of export include access to broadband, capital ownership, age, and size of firm. Our results suggest that firms with access to broadband have a higher likelihood to export, as this may increase their ability to interact with their external partners. Manufacturing firms that are state-owned are less likely to export compared with their counterparts that are foreign-owned. This may be explained by the reason that state-owned enterprises are more oriented towards the domestic market with often no engagement in international markets. In line with the literature, our results suggest also that older firms tend to have a higher likelihood to export, suggesting the importance of experience, and the presence of established supplier and production networks to engage in the international market. While our result also suggest that smaller firms tend to export less compared with larger firms, the results are only significant for micro firms. This implies that small firms (sales values at between R11 million and R50 million per financial year) are less likely to export compared to their large counterparts (sales valued at more than R250 million per financial year), suggesting that possessing adequate financial resources matter significantly in the decision to export or otherwise.

Table 3: Effect of disruptive technology adoption on the likelihood to export

	(1) probit	(2) probit	(3) ivprobit	(4) cmp-LIML
Supplier relations technologies	0.314**	0.062	0.458***	0.156***
	(0.160)	(0.114)	(0.143)	(0.191)
Production management technologies	0.104	0.109	0.868***	0.403***
	(0.094)	(0.081)	(0.539)	(0.063)
Total employment (log)		0.011	0.019	0.007
		(0.028)	(0.104)	(0.087)
Lack of capital		-0.074	-0.041	-0.048
		(0.104)	(0.123)	(0.145)
Universal access to broadband networks		0.007	0.325**	0.275*
		(0.038)	(0.136)	(0.158)
Access to high-end broadband networks		-0.050	-0.068	-0.102
		(0.035)	(0.099)	(0.100)
Access to affordable, efficient services for cloud storage and processing		-0.023	-0.159	-0.100
		(0.025)	(0.099)	(0.111)
Lack of adequate digital infrastructure		-0.083**	-0.284**	-0.178
		(0.037)	(0.111)	(0.153)
Lack of adequate human resources		-0.030	-0.022	-0.027
		(0.036)	(0.038)	(0.036)
Capital ownership (Fully South African)		-0.113	-0.056	-0.076
		(0.095)	(0.207)	(0.190)
Capital ownership (Foreign and South African)		0.125	0.117	0.107
		(0.160)	(0.128)	(0.128)
Capital ownership (State-owned)		-0.370	-0.128***	-0.067***
		(0.271)	(0.119)	(0.083)
Company size (Medium)		-0.050	-0.230	-0.231
		(0.093)	(0.287)	(0.283)
Company size (Small)		-0.340***	-0.842**	-0.654
		(0.089)	(0.354)	(0.412)
Company size (Micro)		-0.399***	-0.100***	-0.962**
		(0.096)	(0.381)	(0.424)
Age (log)		0.064**	0.147***	0.174***
		(0.032)	(0.035)	(0.013)
Observations	281	254	254	254

Notes: Robust standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01. Reported coefficients are marginal probabilities and all estimations clustered at the SETA-level. Foreign-owned and large firms as base outcomes for capital ownership and company size, respectively.

Disruptive digital technologies and the likelihood to innovate

Our estimation results showing the effect of disruptive digital technologies on the probability to innovate are reported in Table 4. Here again, we report results for both the 'probit' and 'cmp' models for robustness check. In line with our earlier findings, the results suggest that disruptive digital technologies have a significantly positive effect on the probability of firms innovating. Firms that introduce supply- and production management-related disruptive technologies tend to be more innovative compared with non-disruptive technology adopters.

Table 4: Effect of digital tech adoption on innovation of firms

	(1) probit	(2) cmp-LIML
Supplier relations technologies	0.242**	0.017***
	(0.112)	(0.587)
Production management technologies	0.008	0.393***
	(0.151)	(1.108)
Total employment (log)	0.062*	0.152*
	(0.034)	(0.079)
Lack of capital	0.051***	0.118
	(0.011)	(0.325)
Universal access to broadband networks	0.004	-0.076
	(0.027)	(0.069)
Access to high-end broadband networks	0.040	0.172
	(0.048)	(0.107)
Access to affordable, efficient services for cloud storage and processing	0.000	0.045
	(0.009)	(0.102)
Lack of adequate digital infrastructure	0.007	-0.029
	(0.058)	(0.062)
Lack of adequate human resources	-0.035**	-0.040**
	(0.018)	(0.020)
Capital ownership (Fully South African)	0.007	-0.137
	(0.076)	(0.194)
Capital ownership (Foreign and South African)	0.006	0.070
	(0.214)	(0.601)
Capital ownership (State-owned)	0.052	0.233
	(0.369)	(0.930)
Company size (Medium)	-0.116	-0.525
	(0.245)	(0.652)

Company size (Small)	-0.275*	-0.714*
	(0.152)	(0.469)
Company size (Micro)	-0.265**	-0.525*
	(0.103)	(0.304)
Age (log)	-0.033	-0.106*
	(0.028)	(0.059)
Observations	198	198

Notes: Robust standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01. Reported coefficients are marginal probabilities and all estimations clustered at the SETA-level. Foreign-owned and large firms as base outcomes for capital ownership and company size, respectively.

Other significant explainers of innovation include total number of employees, human resources, size, and age of firms. In line with the literature, our results suggest that: younger firms are more likely to innovate; small and micro firms in terms of revenue are less innovative than their larger counterparts, suggesting that innovation is expensive; firms with higher number of employees tend to innovate more, while lack of human resources tend to be detrimental to innovation, with both results implying the importance of human resources/capital in the innovation process.

5.0 Conclusions

The prevailing narrative on the effects of advanced disruptive digital technologies on manufacturing firms' outcomes remains inconclusive across the world, particularly in developing economies. While the available evidence suggests a positive net effect of adoption of advanced disruptive digital technologies on manufacturing performance, the evidence tends to be anecdotal in most cases, and limited with a focus on other contexts in other cases. This paper examined the effects of disruptive digital technology adoption on manufacturing performance and capabilities in South African manufacturing firms.

The paper embarked on an empirical investigation utilizing data gathered from the Digital Skills Survey (2020/2021) that surveyed 516 manufacturing firms across three key manufacturing-related Sector Education and Training Authorities (SETAs) (manufacturing and engineering services [MERSETA], chemicals [CHIETA], and textiles and fibre processing [FP&M SETA]) in South Africa. We econometrically analyse the separate effects of the adoption of advanced digital technologies for supplier related and production management business functions on firm performance, specifically, export and innovation. Our results corroborate with the available empirical literature suggesting that, despite the low-level and heterogeneity in adoption, digital technologies enhances the performance of manufacturing firms.

Given the inherent problems facing the South African economy that could hinder a full-scale digital transformation, it is important that the existing policy discussions point out some policy areas that should be considered in the development of South Africa's digital industrial policy (Barnes et al., 2019). These areas include, firstly, the recognition that the opportunities from digital industrialization are about capturing value from incremental changes and disruptive technological innovations as part of the emergence of a new industrial ecosystem. The literature in this paper emphasized this as a crucial distinction of which the design of future policy will need to be cognisant. For example, whether the extent of digital disruptions transverse the purely cyber or cyber-physical and primarily physical value chains, and the importance of understanding whether transitioning to digitally-enabled business models will incorporate major and minor adjustments (Andreoni et al., 2021a). Our results are discussed in mind of this distinction and the concept of disruptive technologies employed in this paper is defined as such.

Secondly, policies aligned to fostering a digital industrial transformation must create the conditions for more domestic value creation and distribution (Barnes et al., 2019). Our results found that the manufacturing performance of South African manufacturing firms is strongly correlated with their size and age (years in operation). This result cuts across both export and innovation capabilities. Smaller manufacturing firms within the surveyed sectors were found to possess lower levels of digital technologies and digital skills that, together, limit their ability to engage in largescale exporting and innovative activities. On the other hand, larger firms were found to more likely be export orientated. Yet, small firms were more inclined towards innovative behaviour despite lacking the financial resources to engage in the adoption of the kinds of digital technologies that embody this process. These results tend to align closely with the existing literature researching this phenomenon in more developed economies. Policy should, therefore, engage with how best to assist smaller manufacturing firms gain the necessary export and innovation capabilities with which to create greater value addition and expand the reach of South Africa's manufactured exports.

Thirdly, there is a need for strategic policy targeting, coordination, and alignment to effectively extract the potential benefits from a digital manufacturing transformation (Barnes et al., 2019). The findings in our paper cut across several policy directions and institutional mandates, which would require stakeholders from different government departments to collectively coordinate their policy design, incentives, and implementation towards a common goal of digitalized future. For example, this would necessitate skills planning to be designed in unison with incentives programmes developed to improve the exporting and innovation capabilities and capacity of South African manufacturing firms. This idea follows the literature emphasizing the essentialness of developing foundation capabilities to ensure a smooth digital transition (Andreoni et al., 2021b).

These findings offer some baseline insights into the performance of South African manufacturing firms in the context of the adoption of advanced and more digital technologies as highlighted in much of the prevailing literature. The findings also provide a useful basis for a deeper and more nuanced discussion on the design and development of new and existing policies focusing on the adoption of digital technologies. This is crucial given the highlighted issues plaguing South Africa as a middle-income country and in light of evidence noting a mixed deployment of digital production technologies (Andreoni et al., 2021a). However, a thorough evaluation of existing digital industrial policies and incentives is outside the scope of this paper. In addition, our study could be extended using a larger sample size and more continuous measures of innovation and exports. Our sample size is low due to the number of firms in the data set as well as missing observations across key variables. Also, future studies of this nature could benefit from an extension of the analysis to other business functions, including product development and customer relations.

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Appendix

Table A1: Definition of variables

Variable	Definition and Measurement
Export	A dummy variable indicating if the firm exports (1) and 0 if otherwise in 2019/20 financial year.
Innovation	A dummy variable indicating if the firm has introduced new production process or made significant improvements to products between 2017/18 and 2019/20 financial years.
Supplier relations technologies	A dummy variable that takes value of 1 if firm's primary method of communicating with suppliers (to place orders) is through real-time monitoring of orders and logistics of suppliers (e.g., computer-managed inventory systems) and 0 if firm places orders manually (e.g., over the phone or via email) or through electronically using computerized systems.
Production management technologies	A dummy variable that takes value of 1 if firm's primary method of managing production is through machine to machine(M2M) communication system and 0 if managing production is through partially or fully automated process or simple automation with unconnected machines.
Total employment (log)	Continuous variable defined as the total number of employees in 2019/2020 financial year in natural logarithm.
Lack of capital	A dummy variable that takes the value 1 if firm considers the lack of capital /funds as an obstacle and 0 otherwise.
Universal access to broadband networks	A dummy variable that takes the value 1 if firm considers as important the universal access to broadband networks and 0 otherwise.
Access to high-end broadband networks	A dummy variable that takes the value 1 if firm considers as important high-end broadband networks and 0 otherwise.
Access to affordable, efficient services for cloud storage and processing	A dummy variable that takes the value 1 if firm considers as important affordable, efficient services for cloud storage and processing and 0 otherwise.
Lack of adequate digital infrastructure	A dummy variable that takes the value 1 if firm considers the lack of adequate digital infrastructure as an obstacle and 0 otherwise.
Lack of adequate human resources	A dummy variable that takes the value 1 if firm considers the lack of adequate human resources/pool of talents as an obstacle and 0 otherwise.
Capital ownership	A categorical variable that takes value 1 if the capital ownership of the firm is foreign-owned, 2 if fully South African-owned, 3 if mixed (South African and foreign-owned), and 4 if state-owned in in 2019/2020 financial year.
Company size	A categorical variable that assumes the value of 1 if the firm is large (sales valued at more than R250 million per financial year), 2 if firm is medium ((sales valued at between R51 million and R250 million per financial year), 3 if firm is small ((sales valued at between R11 million and R50 million per financial year), and 4 if firm is micro (sales valued at below R10 million per financial year) in 2019/2020 financial year.
Age (log)	A continuous variable defined as the total number of years firm has been in operation, constructed as the natural logarithm of the total number of years plus 1.
SETA	A categorical variable that takes value of 1 if firm belongs to MERSETA, 2 if FP&M, and 3 if it belongs to CHIETA.

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