

Article

The Impact of Trade Openness and ICT on Technical Efficiency of Township Economies in South Africa

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Abstract: While the impact of trade openness on economic growth has been widely studied, its effect on township economies remains underexplored. In view of this empirical gap, this study examines the impact of trade openness proxied by export intensity on the technical efficiency of five major township economies in South Africa—Soweto, Khayelitsha, Alexandra, Tembisa, and Soshanguve—while considering the moderating role of information and communication technology (ICT). This aim speaks to the ongoing quest to unravel factors limiting the transformation of South African townships since the advent of democracy in 1994. The analysis uses an instrumental variable stochastic frontier model and annual panel data covering the 1995–2023 period. On average, the five townships were found to have operated 19% below their full potential during the sampling period, with Soweto being the least efficient. Holding constant factors peculiar to township economies, such as crime rates and informality, the main results show that ICT plays a positive moderating role in reducing trade-related technical inefficiencies of these townships. This finding underscores the importance of targeted policy interventions, such as investments in digital infrastructure and digital literacy programs, to ensure that township economies benefit from global markets and achieve their full potential.

Keywords: trade openness; technical efficiency; townships



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1. Introduction

Township economies in South Africa have long been characterized by informality, constrained market access, and limited integration into the broader national and global economy. Historically marginalized under apartheid-era spatial planning, these economies continue to face structural barriers that hinder their growth and competitiveness. Despite various policy interventions aimed at fostering inclusive economic development, townships remain economically isolated, with low levels of formal investment and technological adoption. Given these persistent challenges, trade openness and information and communication technology (ICT) present two avenues for enhancing productivity and efficiency in these underdeveloped areas that the majority of the country's poor people call home.

Trade openness has the potential to unlock new market opportunities for township businesses by facilitating access to international markets, fostering competition, and encouraging innovation. The theoretical and empirical literature suggests that increased trade exposure can drive economic growth by improving resource allocation and enabling firms to benefit from economies of scale. However, it is argued that the extent to which township economies can capitalize on trade liberalization depends on their ability to overcome structural inefficiencies and leverage complementary factors such as technological adoption. In this regard, information and communication technology (ICT) plays a crucial role in

modernizing production processes, improving access to market information, and reducing transaction costs. Digital platforms, mobile banking, and e-commerce solutions have the potential to integrate township enterprises into regional and global value chains, mitigating the disadvantages of geographical and economic marginalization.

Despite the growing recognition of trade openness and ICT as key drivers of economic development, limited empirical research has examined their combined effects within the context of township economies. Most existing studies focus either on the impact of trade openness at a national or sectoral level or on ICT adoption in urban and formal business settings. Consequently, there is a gap in understanding how these factors interact in the unique setting of township economies, where informality, infrastructure deficits, and institutional constraints present unique challenges. This study seeks to fill this gap by probing the moderating role of ICT in the relationship between trade openness and economic growth in five major township economies in South Africa: Khayelitsha, Soshanguve, Soweto, Alexandra, and Tembisa.

Prominent studies on the growth effects of international trade (Dollar, 1992; Frankel & Romer, 1999) have largely demonstrated a positive and significant impact of trade openness on economic growth. While the evidence is, to a large extent, supportive of a positive link between openness and growth, the extent to which the benefits of trade openness accrue to township economies remains underexplored. In addition, very few studies have considered the moderating effect of ICT, which is surprising given the growing prominence of digitalization and its potential role in increasing market access. Against this background, this study contributes to the empirical evidence by examining the impact of trade openness on the technical efficiency of township economies in South Africa while considering the moderating role of ICTs. It defines technical efficiency as the ability of townships to produce at full potential.

Examining the impact of trade openness on the technical efficiency of township economies in South Africa and understanding the moderating role of ICTs is important for several reasons. First, township economies have failed to transform into cities since the advent of democracy in 1994 despite South Africa being a more open economy today than it was thirty years ago. It is generally understood from the literature that township economies face a myriad of factors that inhibit them from achieving their full potential (Moos & Sambo, 2018). Second, the majority of previously disadvantaged populations reside in township economies, where key drivers of economic activity—such as informal businesses, shebeens, and Spaza shops—operate on the margins of global markets due to poor connectivity and limited network coverage (Bvuma & Marnewick, 2020b). It is necessary, against this background, to shed light on whether improvements in ICT infrastructure can help township economies integrate into the global economy and reap the benefits of international trade.

Drawing from existing literature, there is strong evidence to suggest that trade openness and ICT adoption can serve as catalysts for economic transformation by enhancing access to global markets and fostering growth within townships. Trade openness and ICTs can particularly enhance the competitiveness of township economies by reducing transaction costs and enhancing access to information. It is additionally argued that digital technologies facilitate trade participation by lowering entry barriers, enabling e-commerce, and improving market linkages. Despite this potential, the extent to which ICTs moderate the trade-growth relationship in these economies is less known, and understanding this link could be key to unlocking the growth potential of township economies. This paper specifically tests the hypothesis that low ICT infrastructure may impede the ability of township economies to capitalize on trade opportunities.

The study contributes to the literature in the following four ways. First, it provides empirical evidence on the link between trade openness and technical efficiency in township economies, an area that remains underexplored in the existing literature. Second, it assesses the role of ICT as a potential enabler of efficiency gains, shedding light on the importance of ICT investments and their implications for township development. Third, given the current absence of a model that addresses both heterogeneity endogeneity and idiosyncratic endogeneity, this study uses an ad hoc procedure in which a within transformation is applied on frontier inputs based on the [Karakaplan \(2022\)](#) model. This procedure yields inefficiency scores that are not contaminated with unobserved factors specific to each township while at the same time circumventing the bias in frontier and inefficiency specifications. Fourth, it offers policy insights into how township economies can harness globalization and technological progress to enhance their competitiveness.

Given South Africa's ongoing efforts to promote economic transformation and digital inclusion, the findings of this study have important implications for policymakers. In addition, townships are characterized by high levels of poverty and economic stagnation, exacerbated by geographical marginalization. Therefore, targeting these areas from a research perspective could yield policies that may help the government to achieve Sustainable Development Goals (SDGs) 1 (No Poverty) and 2 (Zero Hunger).

Within the literature, this study is closely related to two strands of inquiry. The first strand comprises studies focusing on factors that hinder the growth and development of township economies ([Mbonyane & Ladzani, 2011](#); [Moos & Sambo, 2018](#); [Bvuma & Marnewick, 2020b](#); [Wiid & Cant, 2021](#)). A central conclusion reached in these studies is that township economies are constrained by the lack of government support, poor infrastructure, and lack of access to funding. The second strand of the literature comprises studies focused on the impact of trade openness on cities ([Karayalcin & Yilmazkuday, 2015](#); [Munir & Ameer, 2018](#); [Fang et al., 2020](#)). A common finding in these studies is that trade openness is associated with the expansion of cities and urbanization. While these conclusions shed important insights, they do not reveal much about how trade openness and ICTs affect the growth and development of township economies. This study, therefore, differs from the first strand of the literature by specifically focusing on the impact of trade openness and limited access to global markets. It differs from the second strand of the literature by exclusively focusing on township economies whose place in the trade-growth literature is yet to receive its fair share of scholarly attention.

The primary objective of this study is to empirically examine whether trade openness improves the technical efficiency of township economies in South Africa and whether ICT moderates this relationship. The specific problem motivating this analysis is the persistence of structural inefficiencies in township economies despite decades of economic liberalization. Specifically, the analysis poses the following question: do township economies benefit from trade openness, and can ICT help them overcome the structural barriers to global integration? This analysis seeks to contribute to the literature by combining trade, ICT, and efficiency analysis at a township level, which is a terrain rarely addressed in the existing literature.

The results corroborate the notion that township economies in South Africa operate below their full potential. On average, a typical township is found to have operated 19% below its full potential between 1995 and 2023. Evidence demonstrates the critical role of ICT in reducing inefficiencies associated with the participation of township economies in global trade. In particular, in the absence of adequate ICT infrastructure, exporting is associated with higher technical inefficiencies, highlighting the need for digital transformation for townships to maximize the benefits of participating in global markets. This conclusion aligns with endogenous growth theory, which emphasizes the role of technology

and knowledge diffusion in enhancing efficiency when participating in global trade. From a policy perspective, the results raise the need for targeted interventions such as the expansion of digital infrastructure, subsidies for ICT adoption, and digital literacy programs aimed at enhancing the integration of township economies into global markets.

The rest of the study is organized as follows. Section 2 reviews the theoretical and empirical literature. Section 3 provides the methodology. Section 4 presents and interprets the empirical results. Section 5 discusses the findings, while Section 6 provides the conclusion and policy implications and suggests areas for further study.

2. Literature Review

Township economies in South Africa have their roots in the country's apartheid era when racially segregated urban areas were created to enforce spatial inequality. They were primarily established as residential areas for black South Africans, who were denied access to better opportunities in productive cities. As a result, township economies remained underdeveloped, with limited infrastructure and resources. The apartheid government's policy of economic exclusion meant that these areas were largely isolated from global markets, with the majority of businesses being small, informal, and reliant on local demand.

In the post-apartheid period, where trade liberalization and market access have opened new avenues for growth, township economies are still struggling to compete on an international scale due to persistent barriers such as low productivity, inadequate infrastructure, and a lack of skills. Global market forces, coupled with the challenges of operating in a highly competitive environment, have made it difficult for township businesses to break into international supply chains. The lack of digital infrastructure and the slow adoption of ICTs have further hindered their ability to engage with global markets, leaving many township economies at the margins of South Africa's broader economic growth and limiting their capacity to benefit from globalization.

This section reviews the existing literature on three key areas: (1) the impact of trade openness on economic growth and efficiency, with a focus on developing and marginalized economies; (2) the role of ICT in economic transformation, particularly in improving productivity and market integration; and (3) the intersection of trade openness and ICT in driving economic development.

2.1. Theoretical Framework

This study is grounded in endogenous growth theory, particularly the models developed by Romer (1990) and Grossman and Helpman (1991), which emphasize the role of technological progress and knowledge diffusion in driving long-term economic growth. Romer's (1990) framework posits that technological advancements, facilitated by knowledge spillovers and innovation, enhance productivity and efficiency. In the context of township economies, ICTs serve as a conduit for these spillovers by enabling firms to access, absorb, and implement new knowledge and production techniques. The adoption of digital technologies reduces transaction costs, facilitates market access, and improves business processes, all of which improve technical efficiency. However, the extent of these efficiency gains may be contingent upon the level of digital infrastructure and firms' ability to leverage ICTs effectively.

Grossman and Helpman's (1991) open economy endogenous growth model further provides a theoretical lens through which to examine the role of trade openness in shaping efficiency outcomes. Their framework suggests that exposure to international markets enhances productivity by fostering technology diffusion, competitive discipline, and learning-by-doing effects. In township economies, trade openness creates opportunities for firms to integrate into global value chains, adopt foreign technologies, and improve

their production efficiency. However, without adequate ICT adoption, these benefits may not be fully realized, as firms may struggle to engage in digital trade, optimize supply chains, or absorb external knowledge efficiently. The interaction between ICTs and trade openness is thus conceptualized as a moderating mechanism that determines the extent to which township firms can enhance their technical efficiency. This study, therefore, situates itself within the broader discourse on endogenous growth and technological diffusion, examining how the synergistic effects of ICTs and trade openness shape efficiency dynamics in township economies.

In line with these theories, this study assumes that township economies produce output (Y) using capital stock (K), labor (L), and human capital (H). Further assumed is that, as a result of inefficiencies, the actual observed output deviates from the potential frontier output. The production function is specified as

$$Y = AF(K, L, H) \quad (1)$$

where A represents total factor productivity proxying efficiency in the use of K , L , and H . Assuming a Cobb–Douglas technology, we have

$$Y = AK^\alpha L^\beta H^\theta \quad (2)$$

where α , β , and θ are output elasticities with respect to capital stock, labour, and human capital. Trade openness and ICT are hypothesized to affect Y indirectly by influencing technical inefficiency. With this hypothesis, A can be specified as

$$A = e^{v-u} \quad (3)$$

where v captures deviations of observed output from potential frontier output due to factors beyond the control of township economies, and u is a term capturing deviations of observed output due to technical inefficiency. The final specification is given by

$$u = f(z) \quad (4)$$

where z captures the sources of technical inefficiency, including trade openness, ICT, and their interaction. It is hypothesized that ICT facilitates the benefits of participating in global trade; hence, townships that invest more in ICT are expected to benefit more from trading in global markets. This hypothesis is plausible given the widely documented role of ICT as a complement to international trade. ICT facilitates trade by reducing transaction costs, improving market access, and enhancing business productivity through digital platforms. In township economies, where structural impediments such as poor infrastructure and limited financial access constrain growth, ICT serves as a catalyst for local economic growth. Theoretically, as derived from open economy endogenous growth theories, ICT can enhance the benefits of trade openness by improving firms' ability to integrate into broader markets, access price information, and optimize production. In the context of this study, the interaction between ICT and trade openness is therefore expected to influence the technical efficiency of township economies, as firms that leverage ICT are likely to overcome traditional barriers to market entry and global competition.

2.2. Empirical Literature

Empirical studies examining the relationship between trade openness, ICT, and technical efficiency have largely focused on either macro, sectoral, or firm-level effects. A substantial body of literature highlights the role of trade openness in enhancing firm-level productivity by exposing producers to competitive pressures, encouraging technological

upgrading, and facilitating knowledge spillovers from international markets (Yasin, 2022; Mazorodze, 2020; Wenlong et al., 2023). Similarly, research on the use of ICT emphasizes its contribution to efficiency gains through improved information flows, reduced transaction costs, and enhanced production processes (Adeleye et al., 2021; Ndubuisi et al., 2022). However, the combined effect of trade openness and ICT on technical efficiency, particularly within the context of township economies, remains less understood.

Given the structural constraints and historical legacies of township economies, understanding how ICT adoption moderates the efficiency gains from trade openness is critical. Some studies suggest that ICTs enhance the absorptive capacity of producers, allowing them to capitalize on trade-induced efficiency gains (Suatmi et al., 2017), while others indicate that the benefits of trade liberalization may be limited in the absence of sufficient digital infrastructure (Adeleye et al., 2021). In addition, research has shown that factors such as crime and informality can also hamper the ability of townships to achieve their full potential. The following subsections review key empirical findings on these relationships, with a focus on studies that analyze their implications in developing economies and marginalized areas.

2.2.1. Trade Openness and Growth

A significant strand of the literature examines the relationship between trade openness and economic growth at a macro-economic level, with early contributions such as Dollar (1992) and Frankel and Romer (1999) demonstrating a positive and sizeable effect of trade openness on economic growth. Dollar (1992) argues that trade openness enhances growth by improving resource allocation and facilitating technology diffusion. Using cross-country data, he finds outward-oriented policies facilitating growth compared to restrictive trade policies. Similarly, Frankel and Romer (1999) provide empirical evidence that greater trade integration leads to higher income, primarily through increased specialization, economies of scale, and knowledge spillovers using an instrumental variable approach to pin down causality.

These studies largely suggest that trade liberalization promotes economic growth by expanding market access, encouraging investment, and accelerating technological progress. However, the magnitude of these effects depends on complementary factors such as institutional quality, infrastructure, and human capital. While trade openness creates opportunities for efficiency improvements, its benefits are not automatic, particularly in economies with structural constraints. Recent studies supportive of a positive causal effect of trade openness on economic growth include but are not limited to Jalil and Rauf (2021), Ibrahim and Abdulmalik (2023), and Abdulkarim (2023). A key methodological caveat raised and addressed in these studies relates to the endogeneity of trade openness. Most studies in this area use the panel Generalized Method of Moments (GMM), which uses lagged values of endogenous regressors as instruments.

2.2.2. ICT and Growth

Several studies have explored the impact of ICT on economic growth. These studies emphasize the role of ICT in enhancing productivity, innovation, and knowledge diffusion. Early studies, such as Röller and Waverman (2001), establish a positive relationship between ICT infrastructure and economic performance, arguing that digital connectivity facilitates efficiency gains by reducing transaction costs and improving access to information. More recently, using the partial least squares, Fernández-Portillo et al. (2020) similarly demonstrate that ICT contributes positively to economic growth, particularly in developed economies where digital adoption is widespread.

Some of the studies, including [Pradhan et al. \(2021\)](#), have differentiated between long-run and short-run effects. Pradhan et al. particularly focus on the role played by ICT in economic growth using data on 20 Indian states observed between 1991 and 2018. The results from their analysis demonstrated a causal effect of ICT on economic growth. This result is similarly documented in [D. Wang et al. \(2021\)](#), [Dumor et al. \(2024\)](#), and [Saba et al. \(2024\)](#). Particularly confirmed by [Dumor et al. \(2024\)](#) is that ICT and infrastructural growth have provided the East African Community (EAC) with opportunities to boost intra-regional trade. These findings, therefore, collectively suggest that ICTs are a catalyst for economic growth and could be vital for township economies where the participation of firms in global markets is impeded by structural barriers and geographical marginalization.

2.2.3. Trade Openness, ICT and Growth

Recent studies have considered the moderating effect of ICT on trade openness. These studies are mainly premised on the notion that ICTs improve trade efficiency by reducing information asymmetries, lowering transaction costs, and expanding market access. These effects are particularly pronounced in developing economies, where digital infrastructure enables producers to integrate into global supply chains and capitalize on international trade opportunities. Notable studies include [Awad and Albaity \(2022\)](#), who cite openness as one of the factors through which ICT penetration indirectly promotes per capita income growth. Others include [Clarke and Wallsten \(2006\)](#) and [Freund and Weinhold \(2004\)](#). Within this literature, common proxies for ICT include internet penetration, mobile phone subscriptions, fixed broadband subscriptions, ICT investment, telecommunication infrastructure, and ICT service exports.

2.2.4. Summary and Empirical Gap

From the above brief review, it is clear that a well-established body of literature has explored the relationship between trade openness and economic growth, with seminal studies such as [Dollar \(1992\)](#) and [Frankel and Romer \(1999\)](#) demonstrating that trade liberalization enhances economic performance. Parallel to this, the role of ICT in economic growth has been widely examined, with studies such as [Röller and Waverman \(2001\)](#) and [Fernández-Portillo et al. \(2020\)](#) highlighting ICT's ability to reduce transaction costs, enhance productivity, and foster innovation. Additionally, growing research explores how ICT moderates the trade-growth nexus, arguing that digital infrastructure strengthens the efficiency gains from trade, particularly in developing economies ([Clarke & Wallsten, 2006](#); [Awad & Albaity, 2022](#)).

Despite these insights, little attempt has been made to examine the relationship between trade openness, ICT, and economic efficiency at the township level, where structural constraints may limit firms' ability to fully capitalize on trade liberalization. Existing studies primarily focus on macro or industry-level analyses, overlooking the unique challenges and opportunities within township economies. This study extends the approach of [Abdulkarim \(2023\)](#) by incorporating an inefficiency term to account for deviations from frontier output due to technical inefficiency. By applying a stochastic frontier model, this research provides a more nuanced understanding of how ICT and trade openness jointly influence efficiency in township economies, something that has been overlooked in the literature.

3. Methodology

The empirical framework of this study uses the stochastic frontier model pioneered by [Aigner et al. \(1977\)](#). This approach is preferred over its alternative, the data envelopment approach (DEA), due to its ability to separate random noise from technical inefficiencies ([Aigner et al., 1977](#)). Township economies are generally confronted by adverse environ-

mental factors that are beyond their control, making the stochastic frontier analysis (SFA) more appealing. The analysis follows [Abdulkarim \(2023\)](#), who extended a Cobb-Douglas specification to accommodate the effect of trade openness. This study improves Abdulkarim's specification by adding an inefficiency term within a stochastic frontier framework to suit the context of the analysis. The application of a stochastic frontier model in analyzing township economies is particularly justified by the need to measure not only the productive capacity of these economies but also the extent of inefficiency that hinders their growth. Township economies operate in unique environments characterized by resource constraints and systemic inefficiencies. Unlike the traditional production function model applied in [Abdulkarim \(2023\)](#), which assumes that all deviations from the frontier are purely random, the stochastic frontier model explicitly accounts for inefficiency, making it a suitable framework for assessing productivity in these settings. By decomposing output deviations into inefficiency and statistical noise, the model allows for a more nuanced understanding of the constraints faced by township economies. In addition, given the role of ICT and trade openness as potential drivers of efficiency, the chosen framework provides a relevant empirical approach to analyze how these environmental factors interact with inefficiency.

3.1. Model Specification

Building on the theoretical framework presented earlier, the starting point empirically is specifications that take the following form:

$$Y_{it} = f(X_{it}\beta) + \varepsilon_{it} \quad (5)$$

$$\varepsilon_{it} = v_{it} - u_{it}$$

$$u_{it} = f(z_{it}) \quad (6)$$

where subscripts i and t denote township and year, respectively, Y is output, X is a vector of inputs (labour, human capital, and physical capital stock), β is a vector of frontier parameters, and ε_{it} is an error term composed of the random component (v_{it}) and the inefficiency term (u_{it}). The inefficiency term (u_{it}) specifically measures the distance between each township's level of output and its full potential. Equation (6) is then specified to identify the sources of inefficiency. In this equation, z is a vector of variables that affect efficiency. With the actual variables, the econometric specifications in this study take the following form.

$$\log(y)_{i,t} = \gamma_0 + \gamma_1 \log(L)_{i,t} + \gamma_2 \log(K)_{i,t} + \gamma_3 \text{EDU}_{i,t} + \varepsilon_{i,t} \quad (7)$$

$$u_{i,t} = \alpha_0 + \alpha_1 \text{OP}_{i,t} + \alpha_2 \log(\text{ICT})_{i,t} + \alpha_3 \text{OP}_{i,t} \times \log(\text{ICT})_{i,t} + \alpha_4 \log(\text{C})_{i,t} + \alpha_5 \text{INF}_{i,t} + \varepsilon_{ii,t} \quad (8)$$

$$i = 1, \dots, 5; t = 1995, \dots, 2023$$

where $y_{i,t}$ is the level of local GDP in township i year t ; L is labor captured by the number of employed workers; K is fixed capital stock; EDU is education, which is the share of literate population capturing the quality of labor; OP signifies trade openness; ICT captures the stock of information and communication technologies; C captures crime measured by the total number of reported crimes; and INF is informality measured as the number of informal workers as a share of total employment proxying the informal sector. The inclusion of the interaction term ($\text{OP} * \text{ICT}$) is motivated by the hypothesis that the impact of trade openness on technical efficiency in township economies is conditional upon the level of ICT infrastructure. That is, while trade openness theoretically enhances efficiency through exposure to global markets and technology spillovers, these benefits may not materialize

in contexts where townships lack the technological capacity to engage effectively with international markets.

This interaction term allows the model to capture the moderating role of ICT, consistent with the framework of open economy endogenous growth models (Grossman & Helpman, 1991), which emphasize the importance of absorptive capacity often facilitated by technology in realizing the gains from trade. Specifically, ICT facilitates access to market information, reduces transaction costs, and improves supply chain management, which ultimately enables producers in marginalized township economies to better participate in global markets.

The inclusion of crime and informality is driven by the need to account for factors that are peculiar to township economies. A potential criticism of these controls, however, is that both variables are likely to be measured with error. Crimes tend to suffer from underreporting, and the share of informal workers may not accurately reflect the true size of the informal sector. A mitigating factor is that the stochastic frontier method accounts for measurement error and noise in data (Aigner et al., 1977; Meeusen & van Den Broeck, 1977).

In terms of the channels, it is important to note that output growth in the empirical model above is achievable through the accumulation of physical capital, human capital, and labor (Mankiw et al., 1992). Trade openness and ICTs, therefore, affect output growth through raising productivity. Since $u_{i,t}$ is technical inefficiency, a negative slope coefficient in Equation (4) implies a positive relationship with technical efficiency. Negative and significant estimates of α_1 , α_2 , and α_3 would support the hypothesis that trade openness moves township economies closer to their full potential and that the effect increases with ICTs.

A key econometric concern in this analysis is endogeneity, which arises when explanatory variables are correlated with the error term. In the context of township economies, factors such as labor input, capital investment, trade openness, and ICT infrastructure may respond to unobserved shocks or be jointly determined with output, violating the exogeneity assumption. If not addressed, endogeneity leads to biased and inconsistent parameter estimates, undermining the reliability of the results. For example, if more efficient townships attract higher ICT investments or export more due to unobservable managerial quality, the model will overstate the true effect of ICT or trade openness on efficiency. Labor may also be endogenous since producers in townships often adjust employment based on productivity and wages. Capital, on the other hand, is likely endogenous since investment decisions are normally based on expected profits. To address this potential econometric challenge, the study adopts an instrumental variable (IV) stochastic frontier model, which instruments endogenous regressors with their lagged values.

The study specifically follows an approach proposed by Karakaplan (2022). Compared to other panel stochastic frontier models, such as the true-fixed effects of Greene (2005) and the frontier model of Battese and Coelli (1995), this approach accounts for the endogeneity of both frontier inputs and the sources of inefficiency. Using Karakaplan's (2022) approach, against the background of these endogeneity concerns, this study instruments labor, capital, openness, and ICT using their lagged values. The validity of these instrumental variables hinges on their relevance (strong correlation with the endogenous regressors) and exogeneity (uncorrelated with the error term). To establish relevance, first-stage regression results ought to have a strong predictive power of the instruments for the endogenous variables, typically assessed using the F-statistical test from the weak instrument test (Karakaplan, 2022). In the present case, using lagged values assumes that past values of labor, capital, OP, and ICT can only affect output by influencing current employment levels, capital stock, openness, and ICT. This is plausible since lagged values of labor, capital, openness, and ICT capture the dynamic adjustment process inherent in production decisions while remaining

exogenous to contemporaneous efficiency shocks. In addition to this intuition, a formal weak instrument test was performed post-estimation.

An important limitation of Karakaplan's (2022) approach is, however, that it contaminates technical inefficiency with unobserved heterogeneity, which makes it susceptible to overstating the levels of inefficiency. To circumvent this problem, this study applies the within transformation on frontier inputs to eliminate time-invariant factors specific to each township (such as historical, institutional, or geographic characteristics that may influence both output and inefficiency) as recommended by H. J. Wang and Ho (2010). The within transformation, commonly used in panel data analysis, involves de-meaning each variable by subtracting its time average for each cross-sectional unit (i.e., township). This essentially removes any township-specific fixed effects that do not vary over time, allowing for a cleaner identification of the relationships between explanatory variables and the dependent variable. In the context of the stochastic frontier model, this helps isolate the inefficiency effects from confounding township-level factors that are constant over time.

The frontier equation and the inefficiency specification can be estimated using either the two-step approach or the one-step approach. In the two-step approach, the frontier equation is first estimated using the maximum likelihood estimator. The sources of inefficiency are then estimated in the second step. It has long been demonstrated, however, that this traditional approach is biased (H. J. Wang & Schmidt, 2002). Therefore, this study uses the one-step approach in which the frontier equation and the inefficiency specification are simultaneously estimated, as recommended by H. J. Wang and Schmidt (2002) to prevent this bias. The empirical estimation is performed using Stata 17 implemented using the `xtsfkk` command developed by Karakaplan (2022). The within-transformation of frontier inputs is performed using the command: `egen X_mean = mean(X), by(id)`, where X is the frontier variable. This is followed by the command: `gen X_within = educ - X_mean`. For readers interested in replication, the specific codes are available upon request.

3.2. Data and Variable Description

The analysis uses an annual panel dataset comprising 5 major townships in South Africa (Khayelitsha, Soshanguve, Soweto, Alexandra & Tembisa) covering the 1995–2023 period. The use of panel data is justified by the need to account for unobserved factors specific to each township. While the panel dimensions of $T = 29$ and $N = 5$ yield 145, the ultimate sample size reported later in the regression table is 140 observations since the use of lagged values as instruments implies a loss of one observation for each township.

The 5 townships are selected due to their history, economic significance, and population size. Soweto, the largest and most economically active township, is essentially a microcosm of township economic activities in Johannesburg. Khayelitsha is one of the fastest-growing townships in terms of population size in Cape Town, which remains characterized by high unemployment and informal sector reliance. Alexandra, located near Sandton, one of the richest residential areas in South Africa, highlights the stark economic disparities between affluent and underdeveloped urban areas. Tembisa, with its rapidly urbanizing and growing middle-class population, sheds light on the evolving nature of township economies. Soshanguve, located near Pretoria, is home to a diverse population, which mainly includes the Sotho, Shangani, Nguni, and Venda tribes, hence the name SO-SHA-NGU-VE. These townships collectively provide a diverse and representative sample for understanding how trade openness and ICTs can drive township economic growth in South Africa. The sampling period is 1995–2023. The selection of this period is guided by the desire to focus on the democratic era, as South Africa was under economic sanctions prior to 1995.

In terms of measurement, there is currently no consensus on the appropriate measure of trade openness. Common measures applied in literature are tariffs and trade shares. Although tariffs are usually more appealing, they are measured at the macro level and, therefore, do not vary across townships. This makes them inappropriate for this analysis. Trade shares are more appealing for this study since they vary both over time and across townships. For this reason, trade openness was proxied in this study by the share of exports on total output expressed as a percentage. This is referred to in the literature as export intensity. A high value indicates high intensity, which often reflects a more open trade policy stance. While import penetration is an alternative, the use of export intensity measures is consistent with the idea that development is more achievable through outward orientation (Dollar, 1992). ICT is a stock variable expressed in logarithm form so that its effect can be interpreted as an elasticity. Both variables are expected to correlate positively with technical efficiency. Crime and informal labor are included to control some of the peculiar features of township economies. Table 1 contains variable descriptions and data sources.

Table 1. Variable description and sources.

Variable	Notation	Description	Measurement	Source
Output	Y	Local GDP	Log units	Statistics South Africa
Labour	L	Employment	Log units	Quarterly Labour Force Surveys
Capital	K	Fixed capital stock	Log units	Statistics South Africa
ICT	ICT	Stock of ICT	Log units	Statistics South Africa
Trade openness	OP	Export intensity	% of output	Statistics South Africa
Human capital	EDUC	Functional literacy	% of total population	Statistics South Africa
Informal sector	INF	Informal workers	% of total employment	Statistics South Africa
Crime	C	Number of cases	Log units	South African Police Service

The stock of ICT is measured by Statistics South Africa using the perpetual inventory method, which captures the cumulative value of ICT-related infrastructure and services (e.g., broadband penetration, mobile subscriptions, telecommunications investment) within a township. It is log-transformed to ensure scale comparability and to allow for elasticity-based interpretation. This proxy is widely used in the ICT-growth literature (e.g., Adeleye et al., 2021; D. Wang et al., 2021) and reflects the enabling environment for digital engagement in economic activities.

Human capital, while a broad theoretical concept, is operationalized using the percentage of the population that is functionally literate, a widely accepted and observable proxy in development studies. This aligns with prior research, including Mankiw et al. (1992), that treats literacy as a basic determinant of labor quality.

Labor input is proxied by the number of employed individuals, as reported in the Quarterly Labour Force Surveys (QLFS). It is essentially the number of paid employees and includes casual, seasonal, and informal workers. The QLFS is a nationally representative household survey designed to collect detailed information on labor market dynamics, including employment, unemployment, labor force participation, and characteristics of workers. Employment figures reported in the QLFS include individuals aged 15–64 years who, during the reference week, performed any work for pay, profit, or family gain or who had a job or business but were temporarily absent. This broad definition aligns with International Labour Organization (ILO) standards.

Capital input is proxied by fixed capital stock. According to Statistics South Africa, this refers to the value of all capital goods in a township at the beginning of a period. Fixed capital stock consists of buildings and construction works, transport equipment, machinery, and other equipment and transfer costs. The methodology employed by Statistics South Africa to calculate this stock variable is based on the perpetual inventory method.

Informal employment data are derived from two principal official datasets produced by Statistics South Africa, namely the Quarterly Employment Statistics (QES) and the Quarterly Labour Force Survey (QLFS). The QES, based on enterprise-level surveys, measures formal employment in non-agricultural sectors but excludes domestic workers, while the QLFS, based on household surveys, captures total employment across both formal and informal sectors, including agriculture and domestic work. To reconcile the differences between these sources, Statistics South Africa constructs a harmonized employment dataset by taking the formal employment figures from the QES and augmenting them with formal agricultural workers and domestic workers identified in the QLFS. Informal employment is then calculated residually as the difference between total employment reported in the QLFS and the adjusted formal employment estimate.

Output is measured by goods and services used or consumed by individuals, households, general government, and firms and is not processed further or resold within a township. It is essentially represented by the following equation: Final output = Expenditure on GDP = Gross domestic expenditure + Net exports = Gross domestic product (GDP) at market prices.

Crime is measured by the number of reported criminal cases compiled from administrative records maintained by the South African Police Service (SAPS). Reported crime data are disaggregated geographically, which allows one to match the crime incidents to township-level economic indicators. At the data source, crime figures are grouped into two categories, namely crimes reported by the community and crimes detected by police. In this study, the total of the two is used to represent crimes committed in each township.

To ensure the robustness of the results, several diagnostic checks were performed. These include tests for functional form, the presence of inefficiencies, and weak instruments.

4. Results

The results section proceeds as follows. First, it presents descriptive statistics to obtain a preliminary feel of the data and identify an anomaly prior to estimation. This is followed by a correlation matrix, which seeks to measure the degree of collinearity among the regressors. Subsequently, regression results are presented. Finally, diagnostic test results are presented to ensure the reliability of the main results. Following this chronology, Table 2 contains summary statistics. On average, exports accounted for only 8.4% of local output annually between 1995 and 2023, which falls short of the national average. This low average export intensity confirms the general concerns that township economies are marginalized from global markets. Education literacy averaged 66% of the total population, which is not surprising given how the government has invested in education since 1994. Informal workers accounted for 21% of total employment. Reported cases averaged 34,070 annually, which translates to roughly 93 cases per day.

Tables 3–7 present disaggregated summary statistics across the five townships. Alexandra and Tembisa stand out with the highest average export shares (16.6% and 14.3%, respectively), surpassing the national average and suggesting stronger integration into global markets, unlike Khayelitsha and Soweto, where exports remain below 3%. Education levels vary, with Alexandra leading at nearly 70% literacy, while Soshanguve lags at 61.3%. Informal employment is particularly high in Khayelitsha and Soweto, both exceeding 22%, reinforcing the precarious nature of township labor markets. Crime rates differ remarkably,

with Khayelitsha experiencing the highest average annual cases (57,391), over twice that of Alexandra and Soshanguve.

Table 2. Overall summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	145	11.675	0.291	10.997	12.131
loglabour	145	12.47	0.252	11.937	12.882
logcapital	145	11.617	0.23	11.11	12.041
logict	145	6.46	1.047	4.478	8.083
exports share	145	8.414	6.372	1.333	23.826
educ	145	66.022	5.757	50.941	73.862
informal share	145	21.132	4.319	12.83	29.926
crime	145	34,070.313	14,545.315	17,701	77,628

Table 3. Summary statistics—Khayelitsha.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	29	11.62	0.276	11.075	11.917
loglabour	29	12.687	0.15	12.442	12.88
logcapital	29	11.437	0.23	11.11	11.751
logict	29	6.324	1.058	4.509	7.757
exports share	29	2.804	0.52	1.612	3.833
educ	29	62.794	5.383	51.898	68.998
informal share	29	22.535	4.178	15.899	29.461
crime	29	57,391.002	13,753.95	32,126.7	77,628.33

Table 4. Summary statistics—Tembisa.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	29	11.804	0.294	11.175	12.131
loglabour	29	12.372	0.195	12.051	12.629
logcapital	29	11.684	0.22	11.347	11.971
logict	29	6.459	1.078	4.614	7.947
exports share	29	14.312	2.654	9.636	19.168
educ	29	68.997	4.983	57.762	73.384
informal share	29	19.871	4.042	13.601	26.607
crime	29	22,492.007	3178.46	17,701.42	29,053.93

Table 5. Summary statistics—Soweto.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	29	11.721	0.235	11.25	11.946
loglabour	29	12.716	0.13	12.521	12.882
logcapital	29	11.644	0.165	11.441	11.861
logict	29	6.521	1.016	4.756	7.883
exports share	29	2.306	0.317	1.333	2.663
educ	29	67.068	4.091	58.248	71.029
informal share	29	22.624	4.211	15.862	29.926
crime	29	36,483.987	4276.827	28,424.15	43,316.79

Table 6. Summary statistics—Alexandra.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	29	11.726	0.317	11.058	12.042
loglabour	29	12.218	0.167	11.937	12.435
logcapital	29	11.78	0.211	11.429	12.041
logict	29	6.648	1.057	4.756	8.083
exports share	29	16.566	4.308	10.513	23.826
educ	29	69.972	3.84	59.677	73.862
informal share	29	18.53	3.676	12.83	24.929
crime	29	29,803.701	5478.619	17,812.58	37,763.73

Table 7. Summary statistics—Soshanguve.

Variable	Obs	Mean	Std. Dev.	Min	Max
logoutput	29	11.504	0.246	10.997	11.732
loglabour	29	12.358	0.143	12.14	12.539
logcapital	29	11.542	0.166	11.329	11.764
logict	29	6.348	1.067	4.478	7.775
exports share	29	6.08	1.044	3.633	7.89
educ	29	61.281	4.966	50.941	66.364
informal share	29	22.099	4.113	15.663	29.068
crime	29	24,180.866	3488.476	18,493.28	30,664.65

The empirical results are presented in Table 8. Model EX ignores endogeneity, while Model EN serves as the baseline model, accounting for endogeneity. The upper section of the table reports frontier estimates, while the lower section presents results from the inefficiency specification. Two key findings emerge from the frontier equation. First, output growth is primarily driven by labor, with a 1% increase in labor associated with a 0.4% increase in output, holding capital and literacy rates constant. The inelastic response of output is typical in township economies where capital constraints limit the productivity gains from additional labor. In the literature, an inelastic coefficient of labor has similarly been observed in Coelli et al. (2003) (0.1%) and is comparable to the 0.59 reported in Bragagnolo et al. (2010). Second, capital has no statistically significant effect on output, while the impact of literacy rates is modest. The insignificance of capital suggests that township economies may be operating in environments where investments in physical capital are suboptimal and inadequate to sufficiently generate productivity gains. The marginal effect of human capital, on the other hand, could reflect the lack of employment opportunities for skilled workers in township economies. With limited employment opportunities, skilled workers often end up trapped in economic activities where their productivity is low.

In the inefficiency specification, the coefficient of log ICT is negative and statistically significant, indicating that ICT enhances efficiency. Export intensity shows up with a positive and significant coefficient, suggesting that exporting is associated with technical inefficiencies. While this result is not as expected theoretically, it is not particularly surprising considering that firms in townships operate on a small scale and lack the necessary resources and infrastructure to efficiently manage the demands of international markets. As theoretically expected, however, the interaction between export intensity and ICT is negative, demonstrating the crucial role of ICT in mitigating the inefficiencies associated with exporting.

Table 8. Trade openness, ICT, and technical efficiency.

Frontier Equation	Model EX	Model EN
Dependent var = Log Output		
Log Labour	0.489 *** (0.067)	0.418 *** (0.114)
Log Capital	0.055 (0.054)	0.031 (0.068)
Literacy (%)	0.003 *** (0.0004)	0.004 *** (0.0004)
Inefficiency equation		
Dependent var: $\ln(\sigma_u^2)$		
Constant	17.227 *** (2.727)	15.384 *** (2.035)
Log ICT	−1.183 *** (0.116)	−1.196 *** (0.107)
Exports/Output (%)	0.101 *** (0.029)	0.046 ** (0.023)
Exports/Output (%) × Log ICT	−0.027 *** (0.006)	−0.018 *** (0.004)
Informal workers/total employment (%)	0.011 (0.011)	0.014 (0.012)
Log Crime	−1.277 *** (0.235)	−1.021 *** (0.172)
Dependent var = Dependent var: $\ln(\sigma_v^2)$		
Constant	−7.555 *** (0.122)	
Dependent var = Dependent var: $\ln(\sigma_w^2)$		
Constant		−7.989 *** (0.125)
Eta1 (Log ICT)		−0.288 *** (0.042)
Eta2 (Exports/Output (%))		−0.019 *** (0.005)
Eta3 (Log Labour)		0.047 (0.151)
Eta4 (Log Capital)		0.848 *** (0.315)
Observations	140	140
Log Likelihood	312.91	1275.33
Mean Technical Efficiency	0.8318	0.8089
Median Technical Efficiency	0.8786	0.8580

*** and ** denote significance at 1% and 5%, respectively. Figures in parentheses are standard errors. In the specification, labor, capital, OP, and ICT are treated as endogenous, and they are instrumented by their first lag (i.e., $t - 1$).

With respect to the control variables, the evidence shows no significant link between informality and technical inefficiencies. Worrisomely, the crime variable is significantly negative, suggesting that criminality has a positive effect on economic activity in these

townships. The average technical efficiency based on the preferred model is 0.8089, suggesting that a typical township municipality produced about 81 percent of its potential output. Thus, a typical township economy operated about 19 percent below its full potential. When decomposed by township, Soweto was found to be the least efficient, operating 21% below its full potential. This illustrates a sizeable scope for economic transformation in these townships. It is necessary to mention that the trend variable was excluded from the specification to avoid unnecessary model overfitting, as it turned out to be highly insignificant. Its insignificance demonstrated the absence of technical changes or frontier shifts, which is not surprising given the low levels of innovation at the township level.

Diagnostic Tests

This subsection presents the results from diagnostic tests conducted to ensure the reliability of the results presented above. It was necessary to justify the Cobb–Douglas functional form in particular compared to its flexible counterpart, the Translog specification. It was also necessary to test the presence of technical inefficiencies as their absence would reduce the stochastic frontier model into a normal production function estimable using the standard ordinary least squares method. Lastly, the analysis tested for endogeneity as an instrumental variable approach when the variables are exogenous can be worse than the OLS method (Sturm, 1998). Accompanying this was a test for weak instruments.

Table 9 presents the results from functional form and inefficiency tests. The likelihood (LR) test statistic that compares the restricted OLS regression and the unrestricted stochastic frontier model is significant at a 1% level. This implies that the townships are technically inefficient and that a stochastic frontier model is justified over the standard OLS regression with normal errors. The Wald test was performed to determine the joint significance of interactions and higher-order terms in the frontier specification. As Table 9 shows, the test yielded an insignificant probability value, suggesting that the Cobb–Douglas specification was an adequate representation of the data. Table 10 presents the skewness of the residuals generated from an OLS regression. For a production-type stochastic frontier model, the presence of inefficiencies is normally reflected in negatively skewed residuals (Kumbhakar et al., 2015). The results in Table 6 validate this proposition, lending further support to a stochastic frontier model over a normal OLS regression. Table 11 presents the results of an endogeneity test. The test returns a low probability value, justifying the correction of endogeneity in the model. This result confirms that the true-fixed effects of Greene (2005) and other stochastic frontier models that ignore idiosyncratic endogeneity would be biased.

Table 9. Pre-estimation tests.

Test	Test Statistic	Conclusion
LR Test for technical inefficiencies	$-2 \times (H_0) - L(H_a) = 2218^{***}$	$u_{it} \neq 0$
Functional Form (Wald test)	$\chi^2 = 3.52, p\text{-value} = 0.1724$	Cobb–Douglas

*** denotes significant at 1%.

Table 10. Skewness of OLS residuals.

Variables	Obs	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
OLS residuals	145	0	0.077	−0.22	0.203	−0.135	3.336

Table 11. Endogeneity and weak instrument test.

Test	Test Statistic	p-Value
eta Endogeneity Test	$\chi^2 = 64.89$	0.000
Weak instrument test	$\chi^2 = 478$	0.000

Lastly, to test the strength of the instruments, the study applied the approach proposed by Karakaplan (2022). In Stata 17, this is achievable through the command `est res ModelEN` followed by the command `test iv`, where `iv` is a vector of instruments used in the model. As Table 11 shows, the corresponding probability of the test is low, which, as argued by Karakaplan (2022), suggests that the instruments are not weak.

In summary, the diagnostic tests justify the methodology used in the study. The LR test confirms the presence of technical inefficiency, validating the use of a stochastic frontier model over a conventional OLS regression. The Wald test for functional form adequacy reveals that the Cobb–Douglas specification is a suitable representation of the data, as higher-order terms and interactions were found to be statistically insignificant. Additionally, the skewness of OLS residuals aligns with the expectations of a production-type stochastic frontier model, reinforcing the choice of model. The endogeneity test reveals significant evidence of endogeneity, justifying the use of an instrumental variable approach to avoid biased estimates, while the weak instrument test confirms that the instruments employed are valid. Overall, the baseline results presented in this study can be deemed reliable based on these diagnostic checks.

5. Discussion

The main hypothesis of this study was that low ICT infrastructure may limit the ability of township economies to capitalize on trade opportunities. The evidence supports this claim as the interaction between ICT and export intensity is significantly negative. As argued in the literature, township businesses typically operate in localized and informal markets, limiting their ability to integrate into regional or global trade networks. ICT facilitates market expansion by enabling firms to access market information, connect with international buyers, and optimize supply chain logistics. This enhanced market access allows township firms to capitalize on export opportunities and reduce inefficiencies associated with exporting. The positive coefficient of export intensity is not surprising as it suggests that exporting is associated with technical inefficiencies when ICT is held constant. This result demonstrates the important complementary role of ICT if township economies are to take advantage of global market opportunities and achieve their full potential.

With respect to other variables, the weak positive effect of literacy on local output can be explained by the lack of employment opportunities for skilled workers in townships. The insignificant link between capital stock and local output, on the other hand, may reflect a suboptimal allocation of capital in townships, which limits the productivity of capital. This explanation is plausible considering Cant's (2017) proposition that South Africa's townships are confronted by suboptimal infrastructure.

The negative effect of crime on technical inefficiency suggests that criminality drives economic activity in townships. Although surprising at first glance, this result is consistent with the notion that criminality can be a source of livelihood when income inequality is high, and the labor market has limited employment opportunities. Therefore, crime may act as an informal livelihood strategy in contexts where formal employment is scarce. In such cases, illicit economic activity, although undesirable from a legal and ethical standpoint, might support household income and enable continued economic participation, thereby masking inefficiencies at the aggregate level. Another potential interpretation lies in the entrepreneurial resilience of township economies. In high-crime environments, firms may be compelled to adopt efficiency-enhancing practices (e.g., digital payment systems, security infrastructure, and localized supply chains). These adaptations may inadvertently improve productivity. A third possible explanation may relate to data limitations. Crime reporting is often higher in better-resourced areas due to stronger institutional capacity, which are also the townships with relatively better economic activity. In this view, the

negative relationship may be spurious, reflecting administrative efficiency rather than a causal economic link.

To explore this further, a sensitivity analysis was conducted using the one-year lag of crime to reduce the possibility of reverse causality. The direction and statistical significance of the coefficient remained robust, reinforcing the observed relationship. Nevertheless, given the complexity of crime's socio-economic impacts, this result should be interpreted with caution, and future research is encouraged to unpack this relationship more closely.

The finding that informality does not have a statistically significant effect on technical inefficiency is noteworthy, especially given the centrality of informal economic activity in township economies. One possible explanation is the heterogeneity within the informal sector. Informal businesses range from micro-enterprises with high entrepreneurial capacity to survivalist operations. These divergent characteristics may offset each other in aggregate analysis, resulting in no net effect on inefficiency.

A second consideration relates to measurement challenges. Informality is proxied by the share of informal workers in total employment, which may not fully capture the intensity or productivity of informal enterprise activity. Moreover, informality statistics often underreport actual activity due to definitional ambiguities and data collection constraints.

Lastly, it is plausible that informal businesses operating outside formal regulatory frameworks may already be operating near their efficiency frontier, constrained by limited capital, low overheads, and simplified production processes. In such cases, while these businesses may be small in scale, they might still exhibit technical efficiency within their operational context. These interpretations highlight the complexity of the informal sector's role in local productivity dynamics and suggest that a micro-econometric approach that distinguishes between types of informal activity may be needed in future research.

From a theoretical perspective, the main results of the study align with endogenous growth theory (Romer, 1990; Grossman & Helpman, 1991), which highlights the role of technological progress and knowledge diffusion in driving productivity and economic growth. ICT adoption facilitates knowledge spillovers, reduces transaction costs, and improves coordination, thereby increasing the efficiency of exporting firms in township economies. Empirically, the main results agree with Bvuma and Marnewick (2020a), whose results demonstrated the need to address ICT issues with SMMEs operating in South African townships. Makena et al. (2015) also highlight the positive role of ICT usage on businesses in township economies in the context of Zambia. The complementary role of ICT in exporting is in line with previous studies such as those of Kneller and Timmis (2016) and Adeleye et al. (2021). The analysis of Adeleye et al. (2020) particularly found that ICT enhances the impact of trade on growth in Africa. The current study has contributed to this understanding by presenting estimates drawn at the township level. Such a granular approach is important as it provides localized insights that are more applicable to the realities of townships, bridging the gap between macroeconomic findings and micro-level experiences.

It is important to mention the limitations of this study at this stage. First, the modeling approach employed in this analysis ignored spatial effects. Townships are not isolated economic units and may potentially interact with each other through supply chains, migration, and shared infrastructure. It is possible that technical efficiency improvement in one township could have positive externalities for nearby townships. Neglecting such spatial dependence may, therefore, paint an incomplete picture of inefficiency dynamics in townships. A mitigating factor, however, is that the five townships included in this analysis are hardly close to each other, making spatial spillovers arising from geographical proximity less problematic. In addition, incorporating spatial effects within a stochastic frontier framework remains a developing area of research, and the properties of many emerging

spatial stochastic frontier estimators are not yet well understood. Another limitation of the study relates to data constraints on some of the key challenges affecting the transformation of township economies, such as income inequality and limited access to funding.

Lastly, the study was based on a relatively small sample, which might hinder generalization beyond the five townships analyzed in this study. This sample reflected the best possible number of observations given current data availability and the need to focus on major townships. Township-level annual economic data are only systematically available from 1995 onwards, and extending the sample period further was not feasible. Similarly, data coverage across townships is highly uneven, and only five major township economies had sufficiently complete data to support the analysis. While recognizing the sample size limitation, the use of small-N panel econometric techniques and diagnostics tests performed provides reasonable confidence in the validity of the empirical findings. Future research could expand the scope as more township-level data become available over time.

6. Conclusions

This study set out to examine the impact of trade openness on the technical efficiency of township economies in South Africa and to assess whether ICT acts as a moderating factor in this relationship. Using an instrumental variable stochastic frontier model applied to a balanced panel of five major townships from 1995 to 2023, the results provide clear empirical support for the hypothesis that ICT significantly enhances the efficiency benefits of trade openness. The findings of this study particularly provide strong empirical evidence that inadequate ICT infrastructure constrains township economies from fully capitalizing on trade opportunities. The significant negative interaction between ICT and export intensity underscores ICT's critical role in facilitating market access, optimizing logistics for townships, and reducing inefficiencies. Without sufficient ICT infrastructure in place, exporting is linked to technical inefficiencies, highlighting the urgent need for digital transformation to maximize the benefits of trade liberalization. This conclusion aligns with endogenous growth theory, which emphasizes technology and knowledge diffusion as key drivers of efficiency and long-term economic growth.

These findings contribute to economic theory by extending the application of endogenous growth models to subnational township economies, a domain typically excluded from the macro trade-growth empirical literature. The study introduces new empirical insights to understand productivity dynamics in marginalized urban contexts by demonstrating that the interaction between ICT and trade openness significantly affects technical efficiency.

From a practical perspective, the results carry important implications for policymakers. Targeted interventions to expand digital infrastructure, promote digital literacy, and subsidize ICT adoption can unlock significant efficiency gains in township economies, particularly by enabling informal and small businesses to engage more effectively with global markets. The results essentially highlight the pressing need for policies that strengthen ICT infrastructure in South African townships to ensure that firms reach the full potential of global market participation. Given that ICT mitigates inefficiencies associated with exporting, government interventions may need to, as alluded to shortly above, focus on expanding digital access, subsidizing ICT adoption for small businesses, and implementing digital literacy programs. These initiatives would empower township enterprises to integrate more effectively into regional and global markets, improving efficiency and boosting local economic output.

A key limitation of this study is its inability to account for spatial dependencies, which may influence efficiency spillovers across township economies. Future research could explore recent advancements in spatial stochastic frontier models to capture the potential interdependence of township economies. Additionally, future studies could apply the

indirect production function approach to examine the combined effects of ICT and trade openness on technical efficiency in the presence of borrowing constraints.

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