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Efficiency Frontier of World MNOs: Multinational vs Domestic¹

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ITS 2021 Conference Paper

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1. Introduction

Mobile telecommunication plays an increasingly important role in the development of the world economy and is one of the most vibrantly growing industries. In 2019 mobile technologies and services generated \$4.1 trillion of economic value, accounting for 4.7% of world GDP. This contribution is expected to keep increasing and reach by 2024 \$5 trillion or 4.9% of world GDP respectively (GSMA 2020). New technological solutions in the mobile telecommunication industry are expected to be the catalyst for re-shaping the global economy by creating new jobs and industries dependent on the new technologies. 5G alone based on the current forecasts could enable 2.1% of global income growth in the next decade (GSMA, 2020) and create 4.6 million jobs worldwide by 2034 (Mendel & Long, 2020). Such growth, perspectives of further development, and importance for the global community attract the attention of both business and academia to the industry.

Of particular interest is the efficiency of the mobile network operators (MNO). Efficiency in general is an illustrative indicator of business performance (Reddy et al, 2019). Monitoring MNOs' efficiency over time can provide insight into the dynamics of the enterprise and if the company utilises its resources optimally. Evaluation of performance efficiency is important to the companies because it can reveal the potential sources of inefficiency from both financial and operational standpoints, enabling the development of an appropriate strategy to counter the efficiency pitfalls. It is also beneficial to the end users in the form of better quality of services, as well as for the regulatory agencies in developing the telecommunication policy (Oredegbe & Zhang, 2020).

Efficiency frontier analysis is of importance to MNOs both in the developing and the developed countries. For the latter it is especially beneficial in conditions of highly competitive saturated markets, and pressure from the OTT (Chen, 2019). The developed countries make a good comparison case due to relatively similar levels of telecommunication infrastructure and economic development, while the policies of the regulators and strategies of the companies differ (Castelnovo et al., 2019). Thus, the differences observed among the MNOs in the developed countries are theorised to occur due to the difference in management and policies rather than the gap in technologies. In line with the aforementioned reasoning, the present research focuses on OECD countries, which are regarded as developed market economies with democratic political systems (IMF, 2010).

Another interesting feature of the developed nations is the presence of strong multinational (MNE) and domestic enterprises (DE). Many leading telecommunication companies in OECD countries appeared after the demonopolisation of the telecommunication market and subsequent privatisation of the state-owned telecommunication monopolist. The latter became both MNE (such as Deutsche Telekom, Telefonica) and DE (Polkomtel, KT). While the reasons for such transformations are beyond the scope of this study, availability of relatively equally developed MNE and DE makes an interesting comparison case from an understudied in academia perspective.

Pursuant to the context presented above, this study evaluates the efficiency frontier for 34 mobile operators in 19 OECD countries over the period of five years between 2014 and 2018, and compares the efficiency of MNE and DE. The efficiency score of MNOs is analysed using Data Envelopment Analysis (DEA) based on companies' non-financial operational performance data. Mann-Whitney U-test is used to statistically verify whether there is a difference between the MNE and DE in terms of performance efficiency.

The present paper also explores the efficiency trends in telecommunication industry in the developed countries. Unlike many previous studies on the topic, this research offers to analyse the efficiency frontier with the use of non-financial data. Our findings suggest that DE are overall more efficient than MNE. The authors hypothesise the advantage of domestic companies is associated with the better knowledge of the local market and business practices, and with more cautious management of own resources by the DE. The results might foster better understanding of the efficiency frontier dynamics and provide empirical insights for managers and national regulators to identify the sources of inefficiency, and therefore help to respond to them from an operational perspective. The paper also contributes to the academic discussion on the comparison of the MNE and DE in general, and in telecommunication sector in particular.

The remaining part of this paper is organised as follows. Section 2 presents an overview of previous academic works on two topics: evaluation of efficiency frontier and use of non-financial measures for it, and comparative analysis of domestic and multinational enterprises. Section 3 introduces theoretical framework for the two prominent DEA methodology used in the research: SBM Max model, and Malmquist Productivity Index. Section 4 provides and interprets the empirical results, and touches upon their implications. Section 5 concludes the paper with a brief summary of the study, discusses its limitations, and shares ideas on possible further research of the topic.

2. Literature Review

2.1. Evaluation of efficiency frontier

Evaluation of efficiency frontier of telecommunication sector has been previously approached in the literature in different contexts. Many studies focused on benchmarking MNOs globally or in a certain geographical region. Tsai, Chen, & Tzeng (2006) analysed the efficiency of 39 world's leading telecom operators which had been placed on the Forbes 2000 company ranking. Applying the DEA CCR model with financial input and output variables, the researchers found that only 20.5% of the companies on the list to be technically efficient, thus marking the importance of empirical efficiency benchmarking research. Asia-Pacific operators were also found to be more efficient than the European and North American ones. Lu & Hung in two subsequent articles analysed 36 (Hung & Lu, 2007) and 24 (Lu & Hung, 2008) leading global mobile operators in terms of production efficiency using Forbes 2000 financial data. The studies found the scale of MNOs' operations to have a significant influence on the efficiency score, and that state-owned enterprises were generally more efficient. Contrary to the previous research, the European mobile operators were found to be the most

efficient. Yang et al. (2013) carried out a comparative meta-frontier analysis to trace the impact of regulation on efficiency of 85 MNOs from around the world between 2001 and 2010. While Asian companies enjoyed the highest efficiency scores, the efficiency meta-frontier was spearheaded by the US enterprises. The rapid shift of efficiency primacy from Asia to Europe to the US and Asia again is illustrative to why regular efficiency benchmarking is beneficial for the companies willing to preserve their comparative advantages. Recent analyses of mobile telecommunication efficiency global also went beyond benchmarking and took into consideration new developments in the industry. For example, Chen (2019) using DEA meta-frontier analysis investigated the impact of the OTT on three different facilities-based groups of 41 telecom companies between 2012 and 2017. The results showed that OTT had a significant impact on mobile operators' revenue by partially or fully substituting their IDD, mobile voice, and short messages services.

Another group of works focused on a particular group of countries, united by an international organisation framework. Sueyoshi (1994) analysed the performance of the telecommunication industry in 24 OECD member countries and found smaller countries can be equally efficient as large nations. Lien & Peng (2001) researched the efficiency of 24 OECD countries during the period of 1980 to 1995 and concluded that increased competition had a beneficial influence on the efficiency scores. Pentzaropolous & Giokas (2002) compared 19 European public telecommunication organisations within the OECD. Among the conclusions, the authors argue that both small and large scale companies can achieve full efficiency regardless of the amount of revenue, and noted that managers and organisations should use benchmarking studies to seek and identify key operational characteristics of and similarities among fully efficient cases of benchmarking. In their subsequent study (Giokas & Pentzaropolous, 2008), the authors expanded the scope to 30 OECD members and analyzed the countries from productivity and revenue perspectives, finding the EU lagging behind the US and Asia, attributing it to the issues of EU telecom regulation. Oredegbe & Zhang (2020) examined high- and middle income countries categorised by GNI per capita between 2001 and 2013. The results of the study indicate that the middle-income countries are catching up with the high income countries, and that technical inefficiency was mostly the result of managerial ineffectiveness. Less prominent attention is received by other international frameworks, such as BRIC (Liao & Gonzales, 2009) or G8 (Diskaya, Emir, & Orhan, 2011).

A range of papers focused on regional level performance. Authors researching Europe investigated the effect of privatisation, liberalisation, and protectionism on the regional telecommunication market (Torres & Bachiller, 2011), compared the performance of old and recently joined members of the EU (Usero & Asimakopoulos, 2013), examined relative performance of MNOs in context of number of subscribers and technological change (Asimakopoulos & Whalley, 2017). In Asia-Pacific, Hu and Chu (2008) performed the benchmark of 24 APEC MNO over 1999-2004 and explored the impact of environmental factors on the efficiency scores. The empirical results indicated GDP per capita had a strong impact on performance efficiency, while market competition was interestingly found to have no significant effect on the scores. Hu & Lien (2012) compared 16 APEC telecom operators between 2001 and 2008 in context of technological gap and found operators in countries with

higher penetration rate to be overall more efficient regardless of the scale. Contrary to the results of the previous research, Hu et al. (2018) found the “jumping” countries, i.e. countries, that skipped the development of fixed telecom infrastructure in favour of robust mobile infrastructure, showed higher total asset efficiency. Aside from studies on APEC countries mentioned above, Asia is represented in comparative studies on the telecommunication efficiency frontier with some works on South-East Asia countries (Hendrawan, Nugroho, & Permana, 2020; Sari et al., 2021), and the Middle East (Naimy & Merheb 2014). Less frequent in academia are analyses on Africa, which usually focus on research objectives other than benchmarking due to region's lack of reliable data. A study on the impact of investment on ICT in general by Bollou & Ngwenyama (2009) might serve an example of telecommunication research in Africa. Similarly, Latin America also remains underrepresented in the academic works on the telecommunication industry efficiency frontier (e.g., Llungo-Ortiz, 2014).

Additionally, MNOs' efficiency is compared within one country. India's vibrantly developing telecommunication market has received a lot of attention in particular. Nigam et al. (2012) carried out a benchmarking of 126 public and private MNOs in India and used sensitivity analysis to identify the most inefficient MNOs for the regulators and policy makers to take notice of. Kumar, Shankar, & Debnath (2015) explored consumer's preference in context of technical efficiency of MNOs. Naimy & Merheb (2014) undertook an analysis of MNO efficiency in the Middle East region. S Kwon (2014) combined artificial neural network with DEA to examine the efficiency of the Korean MNO in a novel way and predict the efficiency dynamics in the future. Yang & Chang (2009) applied the DEA window model to investigate the efficiency of Taiwanese mobile operators in a period of growing competition and stagnating subscriber base, and the impact of MNOs mergers. The US telecommunication industry was analysed by Majumdar (1998) from the perspective of resource utilisation, and by Uri (2001) in the context of local exchange carriers. Lam & Shiu (2008) advocated for consolidation of China's telecommunication industry. Having examined the efficiency of many Chinese local operators, they concluded that labour redundancy and varying operating conditions prevented many operators from being fully efficient. The analysis can even pertain to a single company, as in the research undertaken by Giokas & Pentzaropoulos on the Hellenic Telecommunication Organisation (Giokas & Pentzaropoulos, 2000)

Most of the papers discussed above employ DEA based predominantly on financial data for input and output variables. Despite the importance of operational data for monitoring the efficiency of a company emphasized by researchers (Kaplan & Norton, 1992; Chow & Van Der Stede), the works evaluating the efficiency of telecommunication industry based on operational non-finance data are not numerous, thus leaving the operational aspect of efficiency unexplored. Table 1 lists examples of the variables used in DEA in recent studies.

Table 1

Authors	Method	Type	Input(s)	Output(s)
Pentzaropoulos & Giokas (2002)	DEA BCC-O	Financial and operational	<ul style="list-style-type: none"> ● Access Lines ● Mobile Subscribers ● Headcount 	<ul style="list-style-type: none"> ● Revenue
Hung & Lu (2007)	Extended DEA	Financial	<ul style="list-style-type: none"> ● Total Assets ● CAPEX ● Headcount 	<ul style="list-style-type: none"> ● Revenue ● EBITDA ● EBIT ● Net Income
Yang & Chang (2009)	DEA Window Analysis	Financial and operational	<ul style="list-style-type: none"> ● Assets ● Operating Cost ● Operating Expenses 	<ul style="list-style-type: none"> ● Operating Revenues ● Mobile Subscribers ● Mobile Calls
Torres & Bachiller (2011)	DEA Dual oriented BCC-I	Financial	<ul style="list-style-type: none"> ● Headcount ● Total Assets 	<ul style="list-style-type: none"> ● Operating Revenue
Yang et al. (2013)	DEA Meta Frontier	Financial	<ul style="list-style-type: none"> ● Total Assets ● Headcount ● CAPEX 	<ul style="list-style-type: none"> ● Net Sales
Hendrawan, Nugroho, & Permana (2020)	DEA & SFA	Financial and operational	<ul style="list-style-type: none"> ● CAPEX ● OPEX ● total assets 	<ul style="list-style-type: none"> ● Revenue ● Mobile Subscribers ● Data Traffic
Oredgebe & Zhang (2020)	DEA CCR-I + TOBIT	Financial and operational	<ul style="list-style-type: none"> ● CAPEX ● Subscribers ● Headcount 	<ul style="list-style-type: none"> ● Revenues ● Teledensity

2.2. Multinational vs Domestic

Globalization and expansion of MNE internationally have been reflected in academia with an increased number of papers aimed at researching the phenomenon. Foreign direct investments (FDI) being the crucial mechanism for MNEs' expansion over the world (Tijdens, Gregory, & van Klaveren, 2013), many of the works on MNE focused on their financial performance and impact on the targeted for expansion markets. In particular, fear that MNEs

would put additional pressure on DE, thus reducing the efficiency of the latter or pushing them out of business, prompted research on performance, comparative advantages, and interaction of DE and MNE.

Despite MNE being theoretically posed as having numerous advantages over DME, empirical studies are not unanimous about this notion. The results of MNE and DE performance comparison by Michel & Shaked (1986) indicated that despite significantly larger capitalization of MNE, DE appeared as significantly superior in risk-adjusted market performance. Lee & Kwok (1988) analysed capital structure of DE and MNE in the US and empirically showed that US MNE actually tended to be less leveraged than American DE, although the tendency differed across industries. Bhattacharya & Michael (2008) reviewed fifty DE which won their local markets, and analysed the possible reasons for such a domination, pointing out that DE can effectively rival large MNE. The results of the research in question, however, should be interpreted carefully due to the focus on protectionist markets of such countries as China, which favour their home companies. Shah, Anwar, & Hasnu (2018) presented an ambivalent result with DE having higher efficiency in managing the work capital yet lagging behind MNE in terms of financial performance.

Empirical results from a range of papers present an opposite opinion. In the case of the US, the results of Doms & Jensen (1998) indicate superior operating characteristics and higher productivity of the foreign-owned manufacturing enterprises. They underline, however, that the difference is largely explained by belonging to a MNE rather than simple foreign ownership. Pfaffermayr & Bellak (2002) compared MNE and DE in Austria and came to similar conclusions, attributing increased productivity to the spillovers from MNE network. Similar results were obtained in the cases of the UK (Criscuolo & Martin, 2005) and Germany (Temouri, Driffield, & Añón Higón, 2008). The MNEs were found to be overall more productive in line with the advantages predicted by the theoretical models of MNE. On an international level, Chacar, Celo, & Thams (2010) also found MNE to outperform DE, although the results suggested diminishing performance gap over time.

Some studies, however, question whether there is a significant difference between DE and MNE. Bellak (2004) conducted an extensive analysis of a large pool of literature comparing MNE and DE, namely about the advantages MNE supposedly had over DE in accordance with the Multinational Enterprise Theory, and other theoretical background. Having scrutinised previous empirical works, Bellak concluded that the differences between MNE and DE, including the performance gap, were due to the differences between the individual characteristics of the companies rather than nature of ownership.

Based on the works above, the comparative advantages of DE and MNE can be summed up, albeit not exclusively, as follows in Table 2:

Table 2

DE	MNE
<ul style="list-style-type: none">● Superior knowledge of domestic market, business practices, and consumer preferences (Griffith, Redding, & Simpson, 2002).● Easy customization of the products to the local needs (Bhattacharya & Michael, 2008).● Faster scaling up and going national (Bhattacharya & Michael, 2008).● Innovative business strategies (Bhattacharya & Michael, 2008).● Grooming local talents (Bhattacharya & Michael, 2008).● Better connections in local regulatory circles (Shah, Anwar, & Hasnu, 2018).	<ul style="list-style-type: none">● Reduced Probability of Bankruptcy (Michel & Shaked, 1986).● Extensive set of information for evaluating different situations (Bellak, 2004).● Larger managerial resources to tackle more complex issues (Bellak, 2004).● More instruments against governments and regulations (Bellak, 2004).● More skilled personnel as a result of higher wages (Bellak, 2004).● Higher labour productivity (Griffith, Redding, & Simpson, 2002).● Increased consumer base (Shah, Anwar, & Hasnu, 2018).

As noted in previous works, the gap between MNE and DE varies across different industries (Lee & Kwok, 1988). Yet many previous researches comparatively analysing MNE and DE did not focus on a particular industry and reviewed a broad set of companies of various backgrounds. Telecommunication industry in particular has not been thoroughly examined in the context of comparative performance of multinational and domestic companies. According to the data on corporate internationalisation in the EU, telecom industry was the most diversified as of April 2008 with 3.8 subsidiaries per MNE (Tijdens, Gregory, & van Klaveren, 2013), indicating a robust network of MNEs in the developed European countries.

With the results of previous academic research on MNE and DE predominantly indicating the advantage of MNE and strong presence of MNE in many developed countries, we hypothesise that multinational telecommunication companies having greater access to innovative technologies, experience of operating under different regulator policies, and higher labour productivity are more efficient than domestic telecommunication companies.

H_1 : MNE are more effective than DE.

3. Methodology

This research includes three stages. In the first stage DEA SBM Max model is used to obtain the efficiency scores as well as the slacks of the telecommunication companies separately for every time frame.

During the second stage Malmquist Index (MI) is used as an additional efficiency analysis tool to examine technological frontier changes, catch-up effect, and dynamics of total factor productivity of the enterprises observed over time.

Finally, Mann-Whitney U test is carried out to examine if there is a statistically significant difference between DE and MNE in terms of performance efficiency and to test our hypothesis H_1 . The calculations of DEA and MI were carried out with Saitech's DEA Solver 15 software, and Mann-Whitney test in Stata 16 software respectively.

3.1. DEA Model

DEA is a recently gaining popularity method for comparatively evaluating efficiency of decision making units across different industries from banking (Paradi, Rouatt, & Zhu., 2011), to healthcare (Zheng et al., 2018). The result of DEA is a scalar measure of efficiency of a decision making unit (DMU) on a range of zero (zero efficiency) to one (full efficiency) interpreted as a surrogate measure of a firm's performance and as an indicator for a firm's competitive status and potential risks (Kwon, 2013). DEA is especially popular because it offers clear a way for their improvement of a DMU based on empirical findings (Nigam et al., 2012). Other features that make DEA appealing are:

- non-parametric nature of DEA, allowing researchers to work with a broader range of data without the necessity of making assumptions about the data distribution (Kwon, 2013);
- simultaneous handling of multiple input and/or output variables, creating opportunity for a variety of models and approaches;
- unit invariance, which provides flexibility when scaling the data without the risk of influencing the result;
- DEA deals with a reference set based on the research sample rather than the best approximated mean of regression. Comparison to the best performer from among those being studied thus can provide insight into feasible steps for performance improvement (Cooper, Seiford, & Tone, 2007).

There has been developed a variety of DEA models since the original CCR model was introduced by Charnes, Cooper, & Rhodes in 1978. Generally, there are two types of DEA models: radial and non-radial. Radial models include CCR and BCC models, and the variants thereof. These models deal with proportional changes of inputs and outputs. Such an approach, however, has drawbacks. Tone (2016) argues that in the real world not all inputs and outputs change proportionally. In DEA slacks stand for excesses in inputs or shortfalls in outputs, thus directly indicating potential sources of inefficiency (Avkiran, 2009). Radial models ignore slacks when reporting the efficiency score, possibly misleading a decision based thereon when the efficiency score is used as the only criterion for evaluation of DMU's performance (Tone, 2016).

Another classification of DEA models presumes input- and output-orientation. Input-oriented models minimise input(s) for a given level of output(s), that is how much input(s) can

be decreased while maintaining the same level of output(s). Similarly, an output-oriented model maximises the output(s) with regard to a given level of input(s) (Huguenin, 2012). While it has been suggested to use input-oriented models to study companies on the premises that companies have more managerial control over inputs (Torres & Bachiller, 2011) and, therefore the focus usually is on how changes in inputs scale with the outputs (Cooper, Thompson, & Thrall, 1996), radial oriented and non-oriented models suffer from infeasible solutions in intertemporal score (Cooper, Seiford, & Tone, 2007).

To overcome these limitations, Tone developed a Slack-Based Measure (SBM) model (Tone, 1997). SBM is a non-radial model which deals with slacks directly and can be non-oriented. Since then a number of SBM model variations have been introduced (Tone, 2015). This research employs one of the latest variations of the SBM model developed by Tone, SBM Max model. Original SBM model or SBM-Min model (Tone, 2001) evaluates the efficiency of a DMU referring to the furthest frontier point within a range. The model developer argued that this led to the projection going to a remote point on the efficiency frontier which is not always appropriate as a reference point (Tone, 2010). In comparison, SBM Max model deals with the nearly closest points on the efficiency frontier. The results of SBM Max allow for a DMU to attain the efficiency status with less input reductions and output expansions, making them more practically useful to the decision makers. Therefore, Tone regards the model as “Kaizen” (improvement - Jap.) tool by DEA (Tone, 2016). With a view to maximise the practical implications of this study, we opt for the SBM Max model.

The non-oriented SBM Max for a DMU (x_o, y_o) ($o = 1, \dots, n$) with optimal solutions $(\lambda^*, s^{-*}, s^{+*})$ starts with solving ordinary SBM model:

$$\rho_o^{min} = \lambda, s^-, s^+ \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{ro}}}$$

Subject to:

$$\begin{aligned} x_{io} &= \sum_{j=1}^n x_{ij} \lambda_j + s_i^- \quad (i = 1, \dots, m) \\ y_{ro} &= \sum_{j=1}^n y_{ij} \lambda_j + s_r^+ \quad (r = 1, \dots, s) \\ \lambda_j &\geq 0 (\forall j), s^- \geq 0 (\forall i), s^+ \geq 0 (\forall r) \end{aligned}$$

Then the reference set of all efficient DMUs is defined:

$$R^{eff} = \{j | \rho_j^{min} = 1, j = 1, \dots, n\}$$

For inefficient DMUs local reference set is defined:

$$R_o^{local} = \{j | \lambda_j^* > 0, j = 1, \dots, n\}$$

For each inefficient DMU (x_o, y_o) , i.e. $\rho_o^{min} < 1$ distance between (x_o, y_o) and efficient DMUs $(x_h^{eff}, y_h^{eff}) (h = 1, \dots, N_{eff})$ where N_{eff} is the number of efficient DMUs.

$$d_h = \sum_{i=1}^m \frac{|x_{ih}^{eff} - x_{io}|}{x_{io}} + \sum_{i=1}^s \frac{|y_{ih}^{eff} - y_{io}|}{y_{io}}$$

Then the efficient DMUs are renumbered in ascending order of d_h so that $d_1 \leq d_2 \leq \dots, \leq d_{N_{eff}}$. Subsequently, R_h set is set:

$$R_h = \{1, \dots, h\} (h = 1, \dots, N_{eff})$$

The efficiency scores and slacks of inefficient DMUs (x_o, y_o) are then evaluated with reference to the set of R_h :

$$\lambda, s^-, s^+ \max \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_{io}^-}{x_{io}}}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{ro}}}$$

Subject to:

$$x_o = \sum_{j \in R_h} x_j^{eff} \lambda_j + s^-$$

$$y_o = \sum_{j \in R_h} y_j^{eff} \lambda_j - s^+$$

$$s^-, s^+, \lambda \geq 0$$

Finally, SBM Max score ρ_o^{max} is defined for inefficient DMUs.

$$\rho_o^{max} = \max\{\rho_o^{pseudo\ max}, \rho_{o1}^*, \dots, \rho_{oN_{eff}}^*\}$$

The model presumes additional steps in case of unfeasible solutions. For details, please see Tone (2015) on which this explanation is based.

3.2. Choice of Input and Output Variables

To use the aforementioned DEA model, the input and output variables are to be chosen by the researcher. As it was mentioned in the literature review section, most of previous research relied fully or partially on financial variables. In this study purely non-financial variables are employed.

Total annual data volume traffic transferred over the network of a given MNO is the only output variable. Data volume is an important performance indicator especially in the developed countries where it is attributed as the primary driver for ARPU growth (Tefficient, 2019). It is also a good indicator of company's dynamics: GSMA reported a surge of mobile data traffic in recent years as more and more people migrate from WiFi to mobile networks

(GSMA, 2015), putting additional strain on the existing infrastructure. In this research we view total data traffic volume as the capacity of a MNO to deliver its services to its clients and whether the MNO is effective in delivering the maximum possible volume of data given the inputs leading to DEA efficiency.

In the DEA model used in this research total data volume is viewed as a function of the total number of connections and total spectrum. Therefore, the two input variables used are the total number of mobile subscriptions and the total spectrum. The total number of subscriptions represents a total number of SIM cards as reported by MNO for the time period regardless of the category (e.g. prepaid, post-paid, etc.) but excluding M2M connections. The total spectrum range stands for a sum of all frequency bands allocated to MNO for the time period being investigated.

The number of subscribers has been used as a variable both as input (Pentzaropoulos & Giokas, 2002; Reddy et al., 2019, Oredegbe & Zhang, 2020), and as output (Yang & Zhang, 2009; Hendrawan, Nugroho, & Permana, 2020). Subscriber base reflects the pressure on the capacities of a MNO. The larger the number of users is, the higher demand for the data is. It should be noted, however, that MNOs with smaller subscriber bases can achieve higher average data consumption (Tefficient, 2019), and a big SIM number does not automatically translate into the highest data usage, allowing for an interesting comparison case. Spectrum largely determines the capacity of MNO to provide faster data transfer speed, better levels of coverage (GSMA, 2015), and reflects the overall capacity of the network (ITU, 2016).

3.3. Malmquist Productivity Index

Malmquist Productivity Index has been previously used as an additional analysis method in conjunction with DEA (Liao & Gonzalez, 2009; Naimy & Merheb, 2014). MI evaluates the change of efficiency of a DMU between two time periods. It is defined as a product of catch-up (CU) and frontier shift (FS) terms. CU denotes the degree of efforts that a DMU undertook to improve its efficiency over the time period observed with the reference to the best performers from among the data sample. FS (also referred to as “innovation” - Cooper, Seiford, & Tone, 2007) relates to the change in efficiency frontiers surrounding the DMUs between the two periods observed. As in the case with DEA, MI analysis can be radial/non-radial and oriented/non-oriented. In line with the same logic applied to the DEA, this study employed non-radial non-oriented MI under various returns to scale (Tone & Tsutsui, 2017).

For a DMU₀ CU between the time period (x_o, y_o) and (x_{1o}, y_{1o}) is measured by:

$$\gamma = \frac{\text{Efficiency of } (x_o, y_o) \text{ with respect to period 2 frontier}}{\text{Efficiency of } (x_o, y_o) \text{ with respect to period 1 frontier}}$$

$\gamma > 1$ indicates an increase in relative efficiency from period 1 to 2, $\gamma = 1$ indicates status-quo, and $\gamma < 1$ indicates a decrease in relative efficiency over the time period observed.

For a DMU₀ FS for the time period (x_{1o}, y_{1o}) is measured by

$$\phi_1 = \frac{\text{Efficiency of } (x_o^1, y_o^1) \text{ with respect to period 1 frontier}}{\text{Efficiency of } (x_o^1, y_o^1) \text{ with respect to period 2 frontier}}$$

Subsequently, FS is measured for the second time period.

$$\phi_2 = \frac{\text{Efficiency of } (x_o^2, y_o^2) \text{ with respect to period 1 frontier}}{\text{Efficiency of } (x_o^2, y_o^2) \text{ with respect to period 2 frontier}}$$

Then FS ϕ effect is defined by the geometric mean of ϕ_1 and ϕ_2 :

$$\phi = \sqrt{\phi_1 \phi_2}$$

FS > 1 indicates progress in frontier technology around DMU from period 1 to 2. FS = 1 indicates status quo. FS < 1 indicates regress in frontier technology (Cooper, Seiford, & Tone, 2007).

MI is thereafter obtained as a product of CU and FS:

$$\mu = \gamma \times \varphi$$

MI represents the dynamics of total factor productivity (TFP) of the DMU between the given time periods. MI, however, does not capture the initial efficiency of DMUs for the base period. To remedy that, an adjusted Malmquist Index (AMI) is used. AMI allows to evaluate properly the DMUs, which scored relatively low in efficiency even when they achieve a large productivity change (Tone, 2017).

First we calculate CMI for a two period base ($s \rightarrow t$) based on the first period and period $t(1 \rightarrow t)$:

$$\tilde{\mu}^{1 \rightarrow t} = \prod_{\tau=1}^t \mu^{\tau \rightarrow \tau+1} \quad (t = 1, \dots, T - 1)$$

Then, AMI is calculated as a product of cumulative Malmquist Index (CMI) and the efficiency score in the period:

$$\tilde{\xi}^{1 \rightarrow t} = \tilde{\mu}^{1 \rightarrow t} \times \theta^1$$

The efficiency scores for MI are obtained using SBM model.

$$\delta^t((x_o, y_o,)^s) = \theta, \eta, \lambda \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \theta_i}{1 + \frac{1}{r} \sum_{i=1}^r \eta_i}$$

Subject to:

$$\theta_i x_{io}^s \geq \sum_{j=1}^n x_{ij}^t \lambda_j \quad (i = 1, \dots, m), \eta_i y_{io}^s \geq \sum_{j=1}^n y_{ij}^t \lambda_j \quad (i = 1, \dots, r), \theta_i \leq 1 \quad (i = 1, \dots, m), \eta_i \geq 1 \quad (i = 1, \dots, r), L \leq e\lambda \leq U, \lambda \geq 0$$

4. Data

Predominance of the use of financial data in previous research can be attributed partially to plenty of financial data on MNO available from both open and paid sources. This is due to the financial variables commonly reported in such open source materials as annual reports and investor presentations, as well as national regulators' reports. These data are of major interest to the stakeholders and potential investors. While non-financial data are generally available in the reports on national operators or such supranational entities as the EU, MNOs do not often disclose non-financial operational data. This posed a challenge during the data collection. Because this research focuses on operator level efficiency and does not take into consideration financial data, the availability of the data influenced the selection of cases. In addition, the data on certain DMUs throughout the period analysed were incomplete, rendering them not fit for the analysis and narrowing down the sample further.

The data on the number of mobile subscribers and total data volume were obtained from GSMA Intelligence Database, one of the most prominent databases on MNOs. The data on spectrum were obtained from Spectrummonitoring database with the tools to access the webpage retroactively for the data on previous years. The data on spectrum available on the resource were not updated every year, and in case no updates were observed total spectrum for the previous year was taken. Due to this there is a possibility of the data being biased towards the MNOs with less frequently reported spectrum bands. The final dataset includes 34 MNOs from 19 OECD countries in the form of a strongly balanced panel data. All of the MNOs included have significant market shares. For the purposes of this research and investigation of the impact of belonging to a MNE network on DMUs' efficiency, each of the subsidiaries of a MNE is treated as a separate DMU.

4. Analysis & Results

4.1. Descriptive Statistics

Table 3 shows descriptive statistics of the input, output, and MNE dummy variable measured as a panel data for all five years observed. Icelandic MNOs had the smallest number of mobile connections. The largest number of mobile connections was reported by a German MNOs. The narrowest total spectrum was used in 2014 by a Turkish operator which did not prevent it to become the leader in data traffic by 2018. The widest spectrum was registered for a Swiss operator in 2018, and Icelandic MNOs had the smallest traffic.

Table 3

Variables	Obs.	Mean	Std. Dev.	Median	Min	Max
Connections (x₁)	170	9955657	10,400,000	5,065,704	113,649	41,700,000
Spectrum (x₂) (Mhz)	170	169.95	49.99	168	52	483.8
Data Volume (y) (PB)	170	182	210	110	0.497	1,050
MNE	170	0.79	0.41	1	0	1

79.41% of all the DMUs were identified as MNE. Prevalence of MNE in the data is attributed to high internationalisation of telecommunication market. As a result of mergers and acquisitions, some of the MNOs from the dataset switch from being MNE to DE or vice versa. According to the information provided by MNOs on their operations, most companies do not limit themselves to domestic markets and render services overseas. For the purpose of this study, MNE will be considered as an enterprise providing services of mobile communication in more than one country (Eurostat, 2020) via a direct subsidiary owned with the controlling share (Markusen, 1995). This assumption is made on the premises that experience of providing non-mobile communication related services overseas is hypothesised not to benefit the non-financial efficiency of a company on domestic market. Therefore a company that provides services not related to mobile communication shall not be considered a MNE. Additionally, it should be noted that the majority of OECD MNOs classified as DE in line with the definition provided above did not disclosed the data used in this study, contributing to skewed representation of MNE.

Prior to carrying out DEA, we correlate the variables to check for isotonicity. The pairwise correlations between the variables used in DEA are presented below in Table 4.

4.2. DEA SBM Max Model Results

Table 4

	Connections	Spectrum	Data	MNE
Connections	1.0000			
Spectrum	0.0361	1.0000		
Data	0.4210	0.1665	1.0000	
MNE	0.2258	-0.0242	0.0118	1.000

The isotonic condition provides that an increase in input variables should lead to an increase in output variables. Both “Connections” and “Spectrum” variables are positively associated with the output variable of “Data” and thus we consider isotonic condition to be observed.

Table 5 below shows the SBM Max efficiency score relative to the other DMUs scrutinised for 34 MNOs from the OECD countries during the period of 2014 to 2018. Multiple operators achieve full efficiency throughout the period observed. Only three MNO managed to operate at full efficiency during the period observed: Elisa (Finland), Nova (Iceland), and Play (Poland). Two out of these MNOs (Nova, Plus) are DE, and Elisa-Finland is a MNE, indicating that DE can rival MNE in terms of efficiency of non-financial performance. There also are three runner-ups, which achieved full efficiency in four out of five years. DNA (Finland) slightly lagged behind its fully efficient domestic rival in 2014 before achieving full efficiency in 2015 and maintaining it for the rest of the period observed. Vodafone Iceland (Sýn) significantly lost in efficiency in 2017 but rebounded in 2018. The drop in efficiency for Vodafone Iceland (Sýn) can be attributed to merger with 365 Media (CommsUpdate, 2017) and rebranding as Sýn. Both DNA-Finland and Sýn-Iceland fall under DE classification used in this study. A MNE runner-up 3-Sweden maintained full efficiency throughout most of period observed except for marginally efficient 0.99 score for 2016. Large MNE DMUs such as Vodafone-Turkey and O2-UK also showed high efficiency scores, achieving full efficiency in three out of five years.

The estimated efficiency frontier comprising of the DMUs with full efficiency is characterised by presence of MNOs from large countries with large subscriber base such as Germany or Turkey, as well as from small countries such as Iceland. This is in line with the previous research (Sueyoshi, 1994; Pentzaropolous & Giokas, 2002) indicating that a country or MNO can achieve full efficiency regardless of its scale. Since this study employs slack-based efficiency evaluation approach, the potential sources of inefficiency for the MNO outside the efficiency frontier can be analysed with regard to the input and output slacks.

Below are shown the slacks of input variables (Tables 6-7), and of output variable (Table 8) for each DMU at a given time period.

Table 5

DMU	2014	2015	2016	2017	2018
Proximus-BE	0.28	0.35	0.34	0.20	0.14
Swisscom-CH	0.35	0.51	0.53	0.58	0.42
T-Mobile-CZ	0.25	0.43	0.40	0.27	0.26
Vodafone-DE	1.00	0.57	0.55	0.57	0.66
O2-DE	0.46	0.4	0.43	0.45	0.52
TDC-DK	0.34	0.56	0.65	0.81	0.80
Telenor-DK	0.46	0.58	0.65	0.75	0.77
Telia-DK	0.49	0.56	0.66	0.66	0.67
Vodafone-EL	0.21	0.28	0.30	0.14	0.13
Movistar-ES	0.59	0.7	0.63	0.74	0.90
Vodafone-ES	0.47	0.7	0.60	0.64	0.66
Elisa-FI	1.00	1.00	1.00	1.00	1.00
DNA-FI	0.92	1.00	1.00	1.00	1.00
BouyguesTelecom-FR	0.53	0.64	0.63	0.62	0.33
Siminn-IS	0.85	0.92	0.93	1.00	0.88
VodafoneIceland-IS	1.00	1.00	1.00	0.48	1.00
Nova-IS	1.00	1.00	1.00	1.00	1.00
TIM-IT	0.97	0.69	0.74	0.76	0.74
Vodafone-IT	0.88	0.71	0.74	0.81	0.74
Tele2-LT	0.34	0.46	0.67	0.65	0.71
Telia-LT	0.42	0.77	0.72	0.64	0.57
BITE-LT	0.41	0.58	0.70	0.61	0.63
Movistar-MX	0.26	0.57	0.62	0.37	1.00
Orange-PL	0.50	0.86	0.76	1.00	1.00
Play-PL	1.00	1.00	1.00	1.00	1.00
Vodafone-PT	0.30	0.54	0.64	0.52	0.52
Telia-SE	0.46	0.55	0.58	0.68	0.55
Tele2-SE	0.74	0.66	0.62	0.70	0.69
Telenor-SE	1.00	0.76	0.67	0.78	0.80
3-SE	1.00	1.00	0.99	1.00	1.00
Orange-SK	0.31	0.43	0.36	0.23	0.19
Vodafone-TR	1.00	0.84	0.79	1.00	1.00
O2-UK	0.92	1.00	1.00	1.00	0.81
Vodafone-UK	0.58	0.75	0.71	0.68	0.59

Table 6

Slacks – Connections (x₁, persons)					
DMU	2014	2015	2016	2017	2018
Proximus-BE	4221739	4028595	4064696	3956997	2611980
Swisscom-CH	0	0	0	0	0
T-Mobile-CZ	3763686	4174504	3819517	0	0
Vodafone-DE	438.811	13660440	10298102	8697978	5172056
O2-DE	20435298	22759168	22641024	20368918	17190350
TDC-DK	0	0	0	0	0
Telenor-DK	1234406	0	0	646018.7	532419.1
Telia-DK	916997.7	0	0	815565.8	759655.5
Vodafone-EL	4327523	5085028	4526689	0	0
Movistar-ES	0	0	0	0	0
Vodafone-ES	0	0	0	0	0
Elisa-FI	0	321018.1	0	0	0
DNA-FI	0	298778.9	0	0	0
BouyguesTelecom-FR	0	3588591	3727493	7315651	0
Siminn-IS	32024.41	21960.62	16372.25	0	15399.58
VodafoneIceland-IS	0	24515.55	0	785.63	0
Nova-IS	0	0	0	0	0
TIM-IT	0	6971291	2071444	2126245	0
Vodafone-IT	0	6026977	3667275	439102.3	0
Tele2-LT	1637470	0	359193.2	1013624	762600.1
Telia-LT	1040740	0	0	742710.4	908961.7
BITE-LT	827963.2	0	0	554012.1	486165.8
Movistar-MX	692494.5	19583919	18628029	4046422	875.525
Orange-PL	0	1379158	796599.2	0	0
Play-PL	0	0	0	0	7.011
Vodafone-PT	712955.4	1929321	0	0	2736020
Telia-SE	0	0	0	0	0
Tele2-SE	0	0	0	0	0
Telenor-SE	4.897	158861.4	0	0	0
3-SE	0	0	0	0	0
Orange-SK	1338980	1926636	2307632	2374066	2280423
Vodafone-TR	449.521	0	5421846	1308.06	0
O2-UK	0	0	474.159	424.701	0
Vodafone-UK	0	1038986	1601893	4409665	0

Table 7

Slacks - Spectrum (x2, MHz)					
DMU	2014	2015	2016	2017	2018
Proximus-BE	45.416	70.769	74.772	16.05	25.199
Swisscom-CH	136.35	126.079	133.235	114.67	337.639
T-Mobile-CZ	65.578	70.893	119.867	80.832	78.489
Vodafone-DE	0	79.268	131.289	130.901	112.094
O2-DE	85.971	197.649	153.173	154.761	136.071
TDC-DK	52.368	69.203	55.094	28.714	21.623
Telenor-DK	67.52	55.842	52.913	24.101	23.843
Telia-DK	83.605	68.174	67.276	21.248	21.326
Vodafone-EL	106.002	114.965	114.953	74.156	71.319
Movistar-ES	95.434	55.989	54.961	52.093	41.619
Vodafone-ES	107.379	75.988	63.587	59.454	37.215
Elisa-FI	0	43.889	0	0	0
DNA-FI	0	0	0	0	0
BouyguesTelecom-FR	73.841	52.003	58.767	13.941	24.861
Siminn-IS	8.76	0.65	4.092	0.024	30.09
VodafoneIceland-IS	0.002	0	0.003	0	0.015
Nova-IS	0.001	27.598	0.001	0.001	0.001
TIM-IT	0	53.985	68.399	61.537	121.891
Vodafone-IT	32.296	53.847	58.318	58.367	117.883
Tele2-LT	65.545	75.904	75.921	19.482	27.951
Telia-LT	62.001	75.515	75.186	17.469	20.194
BITE-LT	47.945	58.349	57.687	16.781	20.77
Movistar-MX	42.999	4.713	4.548	0	0
Orange-PL	0.199	21.502	6.054	0	0
Play-PL	0	47.948	0	0	0
Vodafone-PT	100.531	100.423	92.022	51.66	5.601
Telia-SE	67.416	74.655	73.643	55.202	68.981
Tele2-SE	112.597	122.292	108.009	93.903	113.827
Telenor-SE	0.001	98.355	93.162	83.945	65.103
3-SE	0	26.042	2.3	0	0
Orange-SK	76.046	83.148	83.172	24.036	23.992
Vodafone-TR	0	40.853	25.359	0	0
O2-UK	14.773	144.668	0	0	59.315
Vodafone-UK	107.122	69.928	89.97	68.977	123.606

Table 8

Slacks – Data (y, TB)					
DMU	2014	2015	2016	2017	2018
Proximus-BE	3756.492	8.18475	14.1204	35868.3	148875
Swisscom-CH	54119.39	43284.7	68141	88344.9	193246
T-Mobile-CZ	10284.44	8.18475	14.1204	137868	270335
Vodafone-DE	0	0	0	0	32.3764
O2-DE	0	0	0	0	32.3764
TDC-DK	23226.35	22112.6	34282.1	24496.5	49028
Telenor-DK	0	16373.3	18917.5	0	0
Telia-DK	0	22865.1	17506.1	0	0
Vodafone-EL	2900.902	8.18475	14.1204	163752	287250
Movistar-ES	13296.97	22524.2	65774.2	49775.3	509.346
Vodafone-ES	27155.91	11967	74784.9	103702	169334
Elisa-FI	0	0	0	0	0
DNA-FI	9363.541	0	0	0	0
BouyguesTelecom-FR	24014.31	8.18475	14.1204	411.683	436999
Siminn-IS	0.37514	0	0	3.22236	9.28634
VodafoneIceland-IS	0.18757	617.139	0.46247	4492.07	4.64317
Nova-IS	0.029669	0	0.08935	0.15024	0.1931
TIM-IT	4885.137	0	0	0	4634.39
Vodafone-IT	0.791341	0	0	0	11188.4
Tele2-LT	0	6888	14.1204	0	0
Telia-LT	0	46.1303	1723.81	0	0
BITE-LT	0	3418.42	3276.63	0	0
Movistar-MX	43490.66	8.18475	14.1204	227197	21.0601
Orange-PL	41949.93	8.18475	56170.6	7.95497	1.4791
Play-PL	0	0	0	0	0
Vodafone-PT	21340.52	8.18475	11322.2	74698.6	45908.1
Telia-SE	44059.39	41737.2	54047.4	52462.9	139424
Tele2-SE	2636.987	14125.5	44834.5	34022	44361.9
Telenor-SE	0	1.51698	34181.7	12066.5	17251.4
3-SE	0	0	0	7.85654	11.1668
Orange-SK	6708.195	8.18475	14.1204	24005.1	40447.7
Vodafone-TR	0.260091	878.992	0	0	0
O2-UK	0.791341	0	2.2629	2.09149	12046.5
Vodafone-UK	107.122	69.928	89.97	68.977	123.606

Slacks indicate practical ways of improving the efficiency of a DMU and thus are of particular interest to the managers. The biggest number of remaining slacks (i.e. smallest number of zeroes in a table) befalls on spectrum. Spectrum being an input variable, the slacks indicate an excess of spectrum for the needs of an operator. This observation, however, defies common logic. GSMA report (GSMA, 2015) quotes prominent policy makers and stakeholders in the field of communication encouraging MNOs to actively expand and harmonise their spectrum range available to keep pace with the transforming telecommunication sector and soaring consumer demand for data. Such notion is backed in the academia (Asimakopoulous & Whalley, 2017). Because DEA evaluates relative to the sample leaders' efficiency, the spectrum slacks can be interpreted as a surplus rather than excess. Having available more spectrum than needed by the current data demand can be interpreted as a good prospect for future development. According to the results, a Swiss DE Swisscom as of 2018 had 337.7 MHz of spectrum more than its operations at the time needed to be SBM-efficient. This surplus can be explained by preparation to deploy 5G network in early 2019 and the relevant spectrum auctions (Swiss Federal Communication Commission, 2019). Conversely, spectrum slack can indicate that not all of the capacities are properly utilised and more data can be delivered using the existing infrastructure. This is supported by the data variable slacks. In case of already mentioned Swisscom, data slack shows the capacity of Swisscom's infrastructure to deliver additional 193,246 TB of data without impeding its efficiency. At the same time, Swisscom has optimal number of subscribers with zero slacks from "Connections" variable over all the periods observed. Similar observations can be made for other DMUs when tracing efficiency optimisation associated with decrease or removal of slacks. Caution should be exercised when interpreting the slacks, however, as we discussed in the case of spectrum.

4.3. Malmquist Index Results

Table 9 shows the results of a non-radial non-oriented Malmquist Index model. The table includes the scores on AMI, FS, and CU. Only AMI is present for the initial observation period of 2014 due to CU and FS ignoring the initial efficiency and reflecting the change over time starting from the first year.

Calculated as a product of CMI, growing AMI is associated with increasing total factor productivity. The drops in productivity as shown by a decrease in AMI are marked with bold font.

CU expresses the amount of efforts undertaken by a MNO to catch-up with the leaders on the efficiency frontier. Failing to catch-up with the leader ($\gamma < 1$) is marked in the table with bold italics.

FS reflects the shift in the efficiency frontier surrounding MNOs itself. Slow surrounding process of technology innovation and upgrade associated with $\varphi < 1$ is marked with italics.

Table 9 - Adjusted Malmquist Index (AMI), Catch-up Effect (CU), and Frontier Shift (FS)

DMU	2014			2015			2016			2017			2018		
	AMI	CU	FS	AMI	CU	FS	AMI	CU	FS	AMI	CU	FS	AMI		
Proximus-BE	0.05	0.85	1.65	0.07	1.01	1.45	0.10	1.29	1.16	0.15	1.35	1.32	0.26		
Swisscom-CH	0.21	1.14	1.79	0.43	1.10	1.56	0.74	1.09	1.43	1.15	0.71	1.31	1.08		
T-Mobile-CZ	0.07	0.96	1.74	0.11	0.93	1.49	0.16	1.47	1.43	0.32	1.43	1.30	0.60		
Vodafone-DE	1.11	0.37	2.97	1.23	0.76	2.21	2.08	1.06	1.42	3.13	1.14	1.30	4.62		
O2-DE	0.29	0.81	2.80	0.65	1.17	1.51	1.14	1.09	1.43	1.79	1.10	1.36	2.67		
TDC-DK	0.13	1.81	1.60	0.38	1.52	1.54	0.89	1.25	1.24	1.38	1.18	1.30	2.12		
Telenor-DK	0.24	1.22	1.38	0.41	1.05	1.63	0.69	1.06	1.14	0.84	0.96	1.31	1.06		
Telia-DK	0.33	1.23	1.39	0.56	0.96	1.64	0.87	1.01	1.37	1.21	1.05	1.31	1.67		
Vodafone-EL	0.03	0.91	1.78	0.06	1.15	1.56	0.10	1.31	1.43	0.19	1.27	1.31	0.31		
Movistar-ES	0.36	1.03	1.85	0.69	1.09	1.47	1.11	1.30	1.44	2.08	1.66	1.50	5.19		
Vodafone-ES	0.29	0.95	1.90	0.52	1.38	1.41	1.03	1.18	1.44	1.74	1.29	1.33	2.99		
Elisa-FI	1.19	1.15	1.82	2.48	0.94	1.62	3.79	0.93	1.48	5.23	0.95	1.35	6.70		
DNA-FI	0.88	1.20	1.60	1.69	1.01	1.57	2.67	1.03	1.47	4.01	1.01	1.31	5.31		
BouyguesTelecom-FR	0.33	0.54	1.71	0.30	1.15	1.38	0.48	1.45	1.43	0.99	1.01	1.35	1.36		
Siminn-IS	0.18	1.18	1.51	0.32	1.45	1.15	0.53	3.29	<i>0.34</i>	0.60	0.34	1.15	0.24		
VodafoneIceland-IS	1.10	1.00	<i>0.74</i>	0.82	0.98	<i>0.75</i>	0.60	0.36	<i>0.83</i>	0.18	2.62	<i>0.44</i>	0.21		
Nova-IS	1.23	1.11	1.04	1.42	0.97	1.07	1.48	0.98	0.91	1.33	1.00	1.04	1.38		
TIM-IT	0.92	0.53	2.41	1.17	0.92	1.91	2.07	1.12	1.74	4.02	0.88	1.84	6.51		
Vodafone-IT	0.61	0.80	2.13	1.04	1.01	1.90	2.00	1.07	1.72	3.68	0.94	1.82	6.30		
Tele2-LT	0.04	1.68	1.38	0.10	1.40	1.63	0.24	2.09	1.22	0.61	1.12	1.31	0.90		
Telia-LT	0.15	0.90	1.40	0.19	1.01	1.64	0.32	1.33	1.30	0.56	1.13	1.32	0.82		
BITE-LT	0.08	1.38	1.42	0.16	1.45	1.64	0.39	1.41	<i>0.99</i>	0.54	1.23	1.31	0.87		
Movistar-MX	0.15	1.41	1.09	0.23	1.39	1.64	0.53	1.14	1.63	0.99	3.22	<i>0.42</i>	1.32		
Orange-PL	0.50	0.96	<i>0.77</i>	0.37	1.38	1.62	0.82	1.57	1.32	1.70	1.01	1.13	1.95		
Play-PL	1.30	0.87	1.36	1.53	1.06	1.64	2.67	0.94	1.52	3.78	0.90	1.42	4.84		
Vodafone-PT	0.10	0.83	1.78	0.15	1.81	1.51	0.41	1.25	1.37	0.70	1.82	1.34	1.70		
Telia-SE	0.32	0.91	1.80	0.52	1.03	1.51	0.81	1.04	1.41	1.20	0.89	1.32	1.41		
Tele2-SE	0.52	0.74	1.70	0.65	0.95	1.59	0.99	0.95	1.46	1.38	0.97	1.32	1.78		
Telenor-SE	1.14	0.60	1.84	1.27	0.72	1.63	1.49	0.82	1.49	1.82	0.98	1.31	2.35		
3-SE	1.20	0.86	1.44	1.49	0.88	1.28	1.68	1.16	<i>0.77</i>	1.50	0.99	1.01	1.51		
Orange-SK	0.07	0.91	1.57	0.09	0.79	1.56	0.12	1.03	1.30	0.15	0.90	1.31	0.18		
Vodafone-TR	1.13	0.45	1.37	0.69	1.30	1.88	1.68	1.61	1.48	4.00	1.21	1.51	7.30		
O2-UK	0.60	1.82	<i>0.85</i>	0.93	0.99	1.42	1.31	1.01	1.40	1.85	0.47	1.17	1.03		
Vodafone-UK	0.29	1.08	1.84	0.58	0.91	1.47	0.78	1.13	1.43	1.27	0.93	1.31	1.54		

Majority of MNOs showed steady growth of productivity (AMI) over the time period observed. The decrease in productivity is observed mostly for MNOs with high efficiency reported in Table 5, such as Iceland's MNO. For these operators the productivity decrease is accompanied by insufficient efforts to catch-up with the frontier leaders and decreasing temp of innovation. Nevertheless, the CU scores of these operators remain relative high and close to 1. We assume it is related to these operators being already fully or marginally efficient, and thus it requires increased application of efforts and resources to stay fully efficient.

In contrast to the slight drop of smaller efficient MNOs' productivity, large subsidiaries of MNEs in big countries such as Vodafone-Turkey, TIM-Italy, and Movistar-Spain showed tremendous productivity growth over the time period observed. Vodafone-Turkey should be noted for suffering a drop of productivity in 2015 and rebounding by achieving the highest growth in total productivity (0.45 to 7.30). Finnish MNE Elisa is an outlier with regard to the both cases. Based in a smaller by population compared to Germany, Spain, and Turkey country, Elisa operated at full efficiency during the whole period analysed similarly to smaller Icelandic MNOs, and at the same time managed to drastically increase its productivity (1.19 to 6.70) second only to Turkey. Similar yet less conspicuous results are achieved by the second Finnish operator on the list, DNA. Throughout all five years scrutinised Finnish MNOs were developing in conditions of advancement of innovation reflected in $FS > 0$. This allows to regard Finland as one of the best performers on the telecommunication market from among the ones observed in this study. This corroborates the findings of Reddy et al. (2019), according to which Finnish operators were among the efficiency leaders.

4.4. Mann-Whitney Tests

To ascertain if there is a significant difference between the DE and MNE Mann-Whitney (Wilcoxon Rank-Sum) test is carried out. At 95% confidence interval, the null hypothesis (H_0) is that there is no statistically significant difference between domestic and multinational companies in terms of efficiency. Alternative hypothesis (H_a) respectively provides that there is a statistically significant difference in performance efficiency of MNE and DE. The results of Mann-Whitney test are presented in Table 10.

Table 10

MNE	Obs.	Rank Sum	Expected
0 (DE)	35	3,637	2,992.5
1 (MNE)	135	10,898	11,542.5
Combined	170	14,535	14,535

Unadjusted variance:	67331.25
Adjustment for ties:	-812.44
Adjusted variance:	66518.81
Ho: scoremax(MNE==0) = scoremax(MNE==1)	
	Z = 2.499
Prob >	z = 0.0125
Exact Prob	0.0119

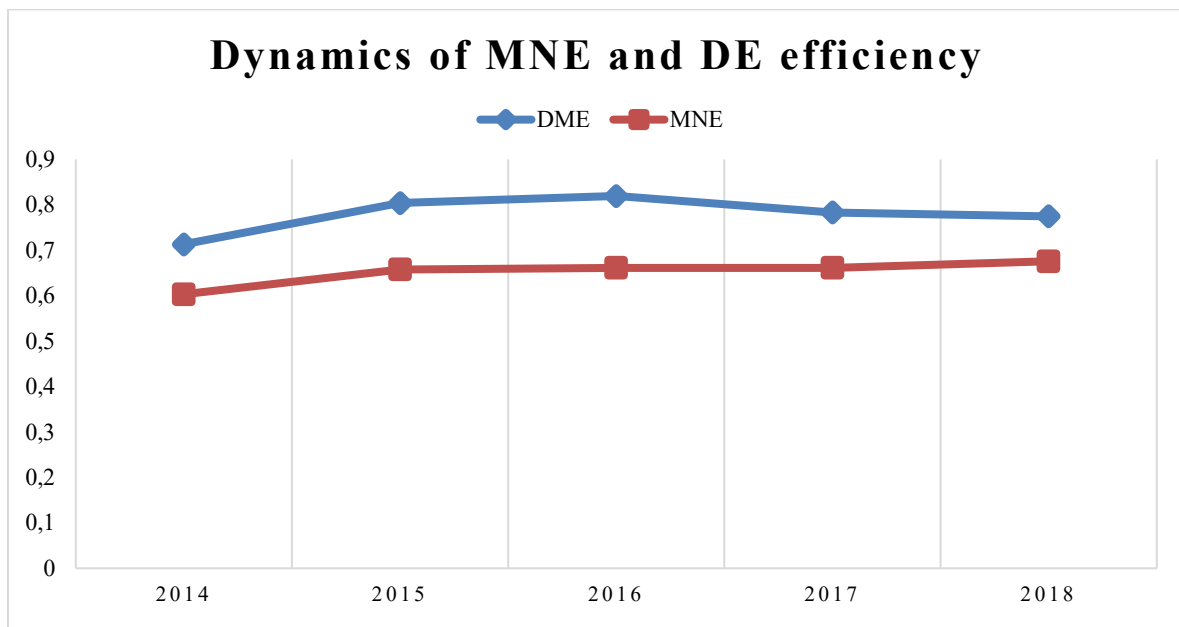
The results indicate that alternative hypothesis (H_a) cannot be refuted and there is a significant difference between MNE and DE in terms of efficiency at 95% confidence interval. We proceed by carrying out subsequent Mann-Whitney tests with regard to AMI, FS, and CU to investigate whether the difference between MNE and DE carries over to productivity, innovation, and capacity to catch up with the efficiency frontier leaders.

Table 11

AMI		FS		CU	
Z =	0.303	Z =	-1.534	Z =	0.447
Prob > z =	0.7623	Prob > z =	0.1251	Prob > z =	0.6551
Exact Prob	0.7647	Exact Prob	0.1262	Exact Prob	0.6587
(H ₀) cannot be refuted		(H ₀) cannot be refuted		(H ₀) cannot be refuted	

According to Mann-Whitney test results in Table 11 above, there is no significant difference between MNE and DE regarding total productivity factor (AMI), innovation (FS), and amount of efforts put into catching-up with the industry leader. Nevertheless, there remains a statistically significant difference between MNE and DE in terms of efficiency. The gap in performance is illustrated on Diagram 1 below.

Diagram 1



DE appear to be on average more efficient than DE. Better performance was demonstrated both by small scale DE providing services to a small population (such as Vodafone/Syn Iceland) and by large DE rendering services to millions of people (e.g. Plus-Poland). However, MNE showed much more robust capacity to catch up with the efficiency frontier leaders, and to keep the pace with innovations. Thus, we have to refute out hypothesis H_1 and conclude that DE are more efficient than MNE based on the data and analysis of the present study.

Slacks reveal a few interesting trends and features of both DE and SME. Majority of MNOs had optimal subscription base, and those with excess subscribers generally tended to decrease the slack. In accordance with the model used, the MNOs could achieve that either by reducing the number of subscribers, which is very unlikely, or by increasing the improving the availability of data to make most of their infrastructure. Reducing the price of the data is one way to approach it, which corresponds the general trend of the mobile data getting cheaper (GSMA, 2019). Alternatively, MNO can invest into upgrading or expanding its infrastructure to increase the capacity of data transferring. Spectrum slacks show that most of the operators did not utilise their spectrum to the maximum. While it is detrimental to the quality of data services rendered to the clients, free available spectrum also shows the capacity of a MNO to grow and adapt to the transforming mobile market (GSMA, 2015).

5. Conclusions & Discussion

This research comparatively evaluated the performance efficiency of MNO from OECD countries between 2014 and 2018. Unlike many previous researches examining the efficiency of telecommunication industry, this study relied exclusively on non-financial operational data, giving insights on the state of the industry from a not thoroughly covered in the academia operational perspective and contributing to the growing pool of academic

literature on telecommunication sector. Utilising practically oriented variations of DEA and Malmquist Index, the authors aimed at providing easily understandable pointers on how the efficiency of a given MNO can be improved within the framework of the model employed.

The findings report that DE demonstrated overall higher performance efficiency than the MNE. This paper thus contributes to the ongoing discussion on comparative advantages of MNE and DE and makes an argument about DEs higher efficiency. While the design of this study does not allow to answer what exactly is causing the DE in the sample to outperform MNE, based on the previous research we hypothesise that several factors are at play. Firstly, it is worth noting that six fully or marginally efficient MNO are from the region of Nordic countries famous for and ranked high in innovativeness (WIPO, 2020), regulatory quality (WGI, 2019), and skilled personnel (UNDP, 2020). This pertains to both DE and MNE and therefore should be considered a regional advantage rather specific to a group of companies. Nevertheless, these advantages primarily being available to the companies operating locally, their impact on the performance of local DE should not be readily refuted. We hypothesise that such conditions for business foster innovative business practices and strategies, supported by skilled labour from both within the company and from the side of regulators. This is in line with the previously discussed in the academia relative advantage of DE in the form of locally groomed talents (Bhattacharya & Michael, 2008). Nordic countries also actively cooperate with each other in the field of telecommunication (e.g. New Nordic Cooperation on 5G), thus reaping the bonuses of harmonisation, underlined as an important factor for the development of telecommunication industry (GSMA, 2015), as well as possibly causing mutually beneficial spillover of technologies. Secondly, we suggest that familiarity with particular needs of the local market and its conditions allowed DE to react to clients' preferences better and operate in a more optimal way. Finland, for example, is world's leader in data consumption per capita (Bell, 2020). The local operators adapted to the needs with appropriate data-focused subscription plans. Without further analysis of the underlying reasons for better DE performance, however, it is not possible to say with certainty whether the difference observed is explained by multinational nature of the companies, or their individual characteristics.

The empirical results of DEA and MI also indicate possible reasons for increased efficiency. DEs on average had significantly less slacks which is computationally associated with higher SBM Max efficiency score. DEs are more careful in using and managing their resources, resulting in more optimal compared to MNE operation. In addition to that, while DEs did not generally show significant increase in FS, AMI, the latter remained steady. Modest results in terms of FS and AMI while operating at full or marginal efficiency mean that the efficient DE MNOs were already operating at the technological frontier with the best technologies at disposal. It is thus likely that the efficiency of DEs from the sample used in this study is associated with their technological superiority over their rivals. Smaller scale of enterprise can in this case be an advantage, making the deployment of new equipment and infrastructure faster and more affordable.

The findings of this study should be interpreted subject to the limitations of the research. Because of the lack of data, the regions of the world are not equally represented in the sample.

Such important players on the telecommunication market as Japan, South Korea, and the USA are not present in the data set. This decreases generalisability of this work. From among the countries included, only 21% were designated as DE, possibly leading to biased representation of DEs with a smaller pool of highly effective companies that are not representative with regard to all telecom DEs in OECD. In addition, large MNEs such as Vodafone and Telefonica have exemplary system of reporting the data while smaller local MNO rarely disclose the data, exacerbating the issue of DEs representability. The definition of MNE used for the purposes of this research can also be a limitation as it focuses on mobile communications while ignoring other operations of MNO such as fixed telecom. However, DEA model proposed relied only on pertinent to mobile communication variables and thus the exclusion of non-mobile business activities of MNOs was deemed justifiable.

Since this research intended to answer the question “if” DEs were more or less efficient than MNEs, the future research should ponder into the reasons of the discrepancy between the efficiency of MNEs and DPEs reported by the authors. The present work also does not consider the impact of environmental factors. Inclusion of specific to the industry environmental factors on the analysis can benefit the depth and generalisability of the study. Previous research used TOBIT model to deal with censored efficiency score obtained from DEA, and longitudinal TOBIT model (Twisk & Rijmen, 2009) can be used to trace the impact of environmental factors over time. It is also worthy expanding the time frame for the analysis to examine the FS and AMI in the context of technological generation shift (e.g. 3G to 4G) as proposed by Asimakopoulos & Whalley (2017). The lack of data self-reported by MNOs, however, remains a big challenge for future analyses of MNOs efficiency from the perspective of operational data.

References

- Asimakopoulou, G., & Whalley, J. (2017). Market leadership, technological progress and relative performance in the mobile telecommunications industry. *Technological Forecasting and Social Change*, 123, 57–67.
- Avkiran, N. (2009). Removing the impact of environment with units-invariant efficient frontier analysis: An illustrative case study with intertemporal panel data☆. *Omega-international Journal of Management Science*, 37, 535-544.
- Bakker, H. (2016). Spectrum and Licensing in mobile telecommunication market. ITU Regional Workshop on “Competition in Telecommunications Market” Khartoum-Sudan, 24-26 May 2016. From: Slide 1 (itu.int).
- Bellak, C. (2004). How Domestic and Foreign Firms Differ and Why Does it Matter? *Journal of Economic Surveys*, 18(4), 483-514.
- Bhattacharya, A.K., & Michael, D. (2008). How Local Companies Keep Multinationals at Bay. *Harvard Business Review*.
- Bollou, F., & Ngwenyama, O. (2008). Are ICT investments paying off in Africa? An analysis of total factor productivity in six West African countries from 1995 to 2002. *Information Technology for Development*, 14(4), 294–307.
- Castelnovo, P., Del Bo, C. F., & Florio, M. (2019). Quality of institutions and productivity of State-Invested Enterprises: International evidence from major telecom companies. Elsevier, vol. 58(C), 102-117.
- Chakar, A.S., Celio, S., & Thams, Y. (2010). The Performance of Multinational Affiliates versus Domestic Firms. *Journal of Management Policy and Practice*, 11(4)
- Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6), 429–444. doi:10.1016/0377-2217(78)90138-8.
- Chen, C. (2019). Evaluating the efficiency change and productivity progress of the top global telecom operators since OTT's prevalence. *Telecommunications Policy*. Elsevier, vol. 43(7), 1-1.
- Chen, C.-M. (2019). Evaluating the efficiency change and productivity progress of the top global telecom operators since OTT's prevalence. *Telecommunications Policy*.
- Chow, C. W., & Van Der Stede, W. A. (2006). The use and usefulness of nonfinancial performance measures. *Management accounting quarterly*, 7(3), 1.
- Cooper, W.W., Thompson, R.G. & Thrall, R.M. (1996) Chapter 1 Introduction: Extensions and new developments in DEA. *Ann Oper Res*, 66, 1–45.
- Cooper, W., Seiford L., Tone, K. (2007). *Data Envelopment Analysis*. Second Edition. Springer, New York.
- Crioscuro, C. & Martin, R. (2005). Multinationals and US Productivity Leadership: Evidence from Great Britain. CEP Discussion Paper No 672. London School of Economics.
- Data demand explained. (2015). GSMA – Mobile Spectrum. From: GSMA-Data-Demand-Explained-June-2015.pdf

- Diskaya, F., Emir, S., & Orhan, N. (2011). Measuring the Technical Efficiency of Telecommunication Sector within Global Crisis: Comparison of G8 Countries and Turkey. *Procedia - Social and Behavioral Sciences*, 24, 206–218.
- Doms, M. & Jensen, B. (1998). Comparing Wages, Skills, and Productivity between Domestically and Foreign-Owned Manufacturing Establishments in the United States. *Geography and Ownership as Bases for Economic Accounting*. University of Chicago Press, 235-258.
- Giokas, D. I., & Pentzaropoulos, G. C. (2000). Evaluating productive efficiency in telecommunications: evidence from Greece. *Telecommunications Policy*, 24(8-9), 781–794.
- Giokas, D. I., & Pentzaropoulos, G. C. (2008). Efficiency ranking of the OECD member states in the area of telecommunications: A composite AHP/DEA study. *Telecommunications Policy*, 32(9-10), 672–685.
- Global innovation Index 2020. Who will finance innovation? (2020). WIPO. From: https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020.pdf
- Glossary: Multinational enterprise (MNE). Eurostat Statistics Explained. From: Glossary:Multinational enterprise (MNE) - Statistics Explained (europa.eu)
- Griffith, R., Redding, S., & Simpson, H. (2002). Productivity convergence and foreign ownership at the establishment level. *IFS Working Papers*, No. 02/22, Institute for Fiscal Studies (IFS), London.
- GSM Association (2020). Mobile technology and economic growth. Lessons to accelerate economic growth and recovery. From: https://www.gsma.com/betterfuture/wp-content/uploads/2020/11/Mobile-technology-and-economic-growth_web.pdf
- GSM Association (2020). The Mobile Economy 2020 (2020). From: https://www.gsma.com/mobileeconomy/wp-content/uploads/2020/03/GSMA_MobileEconomy2020_Global.pdf
- Hendrawan, R; Nugroho, K.W.A, & Permana,G. T. (2019). Efficiency Perspective on Telecom Mobile Data Traffic. *J. Bus. Econ. Review* 5(1) 38 – 44.
- Hu, J.-L. & Chu, W.-K. (2008). Efficiency and Productivity of Major Asia-Pacific Telecom Firms. *Chang Gung Journal of Humanities and Social Sciences*, 1:2, 223-245
- Hu, J.-L., Hsu, H.-H., Hsiao, & C., & Tsao, H.-Y. (2018). Is mobile jumping more efficient? Evidence from major Asia-Pacific telecommunications firms. *Asia Pacific Management Review*.
- Huguenin, J.-M. (2012). Data Envelopment Analysis (DEA). A pedagogical guide for decision makers in public sector. IDHEAP, Lausanne.
- Human Development Report 2020. The next frontier. Human development and the Anthropocene (2020). UNDP. From: hdr2020.pdf (undp.org)
- Hung, S.-W., & Lu, W.-M. (2007). A Comparative Study of the Performance Measurement in Global Telecom Operators. *Total Quality Management & Business Excellence*, 18(10), 1117–1132.
- Kaoru, T. (2010). Variations on the theme of slacks-based measure of efficiency in DEA. *European Journal of Operational Research*. Elsevier, 200(3), 901-907.
- Kaplan, R. S., & Norton, D. P. (1992). The Balanced Scorecard-Measures that Drive Performance. *Harvard Business Review*.

- Kumar, A., Shankar, R., & Debnath, R. M. (2015). Analyzing customer preference and measuring relative efficiency in telecom sector: A hybrid fuzzy AHP/DEA study. *Telematics and Informatics*, 32(3), 447–462.
- Kwon, H.-B. (2014). Performance modeling of mobile phone providers: a DEA-ANN combined approach. *Benchmarking: An International Journal*, 21(6), 1120–1144.
- Lam, P.-L., & Shiu, A. (2008). Productivity analysis of the telecommunications sector in China. *Telecommunications Policy*, 32(8), 559–571.
- Lee, K. C., & Kwok, C. C. Y. (1988). Multinational Corporations vs. Domestic Corporations: International Environmental Factors and Determinants of Capital Structure. *Journal of International Business Studies*, 19(2), 195–217.
- Liao, C.-H., & González, D. B. (2009). Comparing Operational Efficiency of Mobile Operators in Brazil, Russia, India and China. *China & World Economy*, 17(5), 104–120.
- Liao, C.-H., & Lien, C.-Y. (2012). Measuring the technology gap of APEC integrated telecommunications operators. *Telecommunications Policy*, 36(10-11), 989–996.
- Lien, D., & Peng, Y. (2001). Competition and production efficiency. *Information Economics and Policy*, 13(1), 51–76.
- Llungo-Ortiz, J. (2014). Privatization of telecommunications in Latin America, an analysis of its efficiency. 54th Congress of the European Regional Science Association: "Regional development & globalisation: Best practices", 26-29 August 2014, St. Petersburg, Russia
- Lu, W.-M., & Hung, S.-W. (2008). Benchmarking The Operating Efficiency Of Global Telecommunication Firms. *International Journal of Information Technology & Decision Making*, 07(04), 737–750.
- Majumdar, S. K. (1998). On the utilization of resources: perspectives from the U.S. telecommunications industry. *Strategic Management Journal*, 19(9), 809–831.
- Mandel, M., & Long, E. (2020). The Third Wave: How 5G Will Drive Job Growth over the Next Fifteen Years. *National Spectrum Consortium*. Washington, DC: Progressive Policy Institute.
- Markusen, J. R. (1995). The Boundaries of Multinational Enterprises and the Theory of International Trade. *Journal of Economic Perspectives*, 9(2) 169-189
- Michel, A. & Shaked, I. (1986). Multinational Corporations vs. Domestic Corporations: Financial Performance & Characteristics. *Journal of International Business Studies*, 17(3), 89-100.
- Mobile data consumption continues to grow – a majority of operators now rewarded with ARPU. (2019). Tefficient. From: [tefficient-industry-analysis-3-2019-mobile-data-usage-and-revenue-1H-2019-per-operator-5-Sep.pdf](#)
- Mobile radio frequencies for 5G awarded in Switzerland (2019). Swiss Federal Communication Commission. From: [Mobile radio frequencies for 5G awarded in Switzerland \(admin.ch\)](#)
- Naimy, V. Y., & Merheb, C. (2014). Modeling the Efficiency of the Mobile Industry in the Middle East Using Data Envelopment Analysis. *Journal of Statistical and Econometric Methods*, SCIENPRESS Ltd, vol. 3(2), 1-6.
- Nielsen, L. (2011). Classification of Countries Based on Their Level of Development: How it is Done and How it Could be Done. *International Monetary Fund*.

- Oredogbe, A., & Zhang, Y. (2020). Telecommunications industry efficiency: A comparative analysis of high and middle income countries. *Telecommunications Policy*, 44, 101958.
- Paradi, J., Rouatt, S., & Zhu, H. (2011). Two-stage evaluation of bank branch efficiency using data envelopment analysis. *Omega-international Journal of Management Science*, 39, 99-109.
- Pentzaropoulos, G. ., & Giokas, D. (2002). Comparing the operational efficiency of the main European telecommunications organizations: A quantitative analysis. *Telecommunications Policy*, 26(11), 595–606.
- Pfaffermayr, M., & Bellak, C. (2002). Why Foreign-owned Firms are Different: A Conceptual Framework and Empirical Evidence for Austria. *Foreign-Owned Firms*, 13–57.
- Reddy, M. B., Bielov, C., Finley, B., Kilkki, K. & Mitomo, H. (2019). Efficiency of Mobile Network Operators from a Data Service Perspective. *30th European Regional ITS Conference, Helsinki 2019*. International Telecommunications Society (ITS).

References

- Shah, S., Anwar, J., & Hasnu, S. (2018). Does location matter in determining firms' performance? A comparative analysis of domestic and multinational companies. *Journal of Asia Business Studies*, 12(3), 253–272.
- Sueyoshi, T. (1994). Stochastic frontier production analysis: Measuring performance of public telecommunications in 24 OECD countries. *European Journal of Operational Research*, 74(3), 466–478.
- Temouri, Y., Driffield, N. L., & Añón Higón, D. (2008). Analysis of Productivity Differences among Foreign and Domestic Firms: Evidence from Germany. *Review of World Economics*, 144(1), 32–54.
- The Quality of Mobile Services in Latin America. (2015). GSMA Latin America. From: GSMA | The Quality of Mobile Services in Latin America - GSMA Latin America
- The state of Mobile Internet Connectivity. (2019). GSMA. From: GSMA-State-of-Mobile-Internet-Connectivity-Report-2019.pdf
- Tijdens, K., Gregory, D., & van Klaveren, M. (2013). Multinational and Domestic Firms in Europe. Comparing Wages, Working Conditions and Industrial Relations. *Palgrave MacMillan*. London.
- Tone, K. (1997). A Slacks-Based Measure of Efficiency in Data Envelopment Analysis.
- Tone, K. (2015). SBM Variations Revised. GRIPS Discussion Paper 15-05.
- Tone, K. (2016). Data Envelopment Analysis as a Kaizen Tool: SBM Variations Revised. *Bulletin of Mathematical Sciences and Applications*, 16, 49-61.
- Tone, K., & Tsutsui, M. (2017). Malmquist Productivity Index Models. *Advances in DEA Theory and Applications: With Extensions to Forecasting Models*, 40-56.
- Tsai, H.-C., Chen, C.-M. & Tzeng, G.-H. (2006). The comparative productivity efficiency for global telecoms. *International Journal of Production Economics*. 103. 509-526.
- Twisk, J., & Rijmen, F. (2009). Longitudinal tobit regression: A new approach to analyze outcome variables with floor or ceiling effects. *Journal of Clinical Epidemiology*, 62(9), 953–958.

- Uri, N. D. (2001). Technical efficiency, allocative efficiency, and the impact of incentive regulation in telecommunications in the United States. *Structural Change and Economic Dynamics*. Elsevier, vol. 12(1), 59-73.
- Usero, B., & Asimakopoulos, G. (2013). Benchmarking Mobile Operators Using DEA: An Application to the European Mobile Markets. In I. Lee (Ed.), *Mobile Services Industries, Technologies, and Applications in the Global Economy*, 87-103. IGI Global.
- Vodafone's acquisition of 365 approved by regulator. (2017). *Comms Update*. From: Vodafone's acquisition of 365 approved by regulator (commsupdate.com)
- Worldwide Governance Indicators (dataset). From: WGI 2020 Interactive > Home (worldbank.org)
- Yang, A., Lee, D., Hwang, J., & Shin, J. (2013). The influence of regulations on the efficiency of telecommunications operators: A meta-frontier analysis. *Telecommunications Policy*, 37(11), 1071–1082.
- Yang, H.-H., & Chang, C.-Y. (2009). Using DEA window analysis to measure efficiencies of Taiwan's integrated telecommunication firms. *Telecommunications Policy*, 33(1-2), 98–108.
- Zheng W, Sun H, Zhang P, Zhou G, Jin Q, & Lu X (2018) A four-stage DEA-based efficiency evaluation of public hospitals in China after the implementation of new medical reforms. *PLoS ONE* 13(10): e0203780.