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Optimal Intertemporal Broadband Investments to Promote Regional Economic Development

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Abstract

This paper ties broadband development to regional economic growth and focuses on the optimal timing of investments. A Directional Distance Function framework is proposed for characterising the relationship between broadband investment and economic development, and a two-stage estimation procedure combining Convex Nonparametric Least Squares with Linear Programming is developed for estimating optimal investment paths. The model framework is applied to a novel dataset comprising 21 regions in the Baltic countries. The results indicate that Gross Regional Domestic Product could be increased by up to 10 per cent by adopting optimal regional investment paths. We find intercountry differences, where Latvian regions exhibit more inefficient investment strategies compared to regions subordinate to their neighbouring countries. There are also signs of over-investment in broadband in some regions.

JEL Classification: L96, O18, R11, R15

Keywords: Regional economic growth; Broadband; Directional Distance Function; Convex Nonparametric Least Squares; Baltic countries; productivity

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1. INTRODUCTION

The implications of information and communication technologies (ICT), including internet services enabled by a broadband connection, on economic development have received ample attention in the scientific literature. Jung and López-Baso (2020) note that most studies are at the national level and that investigations into the effect of broadband (i.e., internet connection of at least one Megabit per second) on economic growth at the sub-national level are scarce. Like Jung and López-Baso (2020), this study emphasises the degree to which economic benefits from broadband formation are non-uniformly distributed among regions. Our investigations into impacts at the regional scale, on the urban-rural axis, and related to industry composition provide novel and important insights into the drivers of regional development.

Broadband is made available through large infrastructure projects, and cost-benefit assessment is, therefore, often an important element of their business case (Volden, 2019). In this study, we develop a novel project appraisal methodology for broadband investment, where the optimal timing of investment – depending on regional economic conditions – plays a key role. The model framework integrates efficiency analysis with multiple inputs and outputs into an endogenous growth model. While some previous studies have discussed dynamic investment paths for broadband (e.g., Yoon et al., 2005; Fijnvandraat and Bouwman, 2006), their attention is primarily on infrastructure costs and the flexibility of investments. This study ties internet services through broadband formation to economic growth to study the optimal investment path for broadband with regard to maximising the Gross Regional Domestic Product (GRDP).

Our study is consequently related to the debate on ICT as a provider of intangible assets, which suggests that conventional productivity analysis can miss its contribution to productivity growth (Corrado et al., 2021). This is achieved by making a distinction between the up-front cost of broadband development and the subsequent benefits of access to internet services with regard to its contribution to value creation.

The current study proposes a Directional Distance Function (from now on DDF; Chambers et al., 1998) framework for characterising the relationship between broadband investment and economic development. A distinct characteristic of this framework is that broadband is described both as a rival to and facilitator of GRDP formation. The methodology can be placed within the strand of productivity and efficiency literature that focuses on resource allocation among production units, an approach commonly referred to as network technologies in the literature (Färe et al., 2007). This study focuses especially on the allocation of resources over time, a feature known as time substitution (Färe et al., 2010).

While studies regarding time substitution predominately emphasise the (re)allocation of given resource endowments over time (see, e.g., Färe et al., 2010; Bostian et al., 2018), our study does not impose a budget or overall endowment of broadband, but rather incorporates flow conservation constraints – ensuring that the accumulation of internet services depend on past investment in broadband – into the dynamic production model. Flow conservation constraints are frequently used in optimisation-based planning models (e.g., Havre et al., 2022). Still, their adoption in studies using network technologies is, to our knowledge, scarce.

Resource allocation problems using network technologies are predominately based on Data Envelopment Analysis (DEA; Charnes et al., 1978). In contrast, we use Convex Nonparametric Least Squares (CNLS; Kuosmanen, 2008) to describe the production possibility frontier. CNLS is, in principle, a DEA model implemented using regression analysis (Kuosmanen and Johnson, 2010). Like DEA, CNLS estimates the production frontier in a nonparametric fashion, hence avoiding the selection of a functional form for the function to be fitted. A main difference between DEA and CNLS is that the DEA model is deterministic, while CNLS offers a stochastic frontier model framework. Hence, random variation in data can be accommodated by CNLS but not by DEA. We consider this feature a valuable extension to network technology assessment based on DEA.

The Baltic countries have experienced strong economic growth over many years (e.g., Fadejeva and Melihovs, 2008; Burinskas et al., 2021). Still, the expansion of broadband in the region has often lagged behind other European countries (e.g., Rivza and Rivza 2020 and IGS Markit, OMDIA and Point Topic 2021). In our empirical investigation, we apply our model framework to a novel dataset on broadband and economic activities comprising 21 regions in the Baltic countries at the NUTS-3 level (cf. Holmen et al., 2023). We control for population density and country, as well as employment shares for industry sectors.

The results indicate that regional GRDP could be increased by up to 10 per cent by adopting optimal regional investment paths. We find intercountry differences, where Latvian regions exhibit more inefficient investment strategies compared to regions subordinated to their neighbouring countries. There are also signs of over-investment in broadband in some regions.

The paper is organised as follows. Section 2 reviews related studies and pinpoints the placement of the paper within the scientific literature. Section 3 elaborates on the methodological underpinnings, while Section 4 discusses empirical implementation using data from Baltic regions. Section 5 presents the empirical results, while Section 6 concludes.

2. LITERATURE REVIEW

We will now review the literature on economic growth impulses from broadband, first accounting for the theoretical rationales and then moving on to the empirical evidence.

2.1. Theoretical Justification for Economic Growth Impulses from Broadband

Information and communication technologies (ICT) are of paramount importance to human development. These technologies promote the use, production, transmission, diffusion, storage, collection, coding, and adaptation of information and knowledge. ICT frames information, knowledge and technology as such. According to the Solow model (Solow, 1956) and most subsequent growth economics, technology is the main source of economic growth (Acemoglu, 2009)[1]. Dudley (1999) discusses the importance of ICT for economic growth over a millennium. He concludes that over the past millennium, the three centuries with the most rapid demographic growth in the West coincided with the diffusion of a new communications

[1] Most growth models study accumulation of physical and human capital. Produced goods can be consumed or invested. Investments increase production capacity and thereby generate growth. When there are decreasing returns to capital, such accumulation cannot be the source of sustained growth. Technological progress can counteract decreasing returns to capital and is therefore, in economic growth models, the only source of sustained growth in the long run. *Endogenous* growth economics seek to explain technological progress as the result of economic mechanism. These explanations themselves are dependent on *fundamental* causes of growth. Candidates as fundamental causes of growth are geography, institutions, and culture. See e.g. Diamond (1997), Acemoglu *et al.* (2005) or Rodrik *et al.* (2004).

technology. His discussion lends support to the hypothesis of Innis (1950) that there is two-way feedback between such innovations and economic growth.

Many regard the internet as a major breakthrough in ICTs. Regarding the ability to handle information quantitatively and qualitatively, the internet may be a more significant change than previous technological progress in ICT. Google is an intended misspelling of googol, the mathematical number 10^{100}, which denotes an extremely large number (Keen, 2015, p. 53). How important is this? Information and knowledge, on the one hand, and technology, on the other, are related. Technology as a recipe for production is an information good. Information and knowledge are special economic goods. Three aspects are as follows.

Trygve Haavelmo (1954, p. 85) wrote, "Knowledge can be sold and still kept". This reflects that knowledge is non-rival and only partially excludable. Its social value depends crucially on the extent to which it is excludable. If it is not, knowledge is a public good. If it is made excludable (e.g., via intellectual property rights), there will be deadweight losses related to its price. Kenneth Arrow (1962, p. 615) noted that "its (knowledge's) value for the purchaser is not known until he has the information, but then he has in effect acquired it without cost". Arrow points to essential and inherent asymmetric information for information goods. Knowledge is also cumulative. New knowledge is built on existing knowledge and forms the basis for its own destruction from yet-to-come generations of knowledge. A variant of the cumulative nature of knowledge is recombinant growth. Weitzman (1998) analyses how new combinations of existing knowledge produce new knowledge that can, in turn, form new combinations.

ICT, as a network technology, has been characterised as a General Purpose Technology (GPT). GPTs are technologies that are general, have widespread use, stimulate further innovations and are complementary (Helpman, 1998; Dosi, 1988). These are characterised by increasing marginal utility and productivity in their number of users. This implies that there are positive externalities from the use of ICT. The marginal user, however, pays a price that equals their marginal utility. Scotchmer (2004) and Shy (2001) analyse network effects. They demonstrate that markets for network goods may have multiple equilibria and that some may Pareto-dominate others.

The characteristics of ICT have given rise to two controversial hypotheses in empirical research. The first is that ICT, particularly the internet, significantly impacts economic growth. Many studies indicate positive growth effects from ICT. Brynjolfsson and McAfee (2014) summarise major contributions. Major counterarguments are given in Gordon (2016). Gordon compares ICT with previous GPT and argues that the economic impacts of ICT are overstated. The second hypothesis is that the most important growth effects are yet to come. The argument is that trend growth rates in the USA, Europe and Japan have fallen since the golden 1960s. This is so even if the use of ICT has increased rapidly in recent decades.

David (1990) compares the ICT revolution with the development of electricity. Because of network effects, among other factors, it took time before the introduction of electricity increased productivity.[2] David hypothesises that the case of ICT may be similar. Brynjolfsson and McAfee (2014) state that the business process changes and organisational co-inventions that new technologies enable perhaps constitute the most important innovations.

[2] The other reason being the need for complementary innovations in the organisaton of production (Brynjolfson, McAfee 2014).

Other contributions, such as Bresnahan and Trajtenberg (1995) and Helpman and Trajntenberg (1998), construct growth models with substantial lags between investments and subsequent growth effects from the introduction of GPT.

2.2. Empirical Evidence for Economic Growth Impulses from Broadband

Although the rationales for productivity impulses are clear, the empirical evidence is mixed. Brynjolfsson and Hitt (2000) argue that the auxiliary investments needed for successful ICT investments are often incorrectly counted. They find that additional investments in human capital are often also required. For instance, Bresnahan, Brynjolfsson and Hitt (2002) report results from a survey of firms. They found that investments in ICT are associated with increased delegation at the workplace and higher skills and education levels. They also found that these work practices are correlated with each other. On the other hand, Gordon (2000, p. 50) argues that "the greatest benefits of the computer lie a decade or more in the past, not in the future".

There contradicts the evidence about the growth effects of the internet. Using cross-country panel data, Choi and Yi (2009) found evidence that the internet stimulated economic growth in the period 1990–2000. In Maurseth (2018), the period is 1990–2015, and for this period, there is no evidence that the internet has stimulated growth. The regressions indicate a negative and significant effect. This effect is stronger for the post-2000 period; for the 1990-2000 period, the results from Choi and Yi are confirmed.

However, the impact of the internet may vary, and the quality of internet access varies. Old-fashioned dial-up connections can be used for substantially fewer purposes than modern high-speed broadband connections.

Koutroumpis (2009) estimates growth effects from broadband penetration for a sample of 22 OECD countries for 2002–2006. Controlling for endogeneity using an instrument variable technique in which broadband demand is separated from broadband supply, Koutroumpis concludes that broadband significantly increased GDP.

Czernich et al. (2011) study the relationship between broadband investments and growth in a cross-section of OECD countries from 1996 to 2007. They include the level effects of broadband investments (does GDP per capita increase as a function of broadband investments?) and growth effects (does broadband investments result in higher (permanent) growth rates?). An obvious problem is endogeneity. It might well be that richer and fast-growing countries invest more in broadband than other countries. For instance, Tranos and Mack (2016) find that firm-level growth sometimes explains broadband investments, while causality goes in the other direction in other cases. To control for this, Czernich et al. use the existing extensiveness of telephone and cable TV as instruments. They claim their instrument is valid since telephone lines and cable TV explain broadband investments but not subsequent growth. Their results are astonishing – the introduction of broadband increases GDP per capita by 2.7 to 3.9 per cent. A 10 per cent increase in broadband coverage increases the GDP growth rate by 0.9 to 1.5 percentage points. Other studies bring nuances to the table or provide more modest results. For instance, Grimes et al. (2012) find that basic broadband boosts productivity by 7 to 10 per cent at the firm level for New Zealand in 2005 and 2006, but they do not find that broadband quality impacts productivity. Other researchers find more modest results.

Bojnec and Fertó (2012) investigate the impact of broadband on economic growth in panel data from OECD countries from 1998 to 2009. They estimate growth (in GDP per capita) as a function of investments in physical capital, government expenditures and inflation and three alternative measures of broadband availability. The three measures are standard access lines per 100 inhabitants, access channels per 100 inhabitants and total broadband per 100 inhabitants. They find that the first two broadband access measures correlate positively to growth while the last contributes negatively (and partly significantly). Haller and Lyons (2019) find that broadband internet increases the total factor productivity of Irish firms in high-tech service industries, but it has no significant effect in the services sector (when these are taken together).

Akerman et al. (2015) study the effects of broadband on labour productivity and wages. Based on a public programme to support broadband rollout, they obtain exogenous variation in broadband availability to firms. Their instrument allowed them to estimate the effects of broadband on worker productivity. The results indicate that broadband improves wages and productivity for high-skilled workers but has the opposite effect for low-skilled workers. The explanation they propose is that broadband availability increases the demand for skills.

Holmen and Maurseth (2020) scrutinise Norwegian productivity data and their relationships with broadband availability. They use data on changes in broadband coverage in different speed categories. They find that investments in advanced broadband infrastructure do not increase productivity in the business sector. However, basic broadband infrastructure has positive effects.

Acosta and Baldomero-Quintana (2023) estimate the impact of communication infrastructure quality (internet speed) on growth and structural transformation. They find that doubling internet speeds, increases 4-year employment growth by 3.3 to 6.1 percentage points. Faster internet services shifts economic activity towards high-skilled services and away from non-tradeable services.

2.3. Expansion of Broadband in the Baltics

Our prime interest is the relationship between broadband development and regional growth in the Baltic countries. Figure 1 presents the share of the population using the internet in the Baltic countries, the EU, and the world from 1990 onwards. The graph indicates that in the Baltics and the EU, the internet has matured in the sense that diffusion is becoming complete. The figure also shows that the Baltics differed in their use of the internet relative to the European average. Estonia has ranked above, while Latvia and (in particular) Lithuania lagged behind.

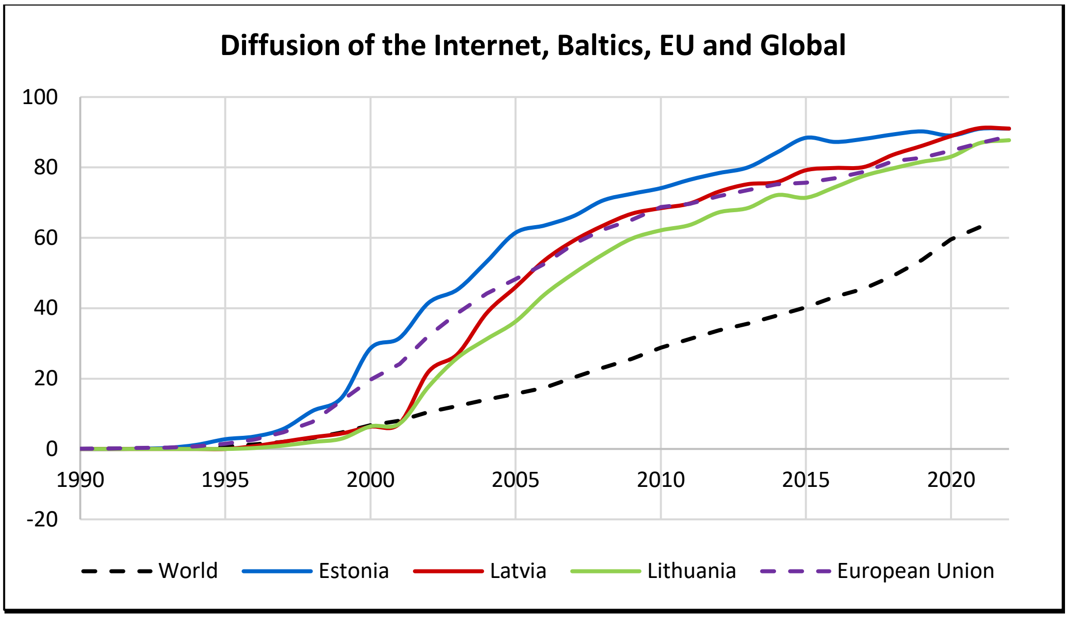


Figure 1. Share of population using the internet in Baltic countries and the EU
Source: World Development Indicators

There are also a few previous studies on the regional impact of broadband; these are important, given our focus on the regional effects of broadband in the Baltics. Jung and López-Baso (2020) found higher productivity gains for broadband in less developed regions of Brazil. Briglauer et al. (2021) found in the analysis of German counties that the positive effect of broadband on regional GDP is almost doubled if the regional externalities are considered.

Given the statistics on high broadband penetration presented, is there a need for policy intervention in the Baltic States to promote the development of broadband internet, or if the general level is high, to achieve a more balanced coverage across the regions? The private sector service providers have primarily been the responsible actors. They have been more interested in developing infrastructure in densely populated areas than in sparsely populated areas, causing a digital gap (Majandus- ja Kommunikatsiooniministeerium, 2016). This may have raised challenges related to low population density (but also the concentration of population in the areas around a few large cities; for example, 46% close to Tallinn in Estonia, Statistics Estonia) compared to most other EU countries and the EU goals set in 2016 to develop high-speed broadband connection networks. The ability to invest in broadband infrastructure has been enhanced in the Baltic States as elsewhere in CEE countries through foreign investments, such as the Swedish group TeliaSonera, which has had the largest market share (Samanta et al., 2012), and, in Estonia, the concession agreement concluded in 1992 guaranteeing a monopoly for Elion (formerly Eesti Telecom) for eight years to ensure connectivity in rural areas in return for profits earned in urban areas (Frank and Nemeth, 2004). Therefore, one may argue that the regional gaps may have been even more significant without such policies. Karnitis et al. (2019) indicate that rural broadband coverage has been better in Lithuania and exceeding the mean EU-28 level due to publicly funded RAIN projects, while analogous projects have also been implemented in Estonia (EstWin project) and Latvia (Development of next-generation electronic communications networks in rural areas); a particular challenge has been establishing the last-mile consumer lines in rural areas.

Ivanov (2023) claims that in the case of Estonia, based on interviews with various stakeholders, the previous policy of broadband internet development, maximising the number of Next-

Generation Access (NGA) networks with minimal financial means, has not been cost-effective due to insufficient planning and the low rate of connected consumers. One particular suggestion was to consult more with local communities in respect to broadband development (Ivanov 2023), which has also been suggested in the case of other regions (Ruiz-Martinez and Esparcia, 2020 for Spain). Therefore, the previous plans are under revision towards the development of a new strategy (Estonian Broadband Development Plan, 2021–2023), with the stated goal that "By 2030, regardless of location, Estonia will have access to ultra-fast, reliable and affordable services, enabling the creation and use of innovative services" (Majandus- ja Kommunikatsiooniministeerium, 2023).

In addition to mere broadband penetration, the question is also what other complementary growth drivers are needed in the case of the Baltic States for broadband development to spur economic growth (Ghosh, 2017), and the realisation of the potential for broadband for growth depends on the implementation of advanced technologies like big data mining and artificial intelligence (Karnitis et al., 2019). Therefore, the limited number of companies in the Baltic States using these technologies would probably need to change for the growth effects to take place (in 2021, 41% of companies in the EU, 58% in Estonia, while in Latvia and Lithuania just 34 and 33% present, respectively, Eurostat isoc_cicce_use). Karnitis et al. (2019) claimed, based on a quantitative analysis of key drivers of digitalisation in the EU countries, that excellent broadband connectivity is one of the strengths of the Baltic States, related, for example, to the proper past investment decisions in fibre coverage instead of DSL wired networks, and rural coverage currently being the single remaining connectivity problem, having potentially much higher returns than the further increase of internet speeds in urban areas, which also motivated our study. The different economic impacts of fixed versus mobile broadband may also need to be considered; for example, the significant 5G investment costs may further exacerbate the existing urban-rural and centre-periphery digital divides in the Baltic States (Wendt-Lucas and de Jesus, 2023).

3. THEORETICAL UNDERPINNINGS

This section discusses production analysis in the context of broadband investment. We start by formulating the theoretical production model before presenting a two-stage estimator of optimal broadband investment paths. To maintain consistency, we tailor the description of the production model to our case study on the Baltic regions. Generalisation of the framework is straightforward (For a general introduction to production theory, see e.g. Färe and Primont 1995).

3.1. Production Theory for Broadband Investments

Let $\mathbf{x} \in \Re_+^2$ denote labour and capital inputs, and let $Q \in \Re_+$ denote the stock of past broadband investments. These are considered inputs to the joint production of new broadband, $q \in \Re_+$, and GRDP, $y \in \Re_+$. Note that the superscripts Q and q refer to broadband stocks and flows, respectively. A technology that summarises technically feasible input-output combinations is defined by Eq. (1).

$$T = \{(\mathbf{x}, Q, y, q) : (\mathbf{x}, Q) \text{ can produce } (y, q)\} \quad (1)$$

The technology is assumed to satisfy standard regularity conditions, including convexity and free disposability. Again, we refer to Färe and Primont (1995) for the details.

Eq. (1) depicts broadband as both a rival and input to GRDP formation. That is, current broadband investment (q) is modelled as an output – implying that broadband investments always take place at the expense of current consumption at the Pareto front (for a given resource endowment). The stock of investments (Q) is, on the other hand, regarded as inputs to GRDP formation. Hence, it reflects the benefit of internet services for value creation. Our modelling approach thereby distinguishes between broadband as a tangible asset (i.e., in the form of a tangible investment when modelled as an output) and as an intangible asset (i.e., in the form of production benefits of access to internet services when modelled as an input), drawing on the ideas of Corrado et al. (2021). The dynamic planner problem studied herein consequently trades off the costs and benefits of broadband development that stem from broadband's dual role as both an input and a rival to GRDP.

A function representation that can be estimated from data is required for empirical analysis. Eq. (1) defines a multi-input multi-output technology which makes distance functions suitable. They allow the underlying technology to be characterised using quantity data only. Herein, we select the DDF (Chambers et al., 1998) as our preferred function representation:

$$\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})=\sup\left\{\theta:\left(\mathbf{x}-\theta\mathbf{g}_x,Q-\theta g_Q,y+\theta g_y,q+\theta g_q\right)\in T\right\} \qquad (2)$$

where $\mathbf{g}$ determines the direction of the projection of an input-output bundle to the production possibility frontier. The distance function inherits the properties of the technology set and is greater than or equal to 0 when $(\mathbf{x},Q,y,q)$ is an element of the technology defined in Eq. (1) (i.e., for technically feasible input-output combinations). The value 0 indicates that the unit under observation operates on the technology frontier, while a positive value signals inefficiency in production.

Two key assumptions can be inferred from the model framework described by Eqs. (1)–(2).

a) Labour (and capital) productivity could be improved by access to internet services. Thus, there is a trade-off between labour input and past investments in broadband for the current output at the Pareto front. Hence, when the broadband stock increases, the need for other inputs to produce a given output bundle is reduced.
b) Broadband development comes at the expense of current consumption (i.e., at the Pareto front, there is a trade-off between investments in broadband and current consumption for the given inputs).

Returns to investment can consequently be considered by evaluating the marginal products of the DDF:

$$\frac{\Delta y}{\Delta q}\frac{\Delta q}{\Delta Q}=\frac{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial q}{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial y}\frac{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial Q}{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial q}=\frac{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial Q}{\partial\vec{\mathrm{D}}(\mathbf{x},Q,y,q;\mathbf{g})/\partial y} \qquad (3)$$

3.2. Estimation of the DDF

We estimate the DDF using CNLS, assuming contemporaneous frontiers (Tulkens and Vanden Eeckaut, 1995), which means that distinct frontiers are being estimated in each time period, t. Consequently, our modelling facilitates intertemporal differences in technology (e.g., due to technical changes) that can influence temporal gains from broadband investments and, thereby, the optimal investment path (which we return to in the subsequent Section).

Let *i* denote a given region in the dataset, and let *h* define its alias. Following Kuosmanen and Zhou (2021), the DDF-CNLS estimator is then defined by Eq. (4).

$$
\begin{aligned}
&\min \sum_{t=1}^{T}\sum_{i=1}^{N}\varepsilon_{it}^{2} \\
&\text{s.t.} \\
&\gamma_{it}q_{it}+\delta_{it}y_{it}=\alpha_{it}+\boldsymbol{\beta}'_{it}\mathbf{x}_{it}+\lambda_{it}Q_{it}+\boldsymbol{\delta}'\mathbf{z}_{it}-\varepsilon_{it},\forall it \\
&\alpha_{it}+\boldsymbol{\beta}'_{it}\mathbf{x}_{it}+\lambda_{it}Q_{it}-\gamma_{it}q_{it}-\delta_{it}y_{it}\le\alpha_{ht}+\boldsymbol{\beta}'_{ht}\mathbf{x}_{it}+\lambda_{ht}Q_{it}-\gamma_{ht}q_{it}-\delta_{ht}y_{it},\forall iht \\
&\gamma_{it}g_{q,it}+\delta_{it}g_{y,it}+\boldsymbol{\beta}'_{it}\mathbf{g}_{I,it}+\lambda_{it}g_{Q,it}=1,\forall it \\
&\gamma_{it}\ge 0,\delta_{it}\ge 0,\boldsymbol{\beta}_{it}\ge 0,\lambda_{it}\ge 0,\forall it
\end{aligned}
\tag{4}
$$

The error term, ε, embodies the DDF. It can either be treated as a one-sided error (i.e., assuming a deterministic DDF model) or as comprising two components: inefficiency and random noise. The latter approach, often referred to as stochastic frontier analysis, is utilised in this study.

The vector $(\alpha_{it},\gamma_{it},\delta_{it},\boldsymbol{\beta}_{it},\lambda_{it})$ comprises variables to be estimated that belong to the DDF. Here, α_{it} characterises returns to scale, while the remaining variables define the derivatives of the DDF. These are all restricted to be non-negative to ensure that the underlying function is monotonically increasing in inputs and decreasing in outputs; cf. the final set of inequality constraints in Eq. (4). The other inequality constraints in Eq. (4) constitute curvature restrictions, ensuring that the DDF is concave. Finally, the summing-up constraints for the direction weights ensure that the DDF satisfies the translation property. We refer to Chambers et al. (1998) for details regarding the axiomatic properties of the DDF.

Note that we have appended the parametric function $\boldsymbol{\delta}'\mathbf{z}_{it}$ to the DDF. This makes it possible to control for the impact of contextual factors on GRDP. We assume that contextual factors affect production in a factor-neutral fashion.

An important consideration when using the DDF is the appropriate assignment of the direction vector. Although there is increasing interest in the endogenous assignment of the vector (e.g., Färe et al., 2013), the vector is normally predetermined or exogenous in empirical applications (Wang et al., 2019). A key concern is that the vector is arbitrarily assigned, which makes efficiency scores less meaningful. In this study, we propose a distinct normalisation of the direction vector with a clear economic meaning for our application for broadband investment.

Proposition: Assume the direction vector $\mathbf{g}=(\mathbf{0},0,1,0)$. Then, the DDF is equally represented by the production function $\mathrm{F}(\mathbf{x},Q,q)$ such that $\partial\mathrm{F}/\partial x_n\ge 0,\partial\mathrm{F}/\partial Q\ge 0$ and $\partial\mathrm{F}/\partial q\le 0$.

Proof: By implementing the proposed direction vector, the set of constraints $\gamma_{it} g_{q,it} + \delta_{it} g_{y,it} + \boldsymbol{\beta}'_{it} \mathbf{g}_{I,it} + \lambda_{it} g_{Q,it} = 1, \forall it$ in Eq. (4) reduces to $\gamma_{it} = 1, \forall it$. By substituting into the other constraints in Eq. (4), we obtain the reduced expression:

$$
\begin{aligned}
&\min \sum_{t=1}^{T} \sum_{i=1}^{N} \varepsilon_{it}^2 \\
&\text{s.t.} \\
&y_{it} = \alpha_{it} + \boldsymbol{\beta}'_{it} \mathbf{x}_{it} + \lambda_{it} Q_{it} - \gamma_{it} q_{it} + \boldsymbol{\delta}' \mathbf{z}_{it} - \varepsilon_{it}, \forall it \\
&\alpha_{it} + \boldsymbol{\beta}'_{it} \mathbf{x}_{it} + \lambda_{it} Q_{it} - \gamma_{it} q_{it} \le \alpha_{ht} + \boldsymbol{\beta}'_{ht} \mathbf{x}_{it} + \lambda_{ht} Q_{it} - \gamma_{ht} q_{it}, \forall iht \\
&\gamma_{it} \ge 0, \boldsymbol{\beta}_{it} \ge 0, \lambda_{it} \ge 0, \forall it
\end{aligned} \tag{5}
$$

Eq. (5) is the conventional CNLS estimator of the production function (see Kuosmanen and Kortelainen, 2012) where $\mathrm{F}(\mathbf{x}_{it}, Q_{it}, q_{it}) = \alpha_{it} + \boldsymbol{\beta}'_{it} \mathbf{x}_{it} + \lambda_{it} Q_{it} - \gamma_{it} q_{it}$, and the sign constraints ensure the appropriate signs of its marginal products. Q.E.D.

In this study, we implement $\mathrm{F}(\mathbf{x}_{it}, Q_{it}, q_{it})$ as our preferred function representation of the technology. It immediately captures the dual role of broadband investments as both a facilitator of and a rival to economic development, cf. the opposite signs of the marginal products of the broadband input and output. Moreover, by choosing the direction vector $\mathbf{g} = (\mathbf{0}, 0, 1, 0)$, the analysis gives weight to GRDP as a key measure of regional economic growth.

3.3. Optimal Dynamic Path

Having estimated the technology, we now turn to the optimal dynamic path for broadband investment. This can be solved using Linear Programming (LP), which uses the estimated shadow prices of the production function $\mathrm{F}(\mathbf{x}, Q, q)$ as input to jointly optimise the broadband input and output. This optimisation problem is described by Eq. (6). Note that pre-estimated parameters obtained from the production function in Eq. (5) here are indicated by hat. At the same time, we use tilde to distinguish quantity parameters (i.e., exogenous variables) from variables (i.e., endogenous variables) in the subsequent LP problem.

$$
\begin{aligned}
&\max \sum_{t=1}^{T} \sum_{i=1}^{N} \rho_{it} \\
&\text{s.t.} \\
&\rho_{it} \le \hat{\alpha}_{it} + \hat{\boldsymbol{\beta}}'_{it} \mathbf{x}_{it} + \hat{\lambda}_{it} \tilde{Q}_{it} - \hat{\gamma}_{it} \tilde{q}_{it}, \forall it \\
&\tilde{Q}_{i,t+1} = \tilde{Q}_{it} + \tilde{q}_{it}, \forall it / \{T\} \\
&\tilde{Q}_{it} \le D_{it}, \forall it
\end{aligned} \tag{6}
$$

where D_{it} is the population size in region *i* at time *t*.

The first set of (inequality) constraints in Eq. (6) ensures that GRDP cannot exceed technical limits, as characterised by the production function $\mathrm{F}(\mathbf{x}, Q, q)$. The second set of constraints are flow conservation constraints that ensure that the stock of broadband at any moment is directly related to past investments in broadband. Hence, there is no free lunch, and expenses related to broadband development – at the expense of foregone GRDP – always accrue prior to reaping the benefits of broadband as an input. The final set of constraints ensures that the broadband supply, which in our study is characterised by the number of inhabitants with access to broadband, never exceeds the (potential) demand for broadband. The latter is defined by population size per region and year.

In our growth model, we have focused on the optimal investment path for maximising the production level over time. This simplification is made instead of focusing on the optimal consumption path (which is the focus in traditional growth models), as broadband investments constitute a relatively small part of GDP.

4. EMPIRICAL IMPLEMENTATION

In this section, we present the Baltic region assessed in our study and the data applied.

4.1. Region

In our study, we consider the NUTS-3 regions in the Baltic countries. The three Baltic countries contain a total of 21 NUTS-3 regions, distributed over ten regions in Lithuania, six in Lativa and five in Estonia. The countries and the regions are depicted in Figure 2.

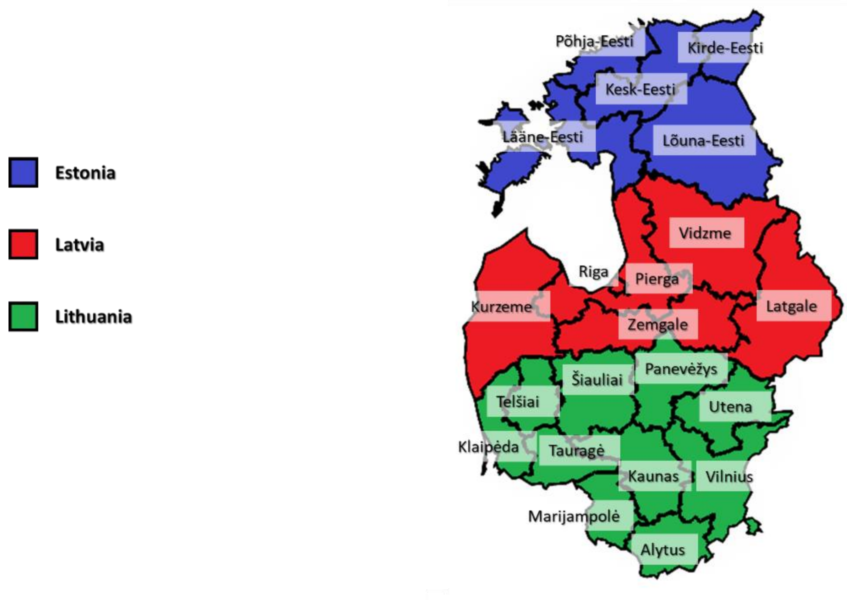


Figure 2. Map of the Baltic NUTS 3 regions.
Source: Holmen et al. (2023)

Reviewing descriptive statistics for the region, Holmen et al. (2023) point out that the biggest income disparities within the Baltic region are not between countries but between the urban and rural regions. The authors further show that the Estonian regions mostly have better broadband coverage than the Latvian regions, which, in turn, mostly have better broadband coverage than the Lithuanian regions.

4.2. Data Sources

We collect data from regional accounts for the Baltic States obtained from Holmen et al. (2023). The dataset entails annual observations for the 21 Baltic NUTS-3 regions from 2005 to 2019. Most variables in the dataset are collected from providers of macro data, such as Eurostat and the OECD, before being further processed. For variables unavailable for the Baltic regions in such sources (e.g., fixed capital stocks), the data is estimated by combining macro sources and firm data.

The broadband variable is the share of households with the possibility to subscribe to an internet connection of at least one Megabit per second. Therefore, it is a measure of latent broadband coverage. In the original data from the OECD, there are some measurement errors associated with survey-based data collection. In the processed data applied, this is handled by assuming that the broadband coverage cannot decline and by replacing extreme outliers based on their interpolated values (cf. Holmen et al., 2023). To obtain the expansion in broadband coverage in 2019, the data series is extended to 2020 based on additional data collected from the OECD Regional Database for this year.

We apply the gross domestic product in fixed 2010 prices as output. Furthermore, the annual average for employment and fixed capital stocks in fixed 2010 regions are used as inputs. As contextual variables, we use population density, which is measured as the average population per land area during a year. Furthermore, we control for the sector employment shares, distinguishing between commodity industries (NACE 1 to 43), market-oriented service industries (NACE 45 to 82) and nonmarket-oriented service industries (NACE 84 to 99), where the latter is used as the reference basis. In addition, we control for the country where Estonia is utilised as the reference basis.

4.3. Descriptive Statistics

In Table 1, we provide the summary statistics for the dataset. Overall, the table depicts considerable variations in broadband coverage and economic activities across regions and time. The descriptive statistics indicate that the Baltic regions differ greatly in their GRDP (the largest and smallest NUTS-3 regions differ by almost 35 times), both due to the differences in their population size and the GRDP per capita. The same can be said about population density – while the rural regions have a rather low population density in comparison to Western and Central European countries, for instance, the population density is much higher for the urban regions. That is a relevant control variable in the analysis, whereas the low population density in the rural regions of the Baltic States is expected to make broadband development more costly (though the question might also be about choosing the appropriate technology for that).

Broadband coverage is measured as a percentage of households with latent access to broadband, while the population density is calculated as the number of inhabitants per square kilometre of land area. As firms and government organisations tend to be located in central areas where broadband access is good, and broadband expansion tends to occur relatively early in central areas, broadband coverage for the production sector should be expected to be better than the coverage for the household sector. Furthermore, we know that higher speeds of broadband, exceeding basic broadband (i.e., internet connections of more than at least one Megabit per second), were rolled out across our study period. Although access to the internet through at least basic broadband is likely to be most important in most instances, higher speeds may possibly enhance productivity, and new technological opportunities may emerge (e.g., Holmen and Maurseth, 2020). Both the centralisation of broadband supply and the exhaustion of ways to exploit high speeds of broadband suggest diminishing returns of broadband coverage.

Table 1. Summary statistics of the dataset used for empirical analysis

Variables	N	Mean	Sd. Dev	Median	Min	Max
GRDP in fixed prices (Million euro)	315	2.95	3.22	1.45	0.43	14.90
GRDP in fixed prices per employed (Million euro)	315	18.56	5.23	17.49	7.99	33.94
Employment (thousands)	315	137.55	109.28	100.7	39.48	539.07
Fixed capital in fixed prices (Million euro)	315	19.28	26.38	8.46	2.11	124.93
Broadband	315	0.563	0.221	0.609	0.046	0.946
Broadband coverage times population (Millions), level	315	0.177	0.145	0.126	0.009	0.674
Broadband coverage times population (Millions), growth	315	0.016	0.012	0.994	0.000	0.148
Population density	315	161.01	544.09	31.80	12.43	2771.25
Employment share for commodity industries	315	0.398	0.823	0.414	0.193	0.635
Employment share for market-oriented services industries	315	0.340	0.793	0.319	0.166	0.580

The figure below shows that broadband coverage varies in the Baltic States within the range of 75 to 95 per cent, therefore, while being high across the regions, it also demonstrates substantial cross-regional variation. The coverage is the highest in the Estonian regions (even concerning those at a somewhat lower income level, such as Kirde-Eesti). While both Latvian and Lithuanian regions have a lower coverage, Lithuanian regions generally lag further behind Latvia. There is more cross-regional variation in the growth rates, and we can see some evidence of convergence as several regions with lower initial levels show higher growth rates.

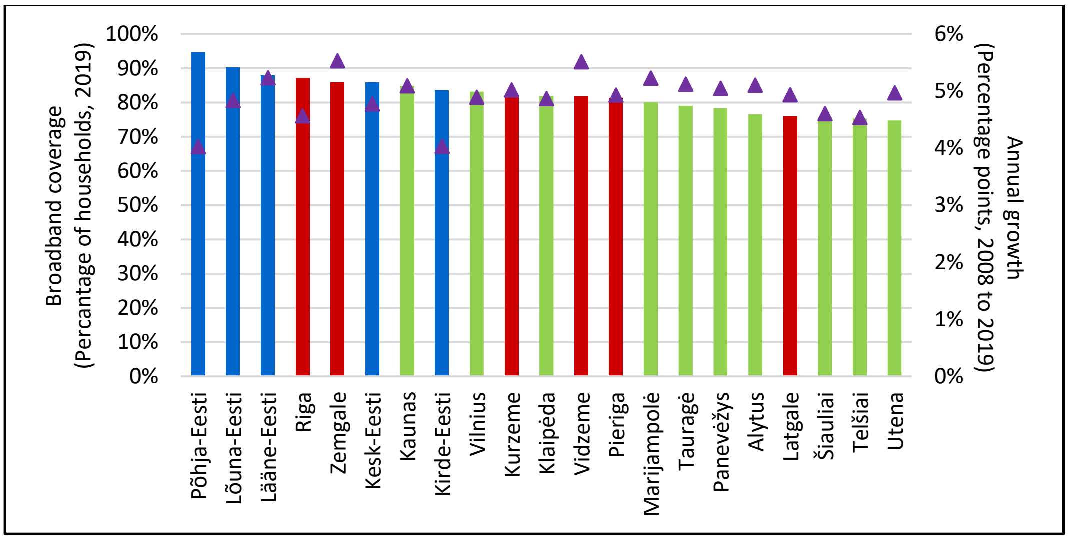


Figure 3. Broadband coverage in 2019 with annual growth rates from 2008 across Baltic NUTS-3-regions in 2019 with annual growth from 2008.
Notes: Colour codes in the single bar charts: Blue is Estonia, red is Latvia, and green is Lithuania. The purple triangle indicates annual growth.
Source: Holmen et al. (2023)

In Figure 4, we have depicted the correlation between broadband coverage and gross value added volumes per person employed (labour productivity) in terms of levels and growth, respectively. There is a positive correlation between broadband coverage and labour productivity in levels, partly because both variables increase over time. The correlation patterns between broadband expansion and economic growth are much weaker. This is partly due to the economic downturn following the financial crisis, which was also a period with relatively large expansions of broadband infrastructure. Whether there are causal impulses from broadband expansion to economic growth thus remains an open question for our investigation to explore.

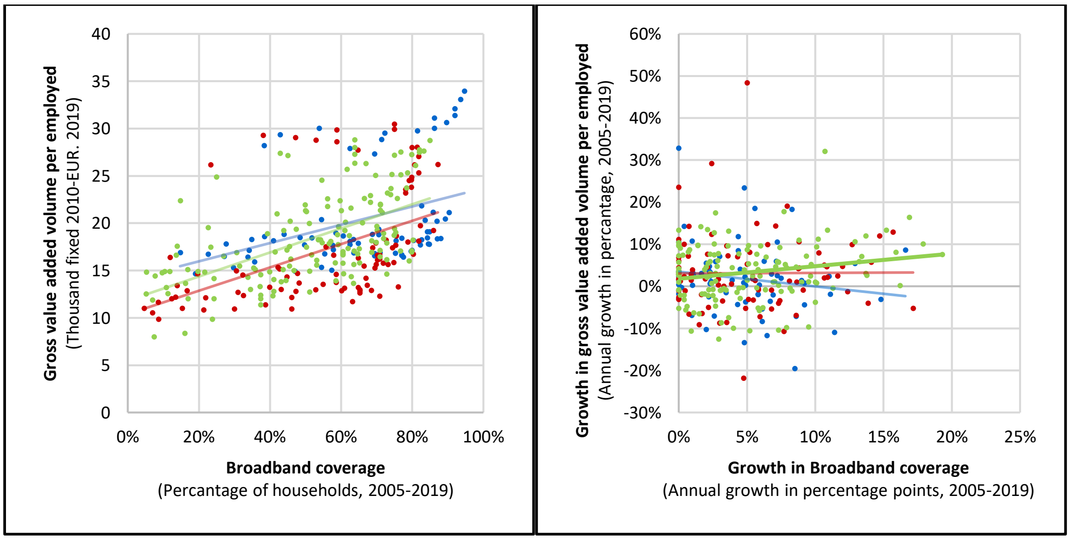


Figure 4. Correlation plots across the Baltic NUTS 3 region between broadband coverage and gross domestic product in terms of (a) status (left panel) and (b) growth (right panel) from 2005 to 2019 with indications of trend lines.
Notes. Colour codes in the plot diagram: Blue is Estonia, red is Latvia, and green is Lithuania.

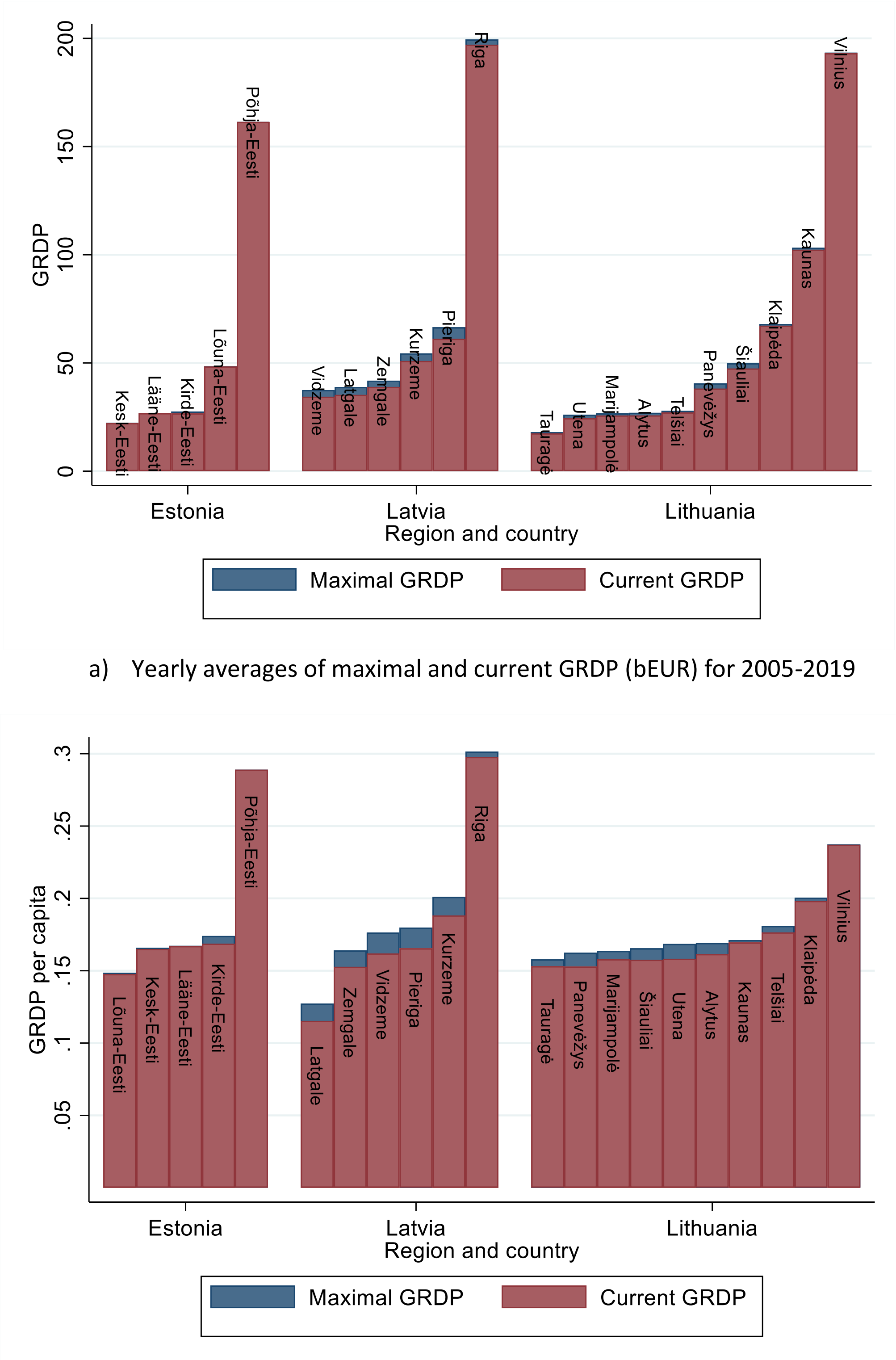
5. Results

We estimate and compare Eq. (5) and (6); that is, the production function subject to current and optimal broadband development. Figure 5 presents and compares the two measures by means of annual average GRDP between 2005 and 2019 (panel a) and GRDP per capita (panel b) according to country and region.

Figure 5 shows that there is a significant difference between the GRDP of the capital regions (i.e., Põhja-Eesti, Riga, and Vilnius) and the other (non-capital) regions. This gap is more pronounced for Estonia and Latvia than for Lithuania, where regions are more equal in terms of economic output. The smallest region in each country accounts for 13.8 % (Estonia), 17.5 % (Latvia), and 9 % (Lithuania) of the GRDP of its capital region, respectively.

We find intercountry differences with regard to the adoption of optimal development paths for broadband. Figure 5 reveals that the potential to increase economic output by adopting an efficient development strategy for broadband is largely exhausted for the regions in Estonia and for all three capital regions. The greatest potential to expand output per capita from broadband development relates to non-capital regions in Latvia, followed by Lithuanian regions associated with the country's lowest regional GRDP. This suggests that while investments in broadband currently target the most economically important regions, there could be economic gains from bringing smaller regions to par with large regions in terms of accessibility to broadband services. Hence, broadband development could be an important regional policy instrument to promote growth and limit interregional inequality, which the various policy documents and measures of the Baltic States have also addressed.

Despite intercountry and regional differences, both panels of Figure 5 suggest that the overall economic gains from implementing the optimal investment path for broadband – compared to the current development – are limited. This is further explored by Figure 6, which uses the ratio of GRDP subject to current and optimal broadband development to define regional efficiency scores. They range from 0.91 to 1.00, with an average efficiency score of 0.96 and a median efficiency score of 0.97. This suggests that the regions operate on or close to the optimal development path for broadband.



a) Yearly averages of maximal and current GRDP (bEUR) for 2005-2019

b) GRDP (mEUR) per capita

Figure 5. Current and maximal GRDP per country and region.

Figure 6 presents efficiency scores according to population density per region. According to this figure, there is a tendency towards more densely populated regions being more efficient. This gap can stem from a lack of incentives for commercial developers to invest in rural regions. Public policy interventions can, in this case, be instrumental in filling the gap.

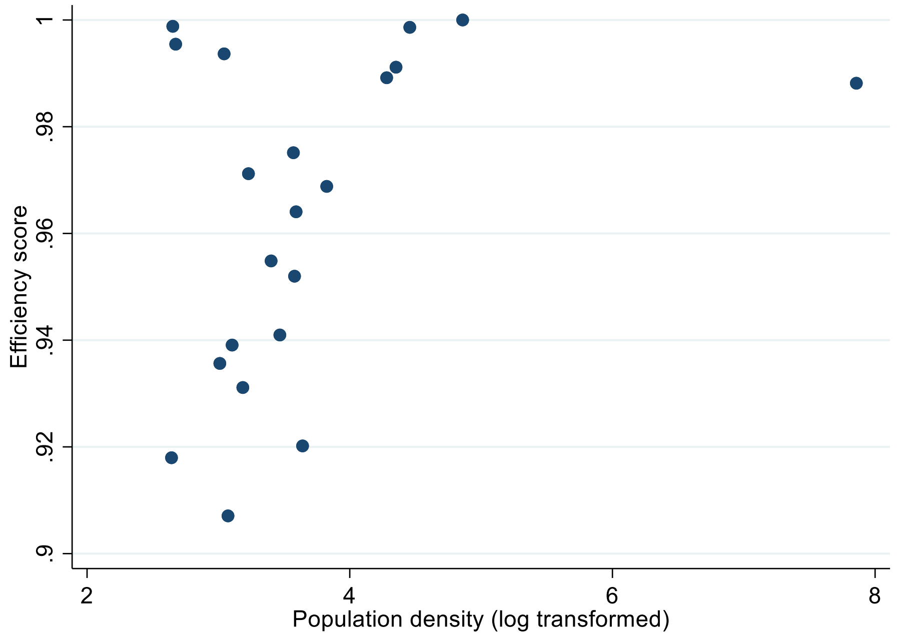


Figure 6. The relationship between the efficiency of broadband investments and the population density.

Note. The regional efficiency scores have been defined as the ratios of GRDP subject to current and optimal broadband development. Riga is excluded to enable a comparable scale with respect to population density.

To gain a better understanding of the drivers of interregional differences with regard to the potential for efficiency improvements (i.e., regarding optimal broadband investment), we undertake a simple regression analysis of selected covariates (population density, employment shares by industry sector and country dummies) on average annual foregone regional output due to sub-optimal investment strategies for broadband. The results are presented in Table 2, which suggests that national strategies for broadband development are important for explaining differences in efficiency scores. All other covariates are found to be statistically insignificant.

Table 2. Regression analysis of foregone average annual regional production due to suboptimal strategies in broadband development (N=21)

Variable	*Coefficient*	*Standard errors*
Population density	-0.047	0.045
Employment share for commodity industries	0.830	7.768
Employment share for market-oriented services industries	0.167	8.688
Latvia (dummy)	3.405***	0.505
Lithuania (dummy)	0.894*	0.457
Cons.	-0.104	5.814
Adj R^2	0.714	

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Finally, we compare actual and optimal broadband investments per country and region. Development paths are described in Figure 7, while the intertemporal differences between optimal and actual investment paths are presented in Appendix 0. These figures show a notable distinction between Estonia and the two other countries: For most regions in Latvia and Lithuania, optimal broadband investments surpass actual investments for all years under consideration. Notable exceptions are Vidzeme in Latvia and Kaunas in Lithuania. For Estonia, the results are mixed and point towards over-investments in broadband in Kesk-Eesti and Põhja-Eesti in recent years. In line with previous findings, this points towards broadband development being more aggressive in Estonia than in neighbouring countries, possibly to the point where there are negative returns to investment with regard to economic output.

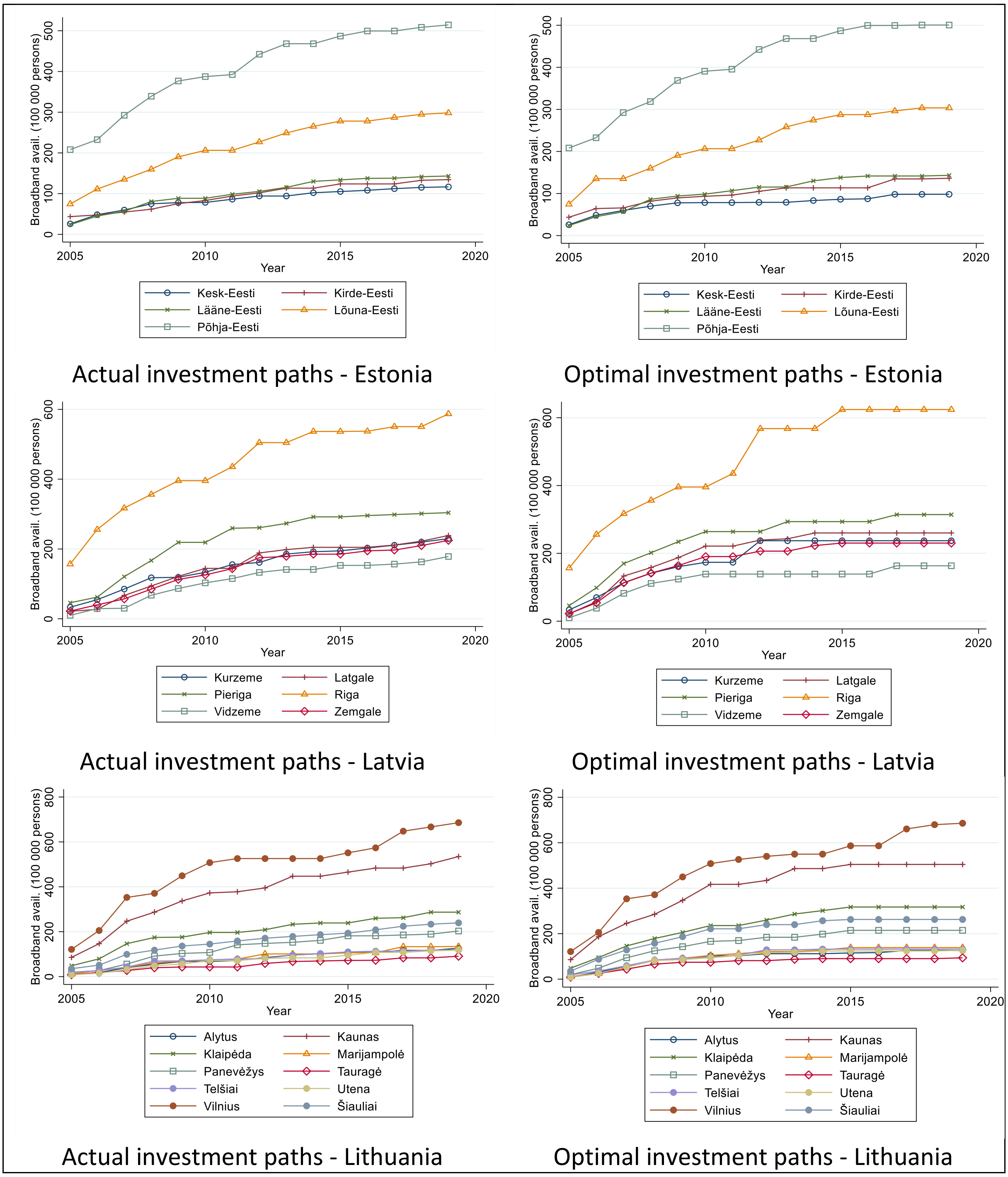


Figure 7. Actual and optimal investment paths for broadband, according to country and region

6. Summary and Conclusions

The development of broadband (hereby synonymous with high-speed internet) has been broadly recognised as critical to the economic development of countries, and so also in the context of the Baltic States. Our article expands that literature first by contributing to the less studied sub-regional level, where in relatively sparsely populated countries such as the Baltic States, the regional differences in the costs and benefits of broadband development cannot be ignored. Second, our article proposes a novel methodological framework for the estimation of the benefits of broadband investments that makes use of the Directional Distance Function framework for characterising the relationship between broadband investment and economic development and the estimation procedure combining Convex Nonparametric Least Squares with Linear Programming, offering thereby a stochastic frontier model framework instead of the more commonly used deterministic DEA approach. The used dataset included information on 21 NUTS-3 level regions of the three Baltic States (Estonia, Latvia, Lithuania).

Our results indicated that the potential of broadband development for economic development evidently depends on the particular region's level of urbanisation and economic development. The potential to increase economic output by adopting an efficient development strategy for broadband is clearly the lowest in Estonia (as the country with the highest level of GDP per capita) and the urban regions of Latvia and Lithuania, while these potential gains are the greatest in the rural regions of Latvia, but also Lithuania. From a different angle, we also found some evidence of over-investment in broadband in some regions, which is an interesting finding. Despite intercountry and regional differences, the results also suggested that the overall economic gains from implementing the optimal investment path for broadband – compared to the current development – are relatively limited. That information should be seriously considered in the cost-benefit analysis for IT infrastructure development projects and whether the same amount of investments in some other areas (say, physical infrastructure or human capital development) could achieve greater benefits for the Baltic States.

We find that our results have important policy implications for national and regional economic development in the Baltic States: The results clearly showed that leaving broadband development to the market alone need not be sufficient to make use of the potential that broadband development could have for economic growth. Therefore, in this case, a government subsidy or other incentive schemes are potentially potent measures to spur regional economic growth. In fact, at least to some extent, the policies have recognised such a challenge. Yet, to have more profound information on the effectiveness of these policies for regional development, one should use, in addition to the more aggregated regional-level data, also firm-level data, provided that the latter includes information both on the regional location of the production activities as well as the broadband development within narrowly defined geographical locations.

In future research, our model may be extended to focus on optimal consumption rather than production. This was not that relevant in our case, as broadband investments constitute a small part of GDP. Another interesting extension would be to consider the dynamics between broadband investments and other capital investments by endogenising capital in the model. Yet another point of departure for future research is to consider the complementarities between broadband and other features of the knowledge economy, such as higher education, patents, and research and development.

Appendix: Elaboration of the Results

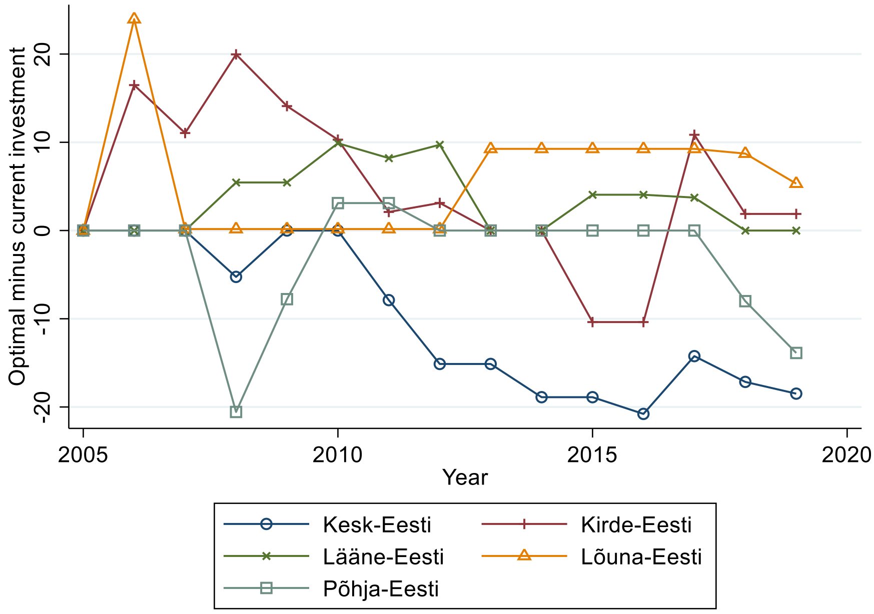


Figure 8. Difference between optimal and actual investment paths by region in Estonia

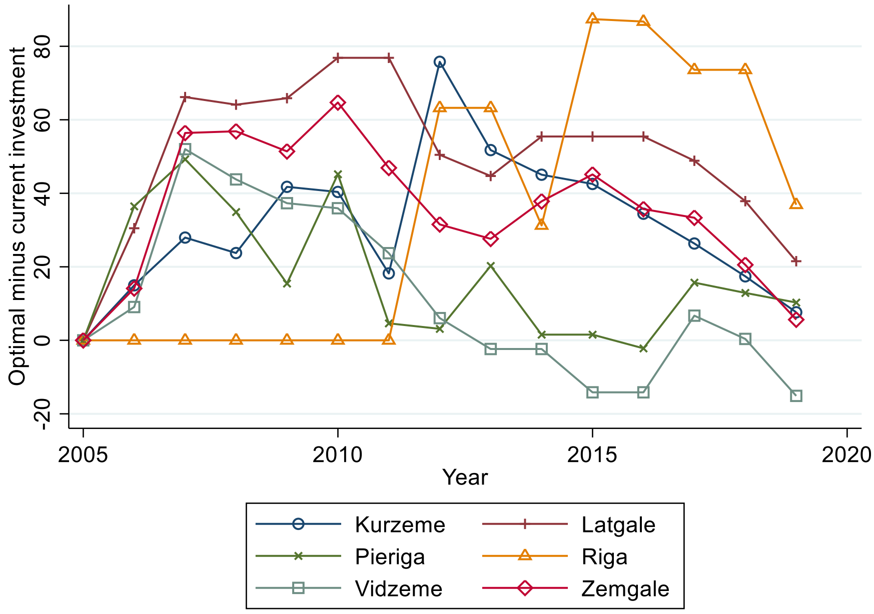


Figure 9. Difference between optimal and actual investment paths by region in Latvia

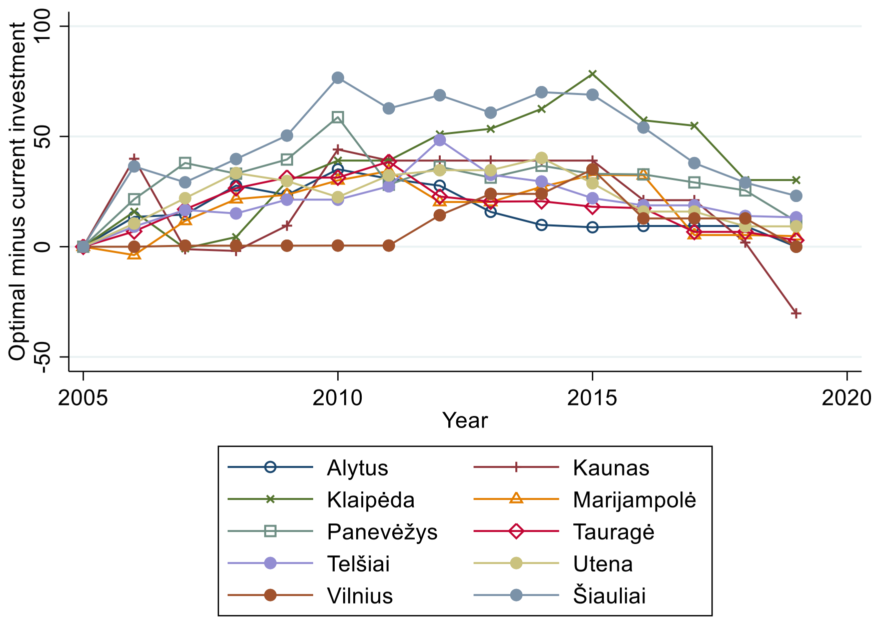


Figure 10. Difference between optimal and actual investment paths by region in Lithuania

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KOKKUVÕTE

Optimaalsed intertemporaalsed lairibainvesteeringud piirkondliku majandusarengu edendamiseks

Käesolev artikkel seob lairiba arendamise regionaalse majanduskasvuga, keskendudes seejuures lairiba investeeringute optimaalsele ajastusele. Lairibainvesteeringute ja majandusarengu vahelise seose analüüsimiseks on artiklis pakutud välja suunava kaugusfunktsiooni (*Directional Distance Function*) raamistik ning optimaalsete investeerimisteede hindamiseks on välja töötatud kaheetapiline hindamisprotseduur, mis kombineerib kumera mitteparameetrilise vähimruutude meetodi lineaarse planeerimise lähenemisega. Mudeli raamistikku rakendatakse uudsele andmekogumile, mis hõlmab Balti riikide (Eesti, Läti, Leedu) 21 NUTS3 taseme tegiooni. Tulemused näitavad, et optimaalse piirkondliku investeerimiskava kasutuselevõtuga saaks regionaalset sisemajanduse koguprodukti suurendada kuni 10 %. Samuti ilmnevad tulemustes teatavad riikidevahelised erinevused, kus Läti piirkonnad näitavad ebatõhusamaid investeerimisstrateegiaid võrreldes Eesti ja Leedu regioonidega. Mõnes piirkonnas tuvastatakse ka märke üleinvesteerimisest lairibaühendusse.