A contribution to the determinants of total factor productivity growth

Inaugural–Dissertation

zur Erlangung des Grades eines Doktors
der Wirtschafts– und Gesellschaftswissenschaften
durch die
Rechts– und Staatswissenschaftliche Fakultät
der Rheinischen Friedrich–Wilhelms–Universität Bonn

vorgelegt von

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Bonn 2008

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Tag der mündlichen Prüfung: 19. August 2008

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert.

to my parents and Suse

ACKNOWLEDGEMENTS

While I was writing this thesis, I received help from a number of people and institutions in various ways. At first place, I thank Professor Jürgen von Hagen for his inexhaustible support, excellent, and guidance throughout the last four years. I also owe special thanks to Professor Martin Hellwig for very valuable discussions and comments. Both professors had always time for me and I always left their room with some of their inspiration. I am grateful to Professor Jörg Breitung, Michał Paluch, Michael Evers, Stefan Niemann, and Michael Massmann for valuable comments and helpful discussions on the various chapters.

I want to thank the Bonn Graduate School of Economics and the European Communities' RTD 6th Framework Programme that funded the research project 'Dynamic Regions in a Knowledge Driven Global Economy' for financial support. I also want to thank Professor Jürgen von Hagen, Professor Georg Nöldeke, and Professor Urs Schweizer for managing the Bonn Graduate School of Economics and the Graduiertenkolleg. Part of this work was written at the University Pompeu Fabra, Barcelona. I express my gratitude for the hospitality I received there. During this stay I received valuable comments on my first chapter from Professor Gino Gancia and Professor Jaume Ventura, whose support is gratefully appreciated.

I am very thankful to Suse for her emotional support and unknown volumes of inspiration. I thank my parents and my sister for their endless love and unrestricted support and understanding in everything I do.

Michał Paluch, Lars Koch, Michael Zähringer, Steffen Altmann, Sotirios Georganas, Jürgen Gaul, Simon Junker, Matthias Wibral, Johannes Abeler, An Chen, David Schröder, Oliver Fries, and Xia Su were the best 'year 2003 graduate class' I could have possibly been part of. They made me enjoy this time!

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Introduction

I.1 Introduction

The successful identification of key policies that foster economic growth and development makes it possible to implement optimal growth strategies that could cut world poverty, affect income inequalities across countries, and improve the standards of living of individuals.[1] However, we implicitly need to solve a closely related puzzle first in order to be prepared to define the scope of such policies: Why do some countries grow and others stagnate?

The Science magazine considers this question as one of the 125 "most compelling puzzles and questions facing scientists today" (Science magazine (2005)). While the importance to identify the key determinants of economic growth and development is obvious, a unified theory that matches empirical facts is still missing. Instead, the emergence of endogenous growth theory since the early 90s induced a vast strand of literature covering numerous potential determinants of economic growth ranging from macroeconomic policies over trade and industrial policies to deep-seated institutional factors, and initial conditions. Clearly, policymakers have direct control over some of these factors, but only limited (long-term) or no control over others.

If we have a closer look at the empirical part of the literature, the overall picture still remains puzzling. In particular, Summers (2003) suggests three main ingredients for growth: (i) economic integration through trade and investment, (ii) maintenance of sustainable government finances and sound money, and (iii) an institutional environment in favor of contract enforcements and property rights. He concludes: "I would challenge anyone to identify a country that has done all three of these things and has not grown at a substantial rate" (Summers, 2003). Indeed, this policy mix

[1]Various studies confirm that conventional measures of standards of living, e.g. health, literacy, life expectancy, etc., are highly correlated with per capita income levels across countries as well as over time (compare, e.g., Barro and Sala-i-Martin (1995)). Moreover, Rodrik (2005) illustrates that disparities in income across countries account for the bulk of global disparities.

appears to be intuitively appealing. Yet, Rodrik (2005) illustrates that corresponding inferences for policy implications are not generally consistent with empirical facts. *Figure* 1 shows that Latin American countries experienced sustained growth during the 1960s and 1970s which represent periods of import substitution policies (high barriers to trade and capital flows) - e.g. El Salvador undertook tremendous reforms since 1989 in favor of macroeconomic stabilization, trade liberalization and private sector deregulations without achieving higher growth (see *Figure* 2). In contrast, *Figure* 3 illustrates that economic growth took off in India in the early 1980s while economic reforms did not take place before 1991. Instead, the initial growth take-off was preceded by substantial public investments in infrastructure in the late 1970s and early 1980s as well as a gradual shift towards a more "business-friendly" policy environment at that time.[2] *Table* 1 denote that China, Vietnam, India and Uganda have experienced tremendous growth during the 1990s in the presence of major barriers to trade and capital flows.[3] Moreover, the index of overall property rights from the Frasier Institute of Economic Freedom reports for China a index number of 6.8 in 1985 and 4.9 in 2000 which is below the one of Mali, Iran, Panama or Romania.

Consequently, it appears that we need to take some care in isolating growth-enhancing strategies and keep in mind to incorporate country-specific conditions accurately. Nevertheless, recent advances in development accounting are pointing the way for future research. Caselli (2005) provides a comprehensive survey and various robustness checks of contributions in development accounting. He concludes that fluctuations in factor accumulation (labor, physical and human capital) account only for 1/3 of the fluctuations of income across countries. Thus, the bulk of international income differences is due to variations in total factor productivity (TFP). It follows that a successful theory needs to explain why some countries experience high productivity growth while others lag behind.

Indeed, a closer look at some case studies supports the pivotal role of TFP-growth as an engine of overall growth in GDP per capita. *Figure* 1 clearly indicates that variations in the growth rate of GDP per capita in Latin America from 1960 until 2000 are primarily due to variations in TFP-growth. The periods of high sustained growth in the 1960s and 1970s comply with periods of high TFP-growth, while the large decrease in GDP-growth in the 1980s is accompanied by a sharp drop in productivity. Moreover, *Figure* 3 shows that growth in India is driven primarily by TFP-growth.

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[2]See Rodrik (2005) for a more detailed description of the growth take-off in India.

[3]In particular, China and Vietnam achieved sustained growth in the absence of trade liberalizations or enhancements of property rights since almost three decades.

In particular, *Figure* 5 and 6 reveal that before 1980, states with a lot of manufacturing activity performed generally poorly, while thereafter, growth is driven primarily by manufacturing intensive states. *Figure* 4 illustrates that TFP-growth is also the primary source of China's 'growth-takeoff'.

The theories of endogenous growth, initiated by Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992), are able to explain TFP differences due to differences in the rate of technological progress across countries. They disclose theoretical mechanisms that provide incentives for firms to invest in innovative activities. These induce new technologies or technology spill-overs. Thus, they explain endogenous technical change which determines the course of TFP-growth in the long-run. It follows that a theory of TFP needs to explain why some countries are more successful in developing or adopting new technologies than others.[4] Several causes have been considered to induce such differences: the quality of institutions (e.g. Acemoglu et al. (2002), Parente and Prescott (1999)), the openness to trade (e.g. Eaton and Kortum (2002)), or the degree of financial development (e.g. Aghion et al. (2005)).

In the following, we provide supplementary approaches that help explain the incentives for firms to invest in innovative activities by accounting for the interdependence between different micro- and macroeconomic factors. We consider three complementary models which suggest new mechanisms that contribute to the explanation of differences in TFP-growth across countries and over time. The first two reveal microeconomic mechanisms that allow for an impact of monetary policy and public infrastructure investments on firm-level technology choices, respectively. The third model demonstrates that part of the differences in TFP-growth across countries have to be attributed to differences in the distribution of capital and labor across firms. In all cases, we provide detailed empirical evidence that is consistent with the predictions of the corresponding models based on cross-country, industry, and firm-level panel data. All approaches provide guidance in which way public policymakers can influence the course of long-run productivity growth.

The first chapter analyzes the impact of infrastructure capital on different sources of economic growth. The conventional literature, which is based on the growth model of Barro (1990), predicts that infrastructure investments induce private capital accumulation. However, we do not find an empirical link between (telecommunication) infrastructure and the accumulation of physical or human capital in a dynamic panel of 36 relatively developed countries from 1970 until 2000. This negative finding is con-

[4]See Barro and Sala-i-Martin (1997), Howitt (2000), or Caselli and Coleman (2005) for theoretical contributions to international technology diffusion and technological catch-up.

firmed by disaggregated panel data as we detect that U.S. firms do not increase capital investments in periods of higher aggregate infrastructure investments. In contrast, we demonstrate a link between infrastructure capital and the rate of technological change in the country as well as the firm panel.[5] We employ a threefold strategy to address the problem of a potential endogeneity of the infrastructure variable.[6] First, we rely on internal instrumental variables as suggested by Blundell and Bond (1998). Second, we alternatively include demographic variables as external instruments which has been suggested by Canning (1999) and Calderon and Serven (2005). Third, the mix of macro- and microeconomic variables allows for an inspection of causality in the firm panel. Our empirical findings challenge the predictions of conventional models on infrastructure and growth. Therefore, we provide an alternative theoretical mechanism that justifies an impact of infrastructure capital on firm-level technology choices. In particular, we develop an extended R&D growth model, which emphasizes a cost-reducing feature of infrastructure capital, to demonstrate a potential link between the level of infrastructure capital and endogenous technological change. Finally, we show that the link between infrastructure and R&D can lead to multiple balanced growth pathes if we endogenize the provision of infrastructure capital. That is, countries or regions with a low initial infrastructure capital stock suffer from little R&D investments which in turn result in a low level of output. The latter implies a low demand for infrastructure services and hence little infrastructure investments. The long-run balanced growth rate is still strictly positive in this "low-growth scenario", but it is also strictly dominated by the growth rate in a "high growth scenario".

In the second chapter, we show that inflation reduces long-run productivity growth if financial markets are incomplete. This result is presented by means of an endogenous growth model whose key ingredients are (i) a nominal short-run portfolio choice for households, (ii) an agency problem which gives rise to financial market incompleteness, (iii) a firm-level technology choice between a return-dominated but secure and a more productive but risky project. In this framework, we show that it is optimal for firms to hold nominal corporate liquidity (i.e. cash and marketable securities) in order to partly insure against investments in risky projects. Accordingly, inflation involves a costs for nominal corporate insurance and hence induces an additional cost of the productive relative to the return-dominated investment project. Thus, inflation causes

[5] The rate of technological change is approximated by investments in R&D and the growth rate of TFP.

[6] Moreover, we include several corporate and aggregate control variables in the estimation specifications to reduce the potential for an omitted variable bias.

long-run real effects in the aggregate due to a link from the short-run interplay between nominal and financial frictions to a firm's qualitative investment portfolio. It follows that economies (time periods) that feature a higher level of inflation are predicted to exhibit lower TFP-growth in the long-run. We confirm the robustness of this aggregate empirical relationship by means of country panel data. Moreover, our theoretical approach generates several model-specific predictions which are confirmed by U.S. industry as well as firm-level panel data. Most importantly, we find that (i) firms insure systematically against risky R&D investments by means of corporate liquidity holdings and (ii) periods of higher inflation restrain firm-level R&D investments by reducing corporate liquidity holdings. Thus, the disaggregated U.S. data support the empirical relevance of our specific microeconomic mechanism.

The third chapter presents a growth model for an economy consisting of firms which are heterogeneous in technologies and input demands. This framework makes it possible to capture the effects of the distribution of input factors among firms on economic growth. We show that the growth rate in this economy depends not only on changes in the aggregate level of capital and labor, but also on changes in the allocation of these inputs across firms. As the latter effects are neglected in conventional growth models, they are misleadingly captured by the residual TFP measure. In contrast, we are able to quantify the influence of these components. Our empirical analysis, which is based on structural estimation from firm-level data, reveals that changes in allocation of capital and labor have pronounced effects on GDP-growth for most European countries. Further, we take cross-country differences in the distributional effects into account to improve conventional growth accounting exercises. In particular, we find that they explain additionally up to 17% of growth differences among 19 European countries. Consequently, allowing for heterogeneity in firm-level technologies and input demands increases the explanatory power of the inputs.

The next three chapters each present one idea as a self-contained unit.

Table 1: World Bank's 'Star Globalizers'

Country	Growth rate in the 1990s	Trade policies
China	7.1%	Average tariff rate 31.2%, national trade barriers, not a WTO member
Vietnam	5.1%	Tariffs range between $30-50\%$, national trade barriers and state trading, not a WTO member
India	3.3%	Tariffs average 50.5% (2. highest in the world)
Uganda	3.0%	Moderate reform

Source: Collier and Dollar (2001: 6)

Sources of Growth, Latin America, 1960-1999					
			Contribution of:		
	Output	Output per Worker	Physical Capital	Education	Factor Productivity
1960-70	5.72	2.88	0.83	0.31	1.74
1970-80	6.48	2.92	1.32	0.38	1.16
1980-90	1.47	-1.66	0.05	0.45	-2.12
1990-99	3.01	0.71	0.14	0.32	0.21

Source: Bosworth and Collins (2003)

Figure 1: Sources of growth in Latin America

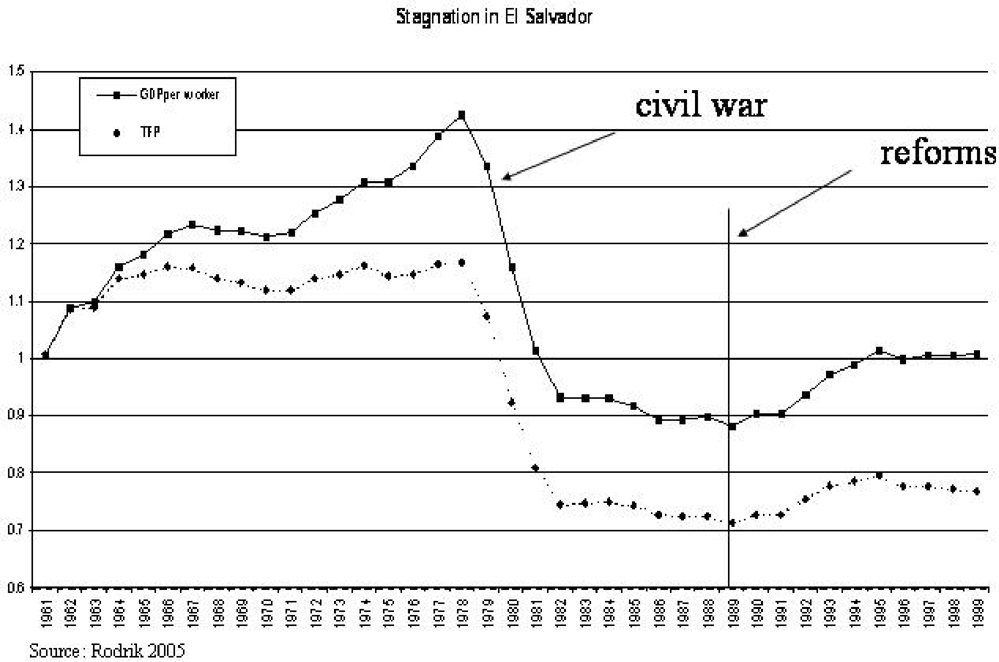


Figure 2: El Salvador - failure of institutional reforms

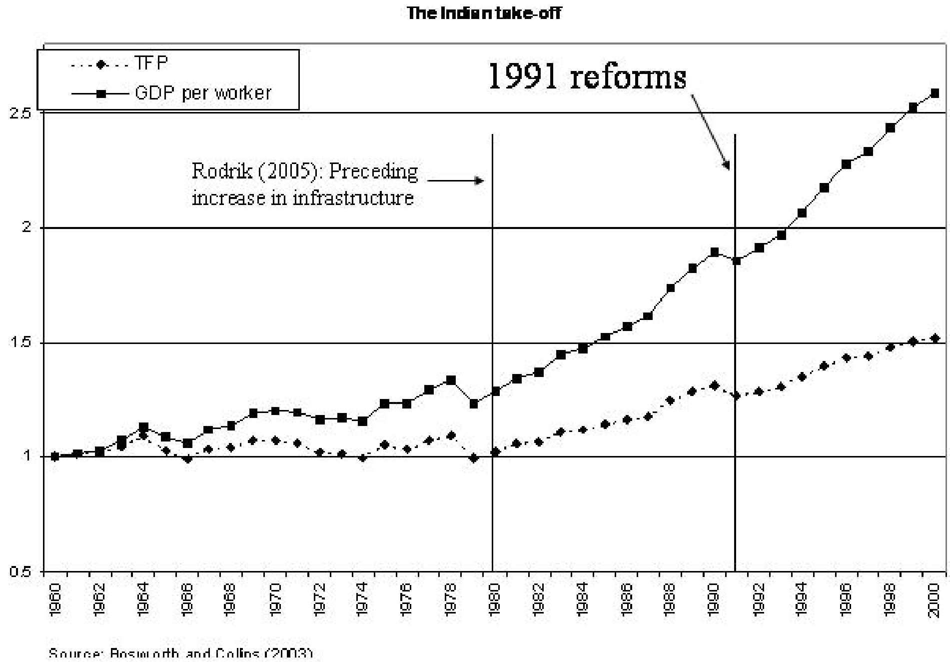


Figure 3: India's growth takeoff

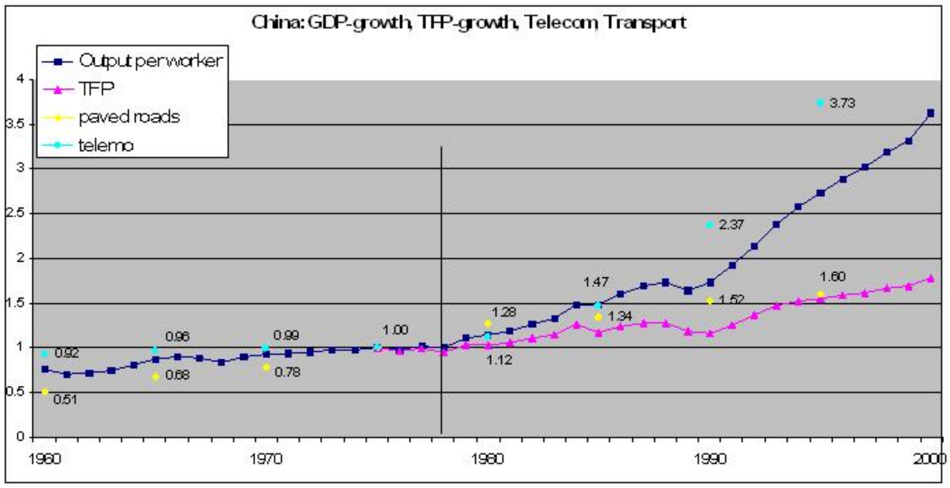
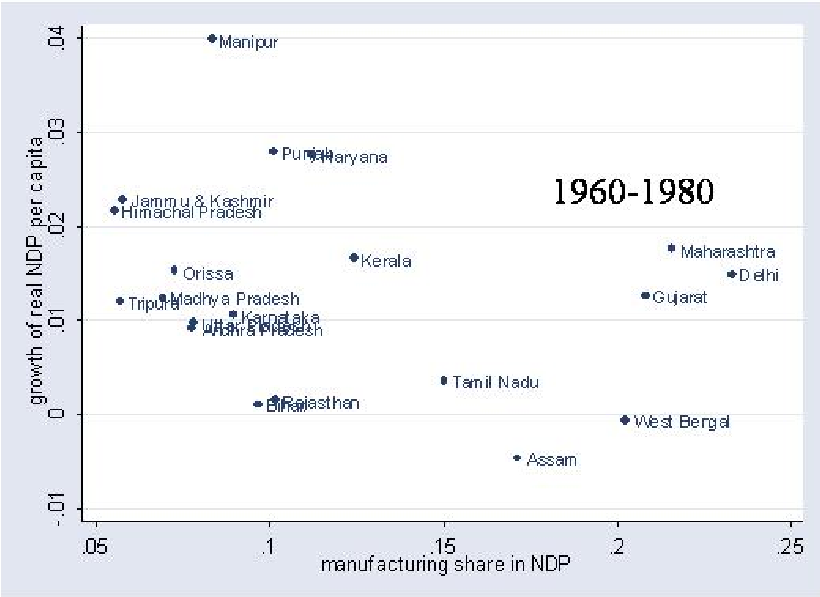
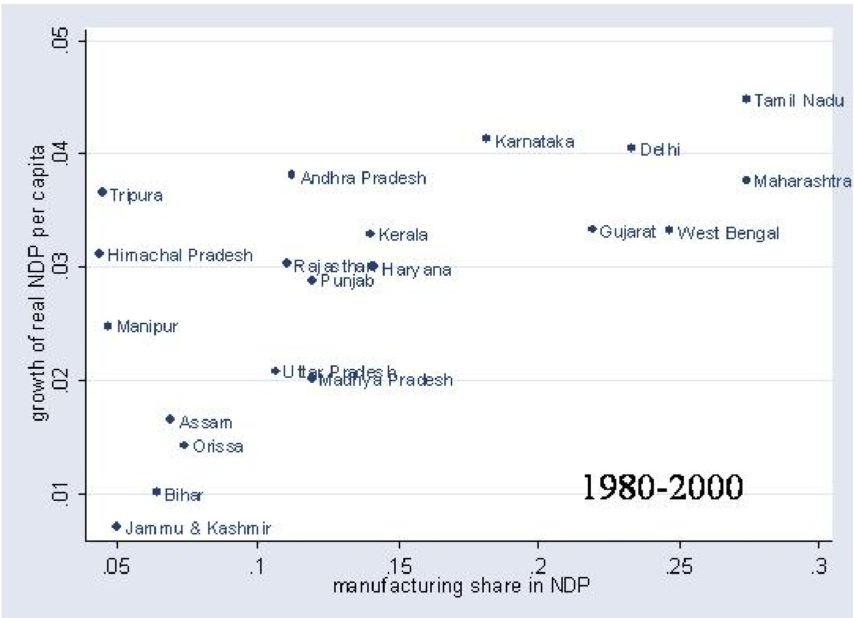


Figure 4: China's 'growth-takeoff': The change in infrastructure stocks and TFP-growth



Source: Rodrik (2005)

Figure 5: Growth and manufacturing across Indian states before 1980



Source: Rodrik (2005)

Figure 6: Growth and manufacturing across Indian states after 1980

Chapter 1

Calling for innovations - infrastructure and sources of growth

This chapter analyzes the impact of infrastructure capital on different sources of economic growth. Starting with the contribution of Barro (1990), the literature on infrastructure and growth mainly focuses on the relationship between private and public capital investments. In contrast, we demonstrate a link between (telecommunication) infrastructure capital and endogenous technological change in the context of an dynamic panel estimation applying aggregate country- as well as U.S. firm-level data. The main empirical finding is that the increase in telecommunication infrastructure during the last 30 years enhanced R&D investments but did not affect the accumulation of physical or human capital in our sample. Moreover, we provide an extended R&D growth model, which emphasizes a cost-reducing feature of infrastructure capital, to demonstrate a potential link between the level of infrastructure capital and endogenous technological change. Finally, we show that the link between infrastructure and R&D can lead to multiple balanced growth pathes if we endogenize the provision of infrastructure capital.

1.1 Introduction

In this chapter, we analyze the effect of (telecommunication) infrastructure capital on different sources of economic growth. That is, we investigate whether infrastructure investments influence the accumulation of input factors, such as private and human capital, or total factor productivity (TFP) and R&D.

Several recent empirical contributions report a positive causal relationship between infrastructure and GDP-growth for different regions and time periods.[1] The main empirical challenge in these studies is the identification of *cause and effects* between infrastructure and growth. Fernald (1999) shows that the rise in road services substantially increased the productivity (TFP) across industry in the U.S. from 1953 to 1973.[2] The author employs an implicit test for endogeneity by showing that productivity growth is above average in vehicle intensive industries. Roeller and Waverman (2001) formulate a structural model for the supply and demand of telecommunication infrastructure to separate cause and effects on aggregate production.[3] They find large positive effects of telecommunication investments on economic growth in a panel of 21 OECD countries from 1970-90. Belaid (2004) confirms the results for a panel of 37 developing countries from 1985-2000. Finally, Calderon and Serven (2005) apply an instrumental variables approach to estimate a positive causal effect of different infrastructure measures on GDP-growth in a panel of 121 countries from 1960-2000.

These studies highlight the importance of infrastructure investments to foster economic growth and development. However, little is known about the explicit role of infrastructure capital in the production process. Does it represent an additional input factor in the production function or does it influence the technology with which other inputs are combined? In other words, are infrastructure investments a complementary input factor to private and human capital accumulation or do they trigger technical change by affecting incentives for R&D? In the first case, infrastructure investments feature temporary growth effects in the presence of fixed input factors (e.g. labor)

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[1] Gramlich (1994) or Holtz-Eakin and Schwartz (1994) survey the earlier empirical literature on infrastructure and growth.

[2] He measures a rate of return of 100% before 1973 and a negative rate from 1973-89. To put it in the words of Fernald (1999): "the interstate highway system was very productive, but a second one would not be".

[3] The identification of cause and effects crucially hinges on the specification of demand and supply functions and the conformance of price elasticities across the OECD countries.

while in the second they improve the efficiency of all other input factors and hence long-run productivity growth. The corresponding policy implications differ substantially in both settings. Moreover, in the former scenario, infrastructure capital is expected to reflect a crucial growth determinant mainly in less developed countries with shortages of physical capital, while it appears to be less important in R&D driven more advanced economies. In this regard, note that the empirical evidence above refers to developed as well as developing countries.[4] Against this background, the present chapter attempts to specify the mechanism that links infrastructure capital to economic growth in relatively developed countries by accounting for different sources of economic growth.

Most part of the theoretical literature on infrastructure and growth suggests that the provision of infrastructure affects economic growth by interacting simultaneously with private capital investments. This literature is substantially influenced by the work of Barro (1990). This approach lumps together private and infrastructure capital with intellectual capital that is accumulated by technological progress. Thus, it is implicitly assumed that (broader) capital accumulation, which is studied by neoclassical theory, and technological knowledge are one and the same. In particular, Barro (1990) assumes a Cobb-Douglas production function that features constant returns to scale for the accumulation of private and infrastructure capital because part of this broader capital accumulation is supposed to reflect technological progress needed to counteract diminishing returns. It follows that infrastructure or private capital investments feature not only level but also growth effects in the long-run which are only limited due to a financing by distortional taxes. The key assumption underlying the Barro (1990) model is the link from infrastructure investments to private capital accumulation. This approach has been generalized in several ways. Turnovsky (1997) accounts for public capital which is subject to congestion, Kosempel (2004) for the

[4]Roeller and Waverman (2001) and Belaid (2004) quantify substantial elasticities of GDP with respect to telephones per 1000 workers for advance (0.45) and developing countries (0.5) for similar time periods using identical estimation techniques.

case of finitely lived households, Turnovsky (2000) for an elastic labor supply, and Ghosh and Mourmouras (2002) for an open-economy framework. An alternative approach is followed by Bougheas et al. (2000) who show that infrastructure investments increase an economy's degree of specialization.

The empirical part of our contribution is related the work of Fernald (1999), Bougheas et al. (2000) and Hulten et al. (2003) who analyze the impact of infrastructure on productivity and product specialization in the U.S. and India, respectively. In contrast to these studies, we focus on different sources of economic growth, use different econometric techniques, and apply panels of mostly developed countries as well as U.S. firms. We approximate the rate of technical change by investments in R&D or TFP-growth. We address the problem of endogeneity by (i) the use of internal as well as external instrumental variables for infrastructure capital, (ii) the inclusion of different institutional control variables, and (iii) the mix of macro- and microeconomic variables in the panel of U.S. firms. We detect that infrastructure investments enhance the rate of technical change in subsequent years in the country panel. Similarly, infrastructure capital is found to boost R&D expenses of U.S. firms. In contrast, we do not find a significant effect on investment rates in private or human capital. Our results refine the outcomes of earlier empirical studies outlined above and qualify the mechanisms and policy implications of existing theories.

Moreover, we present a simple theoretical model in order to explicitly demonstrate the link between the provision of infrastructure and technological progress. The theoretical distinction between the impact of infrastructure capital on private factor accumulation and technological progress is important at least for two reasons: (i) it relates long-run productivity/GDP-growth to the stock of infrastructure capital instead of its growth rate (as in the former literature). (ii) it comprises different policy implications than the existing models which are based on neoclassical inference. That is, we identify policies that influence the efficiency of the R&D sector (higher education, industrial and innovation policy) to foster growth and innovations, instead of neoclassical policies that influence the saving behavior of households. Finally, we show that the link between infrastructure and R&D can lead to multiple balanced growth pathes if we endogenize the provision of infrastructure capital.

Section 2 briefly illustrates some empirical stylized facts in favor of a positive relationship between the provision of infrastructure and subsequent increases in TFP-growth. Section 3 defines the empirical strategy to distinguish between cause and effects and reports the empirical findings. In section 4, we suggests a specific mechanism that illustrates the impact of infrastructure capital on endogenous technical change (R&D). Section 5 illustrates the conditions that ensure the existence of multiple strictly positive balanced growth equilibria for a given endogenous provision of infrastructure capital. The final section concludes.

1.2 Infrastructure and TFP - some illustrations

In this section, we provide some stylized facts on the role of infrastructure investments in the two major success stories in terms of economic growth and productivity in the last 30 years: China and India.[5]

First, we refer to Rodrik (2005) to exemplify the importance of infrastructure investments for the growth take-off in India. The author reveals that the tremendous increase in GDP/TFP-growth in India can not be explained by conventional theories. He shows that the growth-takeoff was not accompanied by institutional reforms, trade liberalizations or improvements of property rights. Instead, as outlined in *Figure* 3, Rodrik underlines that it was preceded by substantial investments in infrastructure. In addition, most of the growth-acceleration took place in the manufacturing sector at that time. That is, the author suggests that the increase in the provision of infrastructure services in India before 1980 augmented the productivity in the manufacturing sector in subsequent years. The empirical work of Hulten et al. (2003) confirms this hypothesis for India.

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[5]China is included in our sample of 36 developed and transition countries which we use in the following section. It is the poorest countries in our sample.

Figure 4, which is based on our own calculations, plots the GDP- and TFP-growth rates together with major infrastructure indices for China.[6] The graph demonstrates that the growth-takeoff around 1980 was preceded by major infrastructure investments in China. In particular, *Figure* 4 illustrates that the number of telephone mainlines per 1000 workers was relatively constant in China before 1975 and improved considerably thereafter. These case studies suggest a link between the provision of infrastructure and subsequent productivity improvements in the two largest developing regions. Our empirical analysis in the following section will approve this conjecture for a panel of developed OECD and some transition countries.[7]

1.3 Empirical Evidence

In this section, we provide empirical evidence for a positive relationship between investments in telecommunication infrastructure and subsequent R&D intensities at the aggregate and firm-level employing dynamic panel estimations. In addition, we find no evidence for an effect on factor accumulation or human capital.

Data

The OECD provides data for "Main Science and Technology Indicators" for 36 countries from 1980 until 2004.[8] We employ the "Gross Domestic Expenditure on R&D as a percentage of GDP" to approximate the R&D intensities per country.[9] To ap-

[6]The construction of TFP follows Caselli (2005) and is outlined in Appendix B. The infrastructure variables are the number of telephone lines per 1000 workers (telecom) and the share of paved roads in total roads (paved) obtained from the World Development Indicators of the World Bank.

[7]The poorest country in the sample is China followed by Turkey.

[8]The sample contains the following countries: Argentina, Australia, Austria, Belgium, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia, Singapore, Slovenia, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

[9]The highest fraction of R&D intensities was achieved in Israel in 2002 (5.08%) and the lowest in

proximate a country's infrastructure capital stock, we use the number of telephone mainlines per 1000 workers (*telewo*). The series stems from the World Development Indicator database. This database provides several different infrastructure measures. Yet, these measures are highly correlated: the correlation coefficient between a country's telephone mainlines per 1000 workers and power generating capacity or the share of paved roads amount to .81 and .61, respectively. Therefore, we exclusively focus on the role of telephone mainlines to avoid problems of collinearity.

Moreover, we consider several variables to control for institutional differences over time and across countries. In particular, we include real GDP per capita in purchasing power parity ($rgdp$), government (gov) and private investment shares (inv) relative to real GDP, trade openness ($open$), the amount of private credits issued by deposit money banks relative to the level of GDP ($credit$), and overall property rights (ppr).[10] The first four variables are obtained from the Penn World Tables. The amount of private credits serves as a proxy for the level of financial development and comes from Levine et al. (2000), while the property right index stems from the Fraser Institute of Economic Freedom database. Moreover, we use the growth rate of real GDP per capita in purchasing power parity ($gdp-growth$) from the Penn World Tables and the average years of schooling in the total population ($tyr25$) from Barro and Lee (1996) as additional dependent and control variables. We consider 5-year averages to smooth out business cycle effects.[11] Overall, our unbalanced panel covers 6 time observations for 36 countries. *Figure* 1.1 and 1.2 show the scatter-plots for telephone mainlines per 1000 workers and the share of private capital investments and R&D investments, respectively.

At the firm-level, we employ U.S. data from the Compustat database. The data relate to the balance sheets of US nonfinancial firms and cover the time period

Greece in 1982 (0.17%). In the U.S. the fraction was roughly around 2.7% during the 1990s, which was apart from Sweden, Israel and Japan the highest in the beginning of the 1990s.

[10]We measure the number of telephone mainlines and real GDP in logs. All other variables enter in levels since they represent shares relative to GDP.

[11]That is, we use the following non-overlapping time averages: 1075-1979, ..., 2000-2004.

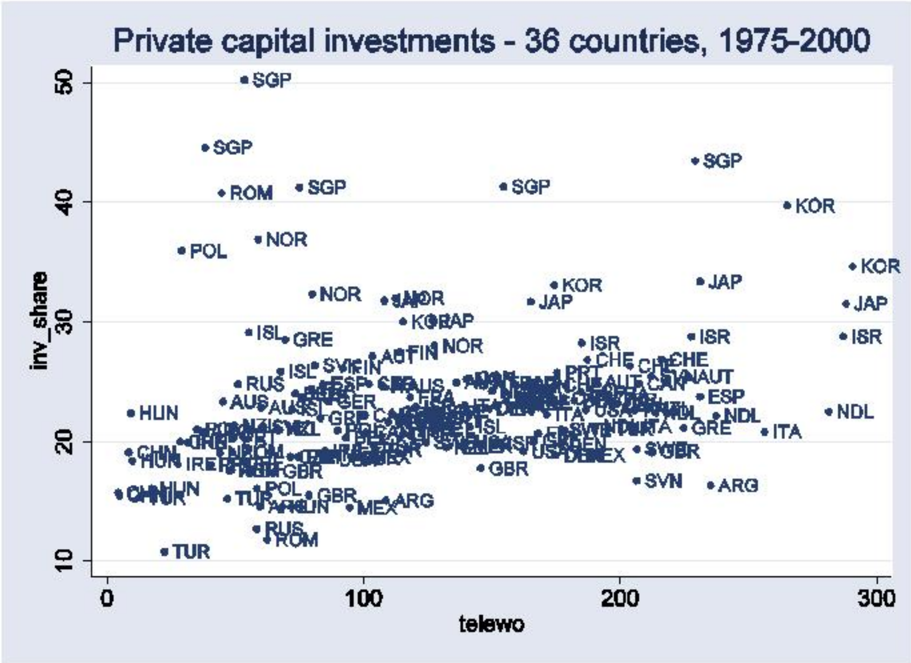

Figure 1.1: Scatter-Plot: Private investments share and telephone mainlines

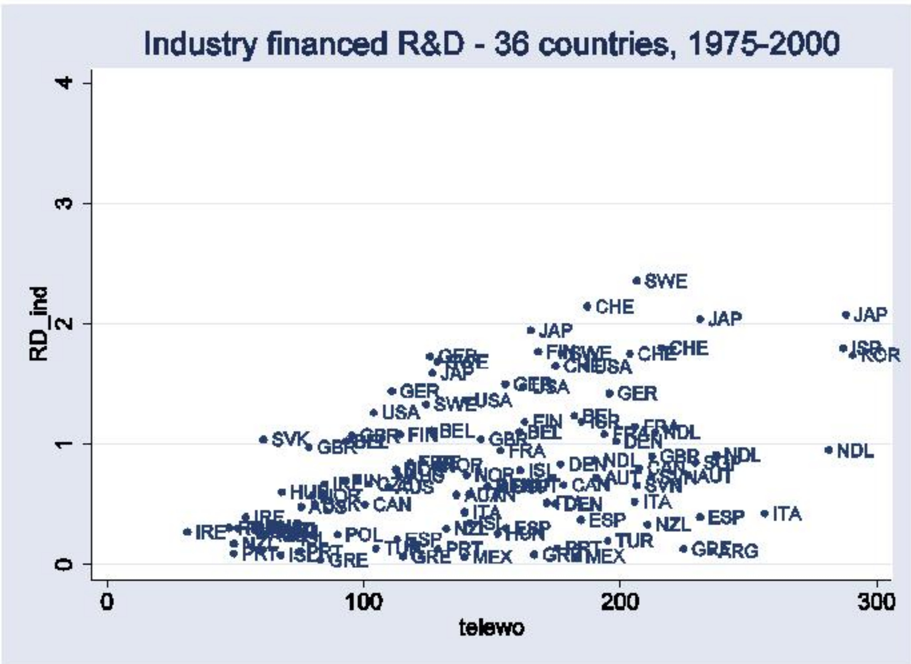

Figure 1.2: Scatter-Plot: Share of industry-financed R&D investments and telephone mainlines

1970-2000. In particular, we include the following firm-level data: R&D expenses, corporate capital investments (*inv*), the amount of total assets (*assets*), total sales (*sales*), and operating income before taxes (*oincome*). All variables are measured in millions of dollars. We employ once more 5-year averages since we focus on a long-run growth frequency. Overall, we have an unbalanced panel consisting of over 3000 firms and six time observations. In addition, we investigate the effect of the macroeconomic infrastructure variable on firm-level investment decisions.[12] In order to ensure that this aggregate variable does not capture general trends in GDP, we also incorporate the U.S. real GDP per capita and the private investment share.

Estimation Procedure

We use different dynamic panel techniques to examine the coherence between our infrastructure variable and different sources of economic growth. Accordingly, we control for country or firm fixed effects to account for unobservable, time-invariant factors that influence infrastructure as well as R&D investments (e.g. institutions, geography). In addition, we incorporate time fixed effects in the country panel which control for common aggregated shocks over time.

Apart from the inclusion of institutional control variables as well as country and time fixed effects, our strategy to address the problem of a potential endogeneity of infrastructure is threefold. First, we rely on internal instrumental variables as suggested by Blundell and Bond (1998). These are appropriate in the absence of autocorrelation which is shown to hold in all conclusive specifications. Second, we alternatively include a set of external instruments provided by demographic variables. In particular, we account for the rate of urbanization and the population density. The use of demographic variables as external instruments is motivated by Canning (1999) and Calderon and Serven (2005), who reveal that much of the observed variations

[12]We stress that our results based on the GMM difference estimator do not suffer from an aggregation bias, as outlined by Moulton (1990), since we employ serial correlation robust standard errors to avoid within-group correlation.

in infrastructure stocks are explained by these variables. Third, the mix of macro- and microeconomic variables allows for an inspection of causality since the marginal investment of a single firm has no contemporaneous feedback effect on aggregate macroeconomic infrastructure investments.

We employ the Arellano and Bond (1991) GMM difference ($GMM - dif$) as well as the Blundell and Bond (1998) GMM system estimator ($GMM - sys$) because of the significance of the lagged dependent variables, e.g. lagged R&D share. These estimation procedures are based on the general method of moments (GMM) and are constructed to yield consistent estimates in dynamic panels. In particular, Arellano and Bond (1991) estimate a dynamic panel data model in first differences and apply appropriate lagged levels as instruments for the first differences of the endogenous variables. These are valid instruments if (i) the time-varying disturbance $\epsilon_{i,t}$ is not serially correlated, and (ii) the explanatory variables $X_{i,t}$ are weakly exogenous. In other words, considering the following dynamic panel data model in first differences:

$$y_{i,t} - y_{i,t-1} = \alpha(y_{i,t-1} - y_{i,t-2}) + \beta(X_{i,t} - X_{i,t-1}) + (\epsilon_{i,t} - \epsilon_{i,t-1}), \quad i = 1, 2, ..., N, t = 3, 4, ..., T,$$

the basic assumptions of Arellano and Bond (1991) are:

$$E[y_{i,t-s}(\epsilon_{i,t} - \epsilon_{i,t-1})] = 0, \qquad \text{for} \qquad s \geq 2; t = 3, ...T$$
$$E[X_{i,t-s}(\epsilon_{i,t} - \epsilon_{i,t-1})] = 0, \qquad \text{for} \qquad s \geq 2; t = 3, ...T,$$

where $y_{i,t}$ is the dependent variable, $X_{i,t}$ a vector of endogenous and exogenous explanatory variables, N the number of cross-sections, T the number of time-periods, $\epsilon_{i,t}$ the error term and α and β parameters to be estimated. In addition, Blundell and Bond (1998) apply supplementary moment restrictions on the original model in levels, whereby lagged differences are used as additional instruments for the endogenous and predetermined variables in levels. Given that $E[y_{i,t}, \mu_i]$ is mean stationary, the Blundell and Bond (1998) estimator incorporates the additional moment restrictions:

$$E[(y_{i,t-1} - y_{i,t-2})(\eta_i + \epsilon_{i,t})] = 0,$$
$$E[(X_{i,t-1} - X_{i,t-2})(\eta_i + \epsilon_{i,t})] = 0.$$

Hence, they require the additional assumption of no correlation between the differences of these variables and the country-specific effect. The authors show that this procedure is more efficient if explanatory variables are persistent.[13] Furthermore, we consider all variables as potentially endogenous apart from the government share and the overall property rights.

Results - R&D

Table 1.1 reports the effects of telephone mainlines and the institutional controls on the R&D share. The first column reports a negative contemporaneous correlation between telephone mainlines and the share of R&D after controlling for the institutional and financial indicators.[14] Accordingly, the negative correlation does not simply capture an economy's degree of financial or institutional development. In the next column, we apply the least square dummy variable estimator to additionally control for country fixed effects. The coefficient of infrastructure is still significant on a 1% level. Yet, the corresponding estimates are biased in the presence of a lagged dependent variable. Therefore, we present the results of the GMM difference estimator in column three. Accordingly, we find that an increase in telephone mainlines by 1% enhances aggregate R&D investments, on average, by .29% in the subsequent five years. The result is significant on a 1% significance level. In contrast, only the level of real GDP and a country's degree of openness influenced aggregate R&D investments significantly. For example, the number of telephone mainlines per 1000 workers increased in the U.S. from 1975 until 1980 by roughly 2%. According to our estimation result, this rise triggered an increase in the R&D share by .58% in the subsequent five years, which amounts to 21% of the overall increase in the R&D share in that period.

[13] We apply heteroscedasticity-robust standard errors and cluster errors at the country or firm level to obtain standard errors that are also robust to within group correlation.

[14] We include the contemporaneous values as well as the first lags of the control variables in the OLS and the least square dummy variable estimation. We do not report the results for the first lags in the corresponding tables.

Table 1.1: Effect of telephone mainlines on share of R&D investments

	R&D share							
	OLS	LSDV	GMM-diff	GMM-sys[1)]				
l1telewo	.1870***	.4866***	.2915**	.1838*	.2842**	.4506***	.2406**	.3598***
	(2.73)	(3.61)	(2.01)	(1.79)	(2.43)	(3.06)	(2.11)	(2.59)
l1R&D	1.04***	1.08***	.9814***	.9828***	.9477***	.9875***	.9618***	.9929***
	(22.59)	(6.83)	(5.18)	(11.28)	(10.02)	(10.15)	(12.13)	(12.19)
rgdp	.0576	-2.73***	-1.79*		.0698	-.3202	.1341	-.1952
	(.14)	(-3.36)	(-1.91)		(.35)	(-1.22)	(.80)	(-.91)
gov	.0098	-.0014	-.0027	.1838	.0105	.0033	.0130*	.0075
	(1.18)	(-.17)	(-.40)	(1.31)	(1.39)	(.44)	(1.65)	(.95)
ppr	.1183***	.0207	-.0033	.0398	.0577	.1407**	.0493	.1273***
	(3.28)	(.46)	(-.10)	(1.45)	(1.19)	(2.45)	(1.12)	(2.59)
credit	.1609	.0208	.0658		-.2054	-.2877*	-.2163	-.2993**
	(.93)	(.20)	(.38)		(-1.38)	(-1.78)	(-1.59)	(-2.10)
open	.0004	.0132**	.0010*		-.0016	-.0004	-.0014	-.0009
	(.08)	(2.64)	(1.91)		(-1.37)	(-.30)	(-1.32)	(-.73)
inv	-.0157	.0203	.0077		.0113	.0140	.0110	.0109
	(-.88)	(1.04)	(.61)		(1.22)	(1.54)	(1.43)	(1.50)
Country/Obs.	108	34/108	33/77	36/114	34/111	34/111	34/111	34/111
country FE	no	yes	yes	yes	yes	yes	yes	yes
time FE	no	no	no	no	no	yes	no	yes
2. order serial correlation			.971	.855	.936	.805	.958	.734
Hansen-test			.953	.164	.994	.998	.998	.998

1) In column 7-8 we instrument *telewo* by external instruments (urban, pop. density). In columns 5-8 we employ only first two appropriate lags of endogenous variables to reduce instruments matrix. Always include constant term, and employ s.e. that are robust to heteroscedasticity and within group correlation. 5-year averages, 1975-2004. t-statistics in parenthesis. ***,**,* significant at 1%, 5%, and 10%.

Table 1.2: Effect of telephone mainlines on factor accumulation

	inv-share				inv-adj		tyr25-growth	tyr25
	OLS	LSDV	GMM-sys		GMM-sys		LSDV	GMM-sys
l1telewo	.6641	1.46	.8675	.4716	.9220	.5507	-.0132	-.0168
	(1.37)	(1.53)	(.52)	(1.01)	(1.04)	(.40)	(-.60)	(-.20)
lag dep. var.	.6532***	.3360***	.7184***	.7472***	.7039***	.7337***	-	.8910***
	(10.70)	(3.86)	(8.26)	(9.78)	(7.54)	(7.95)	-	(33.87)
rgdp	17.88***	24.23***	-1.10	-.5412	-.5363	-.3915	-.1997***	.1702
	(5.12)	(4.86)	(-.77)	(-.30)	(-.24)	(-.22)	(-4.43)	(1.19)
gov	-.0283	-.0014	-.0302	-.0155	.0629	.0643	.0001	-.0064
	(-.48)	(-1.36)	(-.89)	(-.45)	(1.34)	(1.23)	(.08)	(-1.06)
ppr	-.0404	-.3957	.3845	.2774	.3956	.3829	.0068	.0152
	(-.10)	(-1.00)	(.76)	(.48)	(.71)	(.72)	(.55)	(.30)
credit	.9118	4.14***	.2816	.2775	-.3940	-.1922	-.0005	-.0600
	(.64)	(3.35)	(.19)	(.19)	(-.34)	(-.17)	(-.02)	(-.27)
open	-.0081	-.0723	.0172**	.0145**	.0103	.0077	.0014	-.0014***
	(-.18)	(-1.46)	(2.38)	(2.36)	(1.62)	(.77)	(1.33)	(-2.70)
Country/Obs.	147	35/147	35/155	35/155	33/106	33/106	35/155	35/155
country FE	no	yes	yes	yes	yes	yes	yes	yes
time FE	no	no	no	yes	no	yes	no	no
2. order serial correlation			.924	.993	.936	.723		.357
Hansen-test			.999	.998	.972	.948		.988

in columns 3-6 and 8 we employ only the first two appropriate lags of the endogenous variables to reduce the number of instruments. 5-year averages 1975-2004 data. all regressions include a constant term, and employ heteroscedasticity robust s.e. in column 2-8 we include s.e. that are robust to within group correlation.

t-statistics in parenthesis. ***,**,* significant at 1%, 5%, and 10%.

In the following columns, we apply the GMM system estimator.[15] In all specifications, we find that an increase in the number of telephone mainlines promotes R&D investments in the subsequent years. The corresponding coefficients are significant on a 1% or 5% level, respectively. Finally, in the last two columns, we use our set of exogenous demographic indicators to instrument for a country's infrastructure capital stock in a given period. That is, we drop the internal instruments for the infrastructure variable and instead impose a country's rate of urbanization and its population density as exogenous instruments.[16] Column eight, our preferred estimation specification, suggests that a 1% increase in the number of telephone mainlines per 1000 workers augments the share of aggregate R&D relative to GDP by .24% in the subsequent five years. This effect even amounts to .35% if we additionally impose time fixed effects. Both coefficients are significant on a 1% level, respectively. Finally, the Hansen test and the test for second order autocorrelation confirm the validity of our instruments in all specifications which suggests that our models are well specified. Summing up, we find robust evidence in favor of a positive causal effect running from a country's stock of infrastructure to its aggregate R&D investments.

Results - factor accumulation

In *Table* 1.2, we examine the impact of infrastructure capital on the input factors of a human capital augmented production function, i.e. private and human capital. In the first four columns, we report the effect of improvements in the number of telephone mainlines per 1000 workers on aggregate private investments. Accordingly, we are not able to detect a positive impact of infrastructure capital on private capital accumulation which is significant at conventional levels. In contrast, we find that an

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[15]Thereby, we exclusively use the first two appropriate lags of the endogenous variables to avoid *overfitting* - a larger number of instruments relative to the number of cross sections (countries).

[16]All other endogenous variables are still instrumented by their suitable own lags (internal instruments).

increase in a country's degree of trade openness promote private capital investments. The specification tests do not reject that our dynamic panel data model is well specified. Hence, improvements in telecommunication infrastructure do not affect private capital investments if we correctly control for institutional measures or time fixed effects in our sample of mostly developed countries. In columns five to six of *Table* 1.2, we apply an alternative measure since R&D expenditures amount, by definition, for a fraction of the overall private investments. Therefore, we construct an adjusted measure of private capital investments, net of R&D expenditures.[17] Yet, we do not detect stimulating effects of infrastructure investments on the adjusted variable. Finally, the last two columns of *Table* 1.2 show that infrastructure investments have no influence on the growth rate or the level of education in our sample.

Results - productivity growth

In the following, we investigate if the relationship between infrastructure and R&D indeed causes productivity growth. Therefore, we estimate the effect of the lagged values of telephone mainlines on the growth rate of real GDP per capita in purchasing power parities. In line with the empirical growth literature, we include the lagged (initial) level of GDP as a lagged dependent variable in the growth regression.[18] Accordingly, we apply a dynamic panel data model. Moreover, we account for the human capital measure as a supplementary control variable. It follows that the infrastructure coefficient in the growth regression measures the impact on GDP-growth net of private or human capital investments. Therefore, variations in the growth rate of GDP, after controlling for movements in factor inputs, represent by definition variations in TFP-growth. *Table* 1.3 lists the results for the growth regressions. The first two columns report a positive correlation between the number of telephone mainlines and

[17]That is, we subtract the share of R&D investments from the share of overall investments to obtain the adjusted values.

[18]The corresponding coefficient is negative and significant on a 1% level in all estimation specifications. Compare e.g. Calderon and Serven (2005) or Barro (1990).

productivity growth. Column three to five display the results of the GMM difference and system estimation. We detect a significant positive effect of telephone mainlines on productivity growth, whereby the exogeneity of infrastructure can not be rejected. Moreover, we find evidence that economic growth is positively related to the degree of trade openness, the private investment share and the index of overall property rights. In addition, we employ our exogenous demographic instruments for infrastructure in column six of *Table* 1.3. Accordingly, an increase in the infrastructure capital stock significantly enhances economic growth, net of amendments in factor inputs.

In the last three columns of *Table* 1.3, we include the aggregate share of R&D instead of the infrastructure variable. Column seven reveals that an increase in the aggregate R&D share augments economic growth. The corresponding coefficient is significant on a 1% level. In column eight, we incorporate lagged levels and differences of the number of telephone mainlines as an exogenous instrument for the aggregate R&D share. That is, we test if the growth-effect of telephone mainlines is indeed transmitted via R&D investments. In other words, if Y represents GDP, $R\&D$ the aggregate share of R&D, I the infrastructure measure, X the control variables, ϵ the error term and $\alpha_{0,1,2}$, $\beta_{0,1,2}$ parameters, we estimate the following equation by the GMM system estimator:

$$\Delta Y_{i,t} = \beta_0 + \beta_1 Y_{i,t-1} + \beta_2 (R\&D)_{i,t} + X'_{i,t}\beta_3 + \eta_i + \epsilon_{i,t} \quad (1.1)$$

whereby we treat $R\&D$ as endogenous and model it respectively as:

$$(R\&D)_{i,t} = \alpha_0 + \alpha_1 I_{i,t} + X'_{i,t}\alpha_2 + \eta_i + \epsilon_{i,t} \quad (1.2)$$

In accordance with our previous results, column seven reveals that R&D, which is instrumented by lagged levels and differences of the number of telephone mainlines, promotes productivity growth. The corresponding coefficient is significant on a 1% level. Finally, in the last column of *Table* 1.3, we use the exogenous infrastructure instruments - the rate of urbanization and the population density - as instruments for the R&D share. Again, the results suggest that the effect of infrastructure is transmitted via adjustments in aggregate R&D. It follows that a substantial part of

Table 1.3: Effect of telephone mainlines on productivity growth

	GDP-growth								
	OLS	LSDV	GMM-diff	GMM-sys1)			GMM-sys2)		
l1telewo	.8749**	.6940	1.56*	2.65***	1.68***	1.89**			
	(1.98)	(1.39)	(1.89)	(4.50)	(4.83)	(2.42)			
l1rgdp	-3.36***	-6.52***	-6.84***	-4.54***	-4.66***	-3.18***	-4.12***	-4.13***	-3.63***
	(-3.78)	(-4.51)	(-2.71)	(-2.77)	(-6.20)	(-3.62)	(-3.40)	(-4.59)	(-3.33)
gov	-.0065	.0078	-.0350	.1838	-.0213	-.0245	-.0822***	-.0831***	-.0608*
	(-.15)	(.20)	(-.73)	(-1.36)	(-.71)	(-.72)	(-2.61)	(-2.78)	(-1.95)
ppr	.2740	-.0516	.0526	.6186*	.4907**	.3338	.2251	.0162	.2567
	(1.16)	(-.16)	(1.82)	(1.45)	(1.99)	(1.32)	(.70)	(.07)	(.84)
credit	.1663	-1.42	.4152		.5019		.2388	1.35	1.02
	(.13)	(-1.19)	(.29)		(.19)		(-1.59)	(.93)	(1.01)
open	.0118	.1090***	.0437*		.0103		.0200***	.0197***	.0187***
	(.40)	(4.55)	(1.67)		(1.18)		(2.61)	(2.75)	(2.58)
inv	.2490***	.2046***	.0725		.1257*	.1614***			
	(3.43)	(2.62)	(.62)		(1.93)	(4.02)			
tyr25	.1975	-.5983	.4118		.2168				
	(.56)	(-1.12)	(.75)		(1.05)				
R&D							1.16***	1.26***	.7419*
							(2.87)	(3.63)	(1.84)
Country/Obs.	147	35/147	35/118	36/158	35/153	36/158	35/142	35/142	35/142
country FE	no	yes	yes	yes	yes	yes	yes	yes	yes
time FE	no	no	no	no	no	yes	yes	yes	yes
2. order serial correlation			.227	.367	.250	.242	.085	.103	.214
Hansen-test			.702	.050	.999	.841	.932	.916	.984

1) see *Table* 1.1. 2) in column 8 and 9 we use first lag of *telewo* and demographic variables as exogenous instruments for R&D share, respectively. 5-year averages, 1975-2004. t-statistics in parenthesis. ***,**,* significant at 1%, 5%, and 10%.

the impact of telephone mainlines on TFP-growth can be explained by its effect on private R&D investments.

Results - firm-level R&D investments

In *Table* 1.4, we report the effect of telephones mainlines on firm-level R&D investments in the U.S. The application of disaggregated data has the advantage that a corresponding correlation between firm-level decisions and macroeconomic variables can be interpreted as a causal effect running from the latter to the former. The first column displays that an increase in telephone mainlines per 1000 workers augments corporate investments in R&D after controlling for changes in corporate sales, assets, and operating income as well as aggregate real GDP, and aggregate private investments. In the second column, we additionally control for firm-level fixed effects. The results reveal a positive impact of telephone mainlines on firm-level R&D expenses, however, the coefficient is biased due to the presence of the lagged dependent variable. The third column reports the estimates for the GMM difference procedure.[19] Accordingly, an increase of 10 new telephone mainlines per 1000 workers induces an increase in corporate R&D investments, on average, by 3.37 MIO$ in the same period. The corresponding coefficient is significant on a 1% level. In the last two columns of *Table* 1.4, we employ firm-level investments in capital as the dependent variable. We find that telecommunication infrastructure investments do not affect the overall capital investments per firm. The corresponding coefficient is even negative, but not significant at conventional levels. In contrast, we detect that firms increase their capital investments if their assets and their operating income increases or if the aggregate level of real GDP increases. Overall, the firm-level results support the hypothesis that infrastructure investments improve the incentives of firms to invest in R&D, but not to invest in general capital.

Summing up, the empirical findings suggest that the relationship between infras-

[19] We consider the firm-level variables as endogenous and the macroeconomic variables as exogenous.

Table 1.4: Effect of *telewo* on firm-level R&D investments

	R&D investments			Capital investments	
	OLS	LSDV	GMM-diff	LSDV	GMM-diff
telewo	.6599*	.9840***	.3374***	-1.21	-2.44
	(1.78)	(2.67)	(2.60)	(-1.27)	(-1.44)
lag dep. var.	1.23***	.5415***	.5453***	.1624***	.1183***
	(16.51)	(3.86)	(2.89)	(4.35)	(4.09)
assets	-.0023	-.0074***	.0082**	.2164***	.2915***
	(-1.63)	(-3.90)	(2.09)	(5.01)	(3.11)
sales	.0048	.0374***	.0308**	-.0703	-.1488
	(1.52)	(3.29)	(1.89)	(-.68)	(-1.33)
oper. income	.0128	.0261	-.1179**	1.53***	1.84**
	(.61)	(.72)	(-2.26)	(3.13)	(2.49)
rgdp	-.0085*	-.0122***	-.0036**	.0231***	.0404***
	(1.80)	(-2.78)	(-2.47)	(2.73)	(2.65)
aggr. inv	-3.91	-.0116	2.54***		
	(-1.24)	(-2.45)	(3.79)		
Firms/Obs.	6041	3017/6041	2743/5611	2738/10989	2738/5603
country FE	no	yes	yes	yes	yes
time FE	no	no	no	no	no
2. order serial correlation			.228		.345
Hansen-test			.224		.224

5-year averages 1970-1999 data. all regressions include a constant term, and employ heteroscedasticity robust s.e. in column 2-4 we include s.e. that are robust to within group correlation. t-statistics in parenthesis.

***,**,* significant at 1%, 5%, and 10%.

tructure and growth is not linked to factor accumulation in our sample. This finding contradicts the predictions of the theoretical literature on infrastructure and growth which typically links growth-promoting effects of infrastructure investments to a stimulation of private capital investments, compare e.g. Barro (1990). Our results reject this complementarity between public (infrastructure) and private capital investments. Instead, we demonstrate that the provision of telecommunication infrastructure boosts productivity growth and investments in (the adoption of) new technologies (R&D).

1.4 The basic (partial) model

In the this section, we provide a growth model of endogenous technological change à la Romer (1990) that is extended to account for a cost-reducing feature of infrastructure capital for investments in innovative intermediate goods. This model generates a link from infrastructure capital to economic growth via endogenous technical change (R&D). Alternatively, this link can be established if one allows the stock of (telecommunication) infrastructure to directly affect the efficiency of research and development. In this case, the infrastructure stock would enter the law of motion for the stock of knowledge in (1.9). Alternatively, we demonstrate a mechanism that accounts for a positive externality of infrastructure capital on the net present value of the expected return of investment in innovative activities in equilibrium.[20]

Physical infrastructure deviates from other types of capital in two important ways: it is (partly) non-excludable and (partly) non-rival. The former raises the question of an appropriate financing since a partly excludability allows for a private provision. The latter has important implications for economic growth and development. That is, an increase in the infrastructure capital stock exerts an externality on all private producers if infrastructure capital is non-rival and influences private production. In this regard, the provision of infrastructure capital can potentially create long-run growth

[20] Our approach differs from the previous literature, which is based on Barro (1990), in that we account for a general equilibrium effect of the stock of infrastructure capital on the incentives to invest in R&D instead of private capital accumulation.

comparable to the functioning of non-rival knowledge in the endogenous growth theory.

Holtz-Eakin and Schwartz (1994) find robust empirical evidence for a negative relationship between the costs of the establishment of a new business and the provision of infrastructure capital in the economy. Moreover, Bougheas et al. (2000) detect a positive relationship between infrastructure capital and the degree of specialization in the intermediate sector for the U.S. economy. In the following, we take this empirical relationship for granted. In particular, we suppose that the use of a large variety of specialized intermediate goods in the production of final output creates proportional business costs (ϕ) - e.g. transportation, coordination, and search costs.[21] These costs entail an additional markup on the (monopolistic) prices requested from intermediate goods firms and are negatively related to the provision of infrastructure capital in the economy.[22]

We suppose that ϕ is a negative, continuous, monotonic function of the infrastructure capital stock with the following properties: $\phi(G)$, $\phi' < 0$, $\phi'' > 0$, $\lim_{G\to\infty} \to 1$, $\lim_{G\to 0} \to \infty$. Thus, ϕ is convex, approaches a lower bound if G approaches infinity and approaches infinity if G approaches 0. The lower bound represents the constraint that the price premium can not become negative. Moreover, in the absence of infrastructure capital intermediate specialization is not feasible as costs approach infinity.

We assume, in accordance with Romer (1990), that investments in R&D lead to new varieties of intermediate products. Thus, a successful R&D project results in the

[21]For example, ϕ captures fixed entry costs which are necessary to set up a new business. In addition it appears reasonable to assume that such entry costs are decreasing in the provision of infrastructure capital - e.g. the appearance of high-speed telecommunication networks potentiates the firm's ability to sell/transmit specialized goods via internet without the need to establish a widespread distribution system (Fernald and Ramnath, 2004). There are various additional plausible empirical anecdotes in favor of this assumption, e.g. the construction of the interstate highway system in the U.S. (Fernald, 1999), the disposability of electricity in the beginning of the last century (Jovanovic and Rousseau, 2005).

[22]In this regard, its functioning is similar to the one of exogenous iceberg costs in trade models.

entry of a new intermediate producer in a market that is characterized by monopolistic competition. Therefore, $\phi(G)$ is taken as given by potential new market entrants that base their entry decision on the net present value of the return of a potential R&D investment. This value is shown to depend on $\phi(G)$.[23] Thus, ϕ acts like a costly exogenous distortion of the interactions between intermediate and final producers.

The model consists of a competitive final output sector, a intermediate goods sector which is characterized by monopolistic competition, an infrastructure capital goods sector, and a law of motion for the stock of technologies.

Final output sector (Y)

Competitive firms employ manufacturing labor (L_y), a (symmetric) combination of all varieties of specialized intermediate goods (x_j) and an aggregate of all varieties of infrastructure services (G) to produce a final output good (Y). Each specialized intermediate good corresponds to a new technology, whereas A_t denotes the stock of existing technologies. Hence final output is manufactured according to the production function $Y = L_{y,t}^{\chi} G_t^{\beta} \int_0^{A_t} x_{j,t}^{\alpha} dj$, $\alpha, \beta, \chi > 0$.

There are several assumptions underlying the specific functional form of the production function that are worth discussing. As in the basic model of Romer (1990) growth results from an increasing specialization of the intermediate goods sector, whereas each new innovation (A_t) involves a new intermediate good. The specific form of the production function supposes that the elasticity of substitution between different intermediate goods or between intermediates and infrastructure capital is equal to one (Cobb-Douglas).[24]

[23]Our qualitative results would not change if ϕ could be (partly) internalized by intermediate producers as long as infrastructure capital is (partly) non-rival. The reason is that intermediate producers do not internalize the externality of their own demand for infrastructure capital on the costs of entry of other potential producers. The provision of infrastructure in a decentralized equilibrium would be inefficient.

[24]Alternatively, we could have employed a constant elasticity of substitution (CES) production function as in Young (1993). This does not change the functioning of the model. In this more

For convenience, we normalize the price of the final output good to one ($p_y = 1$). The final producers buy the intermediate products, pay a wage (w_y) for manufacturing labor, and a price (p_G) for the usage of infrastructure services in the production process. Hence, infrastructure capital is indeed a productive input in the final output sector which allows for the analysis of a private provision of infrastructure capital (see section 1.5). Though, we do not impose the special case of constant returns to scale in private and infrastructure capital ($\beta + \alpha < 1$). As a consequence, including G in the production function exclusively has level but not growth effects in the long-run.[25] In other words, we separate the infrastructure service in the production of final output from its impact on potential business costs of new intermediate producers. The representative firm in the competitive final output sector takes prices as given and chooses its inputs to maximize instantaneous profits in t ($\pi_{y,t}$):

$$\pi_{y,t} = L_{y,t}^{\chi} G_t^{\beta} \int_0^{A_t} x_{j,t}^{\alpha} dj - \int_0^{A_t} [1 + \phi(G_t)] p_{I,j,t} x_{j,t} dj - w_{y,t} L_{y,t} - p_{G,t} G_t \qquad (1.3)$$

where ($p_{I,j}$) is the price of of an intermediate product j.

Note that infrastructure capital is partly excludable. On the one hand, the provider can exclude final output firms from infrastructure services so that they can be charged for their direct use. On the other hand, the provider can not control that the existence of an infrastructure network causes a positive externality on the costs of the provision of new intermediate goods. The final producer determines its use of $x_{j,t}$, $L_{y,t}$ and G_t to maximize its profit resulting in the first-order conditions:[26]

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general case, the equilibrium growth rate simply depends on an additional parameter measuring the degree of substitutability in the economy.

[25]Thus, the growth-effect of infrastructure characterized below exclusively results exclusively from the cost-reducing infrastructure externality $\phi(G)$.

[26]Note that final output firms demand the same amount of each intermediate so that $x_j = x$, $p_j = p$, $\pi_j = \pi$ and $Ax_j^{\alpha} = \int_0^{A_t} x_j^{\alpha} dj$ hold because of symmetry.

$$p_{I,j,t} = L_{y,t}^{\chi} G_t^{\beta} \alpha x_{j,t}^{\alpha-1} \frac{1}{1+\phi(G)} \quad (1.4)$$

$$w_y = \chi L_Y^{\chi-1} G_t^{\beta} A x_j^{\alpha} \quad (1.5)$$

$$p_{G,t} = L_Y^{\chi} \beta G_t^{\beta-1} A x_j^{\alpha} \quad (1.6)$$

Intermediate capital goods sector (x):

Since the innovation of a specialized intermediate good creates market power, we assume that for each intermediate j in A there exists one monopolist who produces x_j using capital (K) in terms of forgone consumption as an input. An intermediate producer requires η units of K to produce one unit of intermediate j, so that $K = \eta \int_0^A x_j dj$.[27] Each monopolist chooses x_j to maximize his profits ($\pi_{I,j}$) given the perceived inverse demand function for each intermediate ($p_{I,j,t}$) and the interest rate (r) payments per unit of capital. Thus, each intermediate producer faces constant marginal costs ($r\eta$) if the interest rate is constant. Because of symmetry the former is the same for all intermediates ($p_{I,j} = p_I$). The level of infrastructure capital is taken as given.[28] Hence, we obtain the following profit function:[29]

$$\pi_I = p_{I,j} x_j - r\eta x_j = \frac{1}{1+\phi(G)} L_y^{\chi} G^{\beta} \alpha x_{j,t}^{\alpha} - r\eta x_{j,t} \quad (1.7)$$

Computing the first-order condition and substituting for $r\eta$ results in the following profit function:

$$\pi_I = (1-\alpha)px \quad (1.8)$$

R&D sector (A)

The rate of technological change ($\dot{A}$) is a positive function of research labor (L_R), a productivity parameter (λ) and its stock of knowledge (A):

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[27] We abstract from further constraints in the provision of private capital.

[28] At this stage, a new intermediate firm has not entered the market so that the aggregate infrastructure capital stock is exogenous for the potential intermediate producer.

[29] In the following, we concentrate on symmetric balanced growth equilibria, so that we can omit time subscripts to simplify the notation.

$$\dot{A}_t = \lambda L_{R,t} A_t \tag{1.9}$$

It is implicitly assumed that all researchers have free access to the entire stock of knowledge, so that each new innovation/imitation induces a positive externality on future research. This specification is due to Romer (1990). An increase in population raises the rate of technological change, hence it entails scale effects. We abstract from such scale effects by setting population growth to zero (normalize $L = 1$).

Households

Identical, infinitely lived households maximize their utility from consumption (C) subject to a resource constraint and *No-Ponzi* game conditions. The utility function supposes a constant relative risk aversion: $u(c_i) = \frac{c_i^{(1-\sigma)}-1}{1-\sigma}$, where σ is the degree of risk-aversion. We implicitly assume an inelastic labor supply. Thus, the consumption plan satisfies the standard Euler equation:

$$\dot{C}_t = \frac{r_t - \rho}{\sigma} C_t \tag{1.10}$$

where r_t is the real interest rate, ρ a time-preference rate and σ the degree of risk-aversion.

Solution for a balanced growth equilibrium

So far we have not characterized the financing structure of infrastructure capital (the market structure in the sector). Yet, we will solve the (partial) model for a balanced growth equilibrium, in which A, G, C and Y all grow at the same constant exponential rate, to illustrate the mechanism of the model for a given financing structure.

The key mechanism involving technological progress is a free-entry condition into the research sector. It is the basic assumption underlying the market structure of monopolistic competition and translates expected future profits in the intermediate sectors into investments in R&D.[30] In particular, the free entry condition into R&D

[30] Hellwig and Irmen (2001) show that expected future rents due to imperfect competition are not

ensures that the present discounted value of expected future profits from a new innovation equals the costs for the production of a new design. If we assume that monopoly profits last forever the present discounted value equals $\frac{\pi}{r}$, where r is the real interest rate. The costs of a new design are productivity adjusted wages paid to research labor ($\frac{w_R}{\lambda A}$). Thus, the free entry condition amounts to:

$$\frac{\pi}{r} = \frac{w_R}{\lambda A} \tag{1.11}$$

The labor force is free to work in the manufacturing or research sector so that in equilibrium wages in both sectors must be equal ($w_y = w_R$).[31] Given the wage in manufacturing (1.5) and the profit function (1.8) the free-entry condition is solved for the equilibrium demand for manufacturing labor:

$$\Rightarrow L_Y = \frac{\chi r(1+\phi(G))}{\lambda\alpha(1-\alpha)} \tag{1.12}$$

It follows from (1.9) that the equilibrium growth rate of the technology stock amounts to $\gamma = \frac{\dot{A}}{A} = \lambda L_R = \lambda(1 - L_Y)$. We know from the production function that final output grows in a balanced growth equilibrium at the same rate as A. Hence, $\frac{\dot{C}}{C}$ also grows at the rate γ. If we substitute for L_Y from (1.12) and $r = \gamma\sigma + \rho$ from (1.10) we obtain the following growth rate for the stock of technologies:

$$\gamma = \frac{\dot{A}}{A} = \frac{\alpha(1-\alpha)\lambda - \chi\rho(1+\phi(G))}{\alpha(1-\alpha) + \chi\sigma(1+\phi(G))} \tag{1.13}$$

We can infer from (2.20) that the growth rate of the stock of technologies is an increasing function of the stock of infrastructure capital ($\frac{\partial\gamma}{\partial G} > 0$, $\frac{\partial^2\gamma}{\partial^2 G} > 0$). Since (endogenous) technological change is the only source of GDP-growth in a balanced growth equilibrium, GDP also grows at that rate.[32]

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in general necessary to ensure investments in R&D since intentional actions of entrepreneurs looking for profits can trigger such investments even in perfectly competitive markets.

[31] We abstract from any labor market constraints ($L = L_R + L_Y$).

[32] The equilibrium growth rate suggests a minor technical restriction: In order to ensure that consumer's preferences are finite we need to impose that the growth of current utility $(1-\sigma)\gamma$ is less than the discount rate ρ.

Proposition I: Given the cost-reducing feature of infrastructure capital in the intermediate goods sector, the assumptions underlying the production function, and the law of motion for the stock of technologies, it follows that the rate of technical change (and hence output growth) is an increasing function of the stock of infrastructure capital ($\frac{\partial \gamma}{\partial G} > 0$).

Intuitively, a higher provision of infrastructure reduces the business costs in the intermediate sector ($\phi(G)$). This cost-reducing feature of infrastructure capital augments the demand for specialized intermediate goods and hence increases the net present value of the returns of investments in R&D. Due to the research arbitrage (free-entry) condition this leads to a shift of resources from the manufacturing sector (L_y) to the R&D sector (L_R). Consequently, a low provision of infrastructure capital represents an impediment for economic growth because investments in R&D are relatively unprofitable.

Besides, γ is a positive function of the exogenous productivity parameter in the R&D sector (λ). This relationship is quite crucial since the effectiveness of the domestic R&D measured by λ determines the potential scale of the positive infrastructure externality on the incentive to invest in R&D ($\frac{\partial^2 \gamma}{\partial G \partial \lambda} > 0$). If λ is high, the impact of the infrastructure externality is large. Hence, there exists a complementarity between the effect of infrastructure investments and the effectiveness of the R&D sector. Since λ is exogenous it represents all country-specific factors that are neglected in this model and that influence the effectiveness of the R&D sector, e.g. intellectual property rights, tertiary education, or corruption.

It is important to note that the equilibrium growth rate is not necessarily strictly positive. If we set (2.20) equal to 0 we can compute the threshold level for the productivity of the R&D sector (λ^*) such that γ is positive:

$$\lambda^* > \frac{\chi \rho}{\alpha(1-\alpha)}(1+\phi(G)) \tag{1.14}$$

In a zero-growth trap ($\lambda < \lambda^*$), the quality of the institutional framework is not sufficient to ensure that the returns from investments in R&D outweigh the costs of specialization for the given level of infrastructure capital. Thus, (marginal) infrastructure investments have no growth effect and the long-run TFP-level (A_t) remains constant. Consequently, all resources (labor) are allocated to the manufacturing sector.[33] It follows that a country requires to some degree a sound domestic R&D sector to gain sustainingly from infrastructure investments. From a policy perspective this implies that supplementary policies or institutional changes to support corporate R&D activities should be implemented before investments in infrastructure capital are carried out/subsidized.[34]

1.5 Endogenous provision of infrastructure capital

In this section, we endogenize the infrastructure capital stock (G). Ex ante, the interaction between an endogenous infrastructure supply and economic growth is not clear. On the one hand, infrastructure investments are costly or dissipate scarce resources. On the other hand, higher growth facilitates the financing of infrastructure investments due to scale effects. In this regard, our results are based on two additional assumptions. First, investments in infrastructure require different scarce resources than R&D investments. Second, infrastructure capital is partly excludable so that the financing of infrastructure investments depend on the realization of aggregate output. Both assumptions appear to be empiri-

[33]Note that the growth rate cannot become negative because the re-allocation of human capital (L) from research to manufacturing is bounded by 0.

[34]To illustrate the analogous results for the long-run TFP-level (A) we can solve the linear differential equation (2.20). Hence, we obtain the following solution for the level of TFP: $A_t = A_0 \exp{[\Omega - \Gamma]t}$, where $\Omega = \frac{\alpha(1-\alpha)\lambda}{\alpha(1-\alpha)+\chi\sigma(1+\phi(G))}$ and $\Gamma = \frac{\chi\rho(1+\phi(G))}{\alpha(1-\alpha)+\chi\sigma(1+\phi(G))}$. If we take the limit for $t \to \infty$ to approximate the TFP-level in the long-run balanced growth path, we get:

$$\lim_{t\to\infty}(A_t) = \left\{ \begin{array}{ccc} \to\infty & if & \Omega - \Gamma > 0 \\ A_0 & if & \Omega - \Gamma \leq 0 \end{array} \right\}$$

The condition $\Omega - \Gamma > 0$ is of course equivalent to $\lambda > \lambda^*$.

cally plausible.[35] The second assumption entails a reversed causality between the provision of infrastructure and GDP-growth implying the possibility of multiple growth-equilibria. We illustrate the existence of multiple balanced growth equilibria in the presence of increasing marginal infrastructure investment costs over time.

Infrastructure capital goods sector (G)

As discussed in section 2, the assumption of a partly excludable infrastructure capital stock allows for a private provision G_t. Conceptually, we suppose that the infrastructure sector consists of competitive firms supplying infrastructure services and a monopolistic network provider.[36] The competitive service firms take the perceived inverse demand function for infrastructure services ($p_{G,t}$) as given and pay a proportional rental price ($r_{G,t}$) for the access to operate the infrastructure network. Thus, as long as the infrastructure service sector is perfectly competitive, we have $p_{G,t} = r_{G,t}$. In this case, it makes no difference if the network provider supplies infrastructure services himself or sells the rights to do so to competitive firms. The network provider invests I_t in infrastructure capital (G_t) incurring variable ($\mathcal{C}(I_t, t)$) and fixed (F) investment costs. We assume that $\mathcal{C}(I_t, t)$ is an increasing continuous, monotonic function with $\mathcal{C}_1 = \frac{\partial \mathcal{C}}{\partial I_t} > 0$, $\mathcal{C}_2 = \frac{\partial \mathcal{C}}{\partial t} \geq 0$ and $\mathcal{C}_{I_t,t} = \frac{\partial^2 \mathcal{C}}{\partial I_t \partial t} \geq 0$.[37] Note that time enters as an explicit argument in the costs function since we do not exclude that the cost function depends on additional time-dependent (endogenous) variables (e.g. A_t or Y_t). Thus, marginal costs increase over time if the latter condition holds with equality (e.g. strictly convex investment costs). Increasing marginal costs might be a more realistic assumption for an economy that grows according to a balanced growth rate.[38]

[35] The former assumption reproduces that infrastructure investments are intensive in unskilled labor while R&D is human capital intensive.

[36] Due to fix costs (see below) the sector displays a natural monopoly. It does not matter if the network provider is private or public as long as she dynamically optimizes its investments.

[37] The assumption of constant marginal costs is not crucial but simplifies the solution of the model. The case of a convex cost function is reported below.

[38] For example, we might assume that the marginal costs increase in the stock of knowledge or

Monopolistic provider of infrastructure capital

The instantaneous profit function of the monopolist is given by the perceived inverse demand function ($p_{G,t}$), the investment and the fix costs: $\pi_{G,t} = p_{G,t}G_t - \mathcal{C}(I_t,t) - F$. It follows that the monopolist faces a dynamic optimization problem. The depreciation rate of the infrastructure capital stock amounts to δ, so that $\dot{G}_t = I_t - \delta G_t$. Hence, the private monopolist chooses I_t to maximize the (discounted) current value of its expected future profits subject to $\dot{G}_t = I_t - \delta G_t$ and $\int_t^\infty \pi_{G,s} ds \geq \hat{F}$.[39] If the latter condition is satisfied the monopolist faces the following maximization problem:[40]

$$\max_{I_t, G_t} \int_0^\infty e^{-\rho t}[p_{G,t}G_t - \mathcal{C}(I_t,t) - F]dt, \qquad \dot{G}_t = I_t - \delta G_t \tag{1.15}$$

To solve the dynamic optimization problem we define the current value Hamiltonian:

$$H(I_t, G_t, \lambda_t, t) = e^{-\rho t}[p_{G,t}G_t - \mathcal{C}(I_t,t) - F]dt + \lambda_t[I_t - \delta G_t] \tag{1.16}$$

Combining the first-order conditions we get the following optimality conditions:

$$[p'_{G,t}G_t + p_{G,t}] = \mathcal{C}_{I_t}\left(\rho + \delta - \frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}}\right) \tag{1.17}$$

$$\dot{G}_t = I_t - \delta G_t \tag{1.18}$$

$$\lim_{t\to\infty}[\lambda_t I_t] = 0 \tag{1.19}$$

In the case of constant marginal investment costs ($\dot{\mathcal{C}}_{I_t} = \frac{\partial \mathcal{C}_{I_t}}{\partial t} = 0$), the first condition states that instantaneous marginal revenue must equal marginal costs. Otherwise,

GDP to take into account that investment costs are higher if more advanced technologies are applied or if the size of the economy increases.

[39] If the fix costs arise every period we have $[\hat{F} = \int_t^\infty (F)ds]$. If they arise only in the first period we have $[\hat{F} = F]$.

[40] Note that we assume for simplicity that the infrastructure monopolist discounts future profits with ρ and not r. In the latter case $G = G(\gamma)$ would be a higher-order non-linear function of γ. Given $\mathcal{C}(I_t,t) = \mu Y_t I_t$ this results in three balanced growth rates whereas only two are strictly positive. Finally, recall that we abstract from additional private capital constraints in our economy.

the right hand side is adjusted to incorporate the dynamic effects of infrastructure investments on future profits stemming from an increase in the shadow price of infrastructure capital over time. The monopolist extends the provision of G in this case. Intuitively, she anticipates that the shadow price of infrastructure capital increases in the presence of positive balanced growth due to two reasons: (i) future investments are more costly relative to current investments, (ii) the demand for infrastructure capital increases. Hence, she is better off producing more infrastructure capital today since its future value increases for him. The second condition gives the law of motion for infrastructure capital and the third is a transversality condition.

If we substitute in (1.17) for $p_{G,t}$ from (1.6) and solve for G_t, we obtain:

$$G_t = \frac{\beta^2 Y_t}{\mathcal{C}_{I_t}(\rho + \delta - M(\gamma))} \tag{1.20}$$

The infrastructure capital stock is increasing in the level of GDP. In addition, it is an increasing function of the elasticity of final output with respect to infrastructure capital as a rise in β implies a higher demand for G. In contrast, it is decreasing in the depreciation rate (δ) and the inter-temporal elasticity of substitution (ρ). However, we know from (2.20) that G must be constant in a balanced growth path. It then follows from (1.20) that marginal investment costs ($\mathcal{C}_{I_t}$) must grow proportional to GDP in order to sustain balanced growth. Hence, the monopolist faces increasing marginal investment costs. In this case, the growth rate of marginal investment costs is a positive function of the balanced growth rate of the economy: $\frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}} = M(\gamma)$, $M' > 0$, $M'' = 0$. Thus, the infrastructure capital stock is an increasing function of the equilibrium growth rate of the economy ($\frac{\partial G}{\partial \gamma} > 0$).[41]

Moreover, we show in Appendix A that $\frac{\partial^2 G}{\partial^2 \gamma} > 0$ holds for reasonable parameter values. Thus, the infrastructure capital stock is an increasing, convex function of the balanced growth rate ($G = G(\gamma)$, where $G' > 0$, $G'' > 0$). We also know from section 2 that the balanced growth rate is in turn an increasing, convex function of

[41] The exact derivative is given in Appendix A. Besides, we show that a technical sufficient condition for $\frac{\partial^2 G}{\partial^2 \gamma} > 0$ is $\delta + \rho > \gamma$.

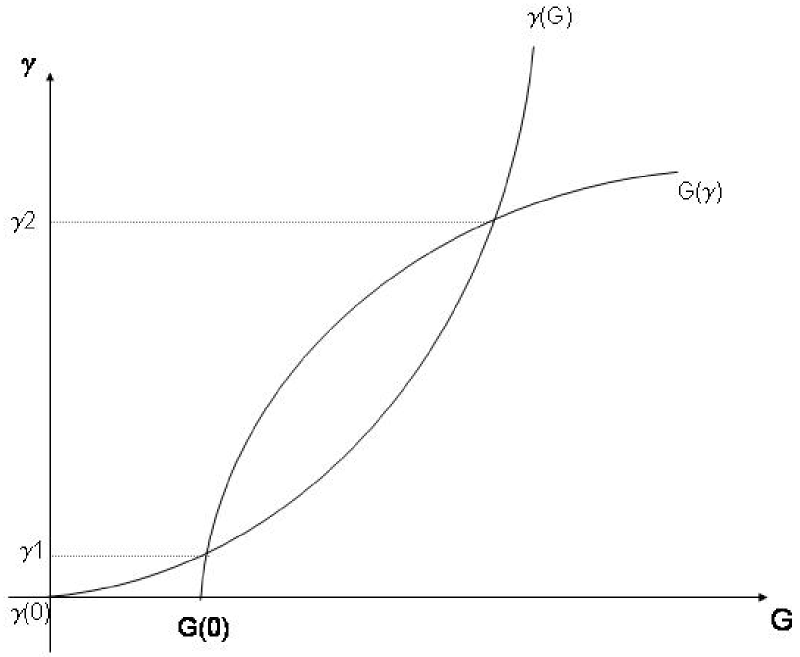

Figure 1.3: Multiple equilibrium growth rates

the stock of infrastructure capital ($\gamma = \gamma(G)$, where $\gamma' > 0$, $\gamma'' > 0$). In addition, both functions are monotonic and continuous. Consequently, we potentially obtain two different equilibrium growth rates (fixed points) if we combine (2.20) and (1.20) to solve for a general equilibrium balanced growth path. Since γ is bounded by zero, $\gamma(0) = 0$ (due to the property that $\lim_{G\to 0} \phi(G) \to \infty$) and $G(0) = G_0 > 0$ holds in equilibrium, we infer that both growth rates are strictly larger than zero if a balanced growth equilibrium exists. The result is illustrated in *Figure* 1.3.

Thus, the reversed causality between the provision of infrastructure capital and economic growth potentially results in two equilibrium balanced growth rates. In the high-growth scenario, the economy is characterized by a high infrastructure capital stock and fast technological change. In the low-growth scenario, the rate of technological change is constraint by the low provision of infrastructure capital which lowers the incentive to invest in R&D and hence the rate of GDP-growth. This in turn limits the demand for infrastructure investments (financing constraint).

Hence, if the initial stock of infrastructure capital (relative to GDP) is too low, the growth rate of the economy is constrained. This, in turn, constraints the supply of infrastructure services so that the economy is trapped in a low-growth equilibrium. It follows from (2.20) that the crucial initial infrastructure level, that needs to be exceeded in order to result in the high-growth equilibrium, is declining in the quality of (R&D-) institutions (λ). In principle, sufficient public subsidies for infrastructure investments, which represent an external financing source in the model, can install the high-growth scenario. Note that public subsidies do not in general induce economic growth, but might trigger the transition to the higher balanced growth path (depending on the financing source).[42] The results of the general equilibrium model with an endogenous supply of infrastructure capital are summarized in Proposition II.

Proposition II: Given the assumptions underlying Proposition I, a positive initial infrastructure capital stock G_0, the requirement of different input factors in the infrastructure- and R&D sector, and the provision of partly excludable infrastructure capital by a dynamically optimizing supplier facing increasing marginal costs proportional to GDP, there exist two strictly positive balanced growth rates with $\gamma_1 > \gamma_2$. The high-growth economy is characterized by fast technological change and a high stock of infrastructure capital, while the low-growth economy by little R&D investments and a low provision of infrastructure capital.

The proof is given in Appendix A.

In the following, we present two explicit examples for different realizations of the cost function. First, we assume a constant marginal costs function ($\frac{\partial^2 \mathcal{C}_{I_t,t}}{\partial I_t \partial t} = 0$) and second, we suppose that investment costs are increasing in the size of the economy measured by GDP ($\frac{\partial^2 \mathcal{C}_{I_t,t}}{\partial I_t \partial t} > 0$).

[42] We do not analyze the transition path belonging to both balanced growth path, but the growth rate during the transition from γ_2 to γ_1 may in principle exceed γ_1. If so, it suggests that the extraordinary growth performance of some recent economies (*growth miracles*) can be explained by one-time growth effects (and its transition path) due to the accumulation of infrastructure capital.

Constant marginal costs

In the following, we assume constant marginal infrastructure investment costs: $\mathcal{C}(I_t) = \mu I_t$. In order to obtain an explicit solution we also need to impose a specific functional form for $\phi(G)$. We assume $\phi(G) = 1 + (G/Y^c)^{-1}$, where $0 \leq c \leq 1$, which is in line with the properties of ϕ stated in section 2. The parameter c measures the degree of congestion in the economy. If $c = 0$ congestion effects are absent and if $c = 1$ only the relative stock of infrastructure capital influences the business cost. Thus, infrastructure capital is allowed to be partly excludable as well as partly rival. Substituting $\mathcal{C}(I_t)$, $\phi(G_t, Y_t)$ and (1.20) into (1.11) research arbitrage equation, we obtain:

$$\gamma^{cm} = \frac{\dot{A}}{A} = \frac{\alpha(1-\alpha)\beta^2\lambda - \chi\rho\beta^2 - \chi\rho\mu(\delta+\rho)Y_t^{c-1}}{\alpha(1-\alpha)\beta^2 + \chi\beta^2\sigma + \chi\sigma\mu(\delta+\rho)Y_t^{c-1}} \tag{1.21}$$

Thus, the long-run growth rate of the stock of technologies is increasing in the level of GDP. Hence, if $c < 1$, a balanced growth path does not exist. The economy features unbalanced, exponential growth. A positive balanced growth path only exists if the business costs depend on the relative infrastructure capital stock ($c = 1$). In this case, congestion effects completely eliminate scale effects from final output. Note that this (intuitively appealing) special case can be derived endogenously by assuming that in equilibrium final output firms exclusively demand infrastructure capital to offset congestion effects in the economy. Besides, γ^{cm} is decreasing in μ, ρ, and δ as these factors reduce the equilibrium provision of infrastructure capital and is increasing in the share of G_t in the final output sector (β) and the exogenous (institutional) productivity parameter of R&D (λ).

Increasing marginal costs

In the following, we assume that the marginal costs of infrastructure investments are increasing in the level of GDP: $\mathcal{C}(I_t) = \mu Y_t I_t$.[43] This relationship is intuitively appeal-

[43]We et $c = 0$ because this cost function already captures congestion effects.

ing since the production costs of infrastructure services are expected to depend on the wage level of an economy just like the production costs of final output or R&D. This cost function can be derived endogenously by assuming that the monopolist needs to hire unskilled labor (U) in order to produce infrastructure capital. If the wage of unskilled labor is proportional to the wage of skilled labor (L) the costs of infrastructure investments are increasing in the level of GDP. The costs function satisfies the sufficient conditions for multiple balanced growth equilibria outlined above. Substituting $\mathcal{C}(I_t, t)$, $\phi(G_t)$ and (1.20) into (1.11), we get:[44]

$$\gamma_1^{im} = \frac{\alpha(1-\alpha)\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)+Z^{1/2}}{2\mu(\alpha(1-\alpha)+\chi\sigma)} \quad (1.22)$$

$$\gamma_2^{im} = \frac{\alpha(1-\alpha)\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)-Z^{1/2}}{2\mu(\alpha(1-\alpha)+\chi\sigma)} \quad (1.23)$$

where $Z = [\alpha(1-\alpha)\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)]^2-4\mu[\alpha(1-\alpha)+\chi\sigma][\alpha(1-\alpha)\lambda\mu(\delta+\rho)-\rho(\beta^2+\chi\mu(\delta+\rho))] > 0$. As long as $\lambda > \lambda^{**} = \frac{\rho\beta^2+\rho\chi\mu(\rho+\delta)}{\alpha(1-\alpha)\mu(\delta+\rho)}$ both growth rates are strictly positive. This conditions relates the exogenous productivity of the R&D sector to the weighted cost of infrastructure investment/capital and ensures that expected future profits from R&D investments are positive. Moreover, the first regime strictly dominates the second in terms of economic growth ($\gamma_1 > \gamma_2$).

Both equilibrium growth rates are strictly increasing in λ (given $\lambda > \lambda^{**}$).[45] In addition, an increase in the exogenous (institutional) productivity parameter has a larger impact on the growth rate in the high-growth regime ($\frac{\partial\gamma_1}{\partial\lambda} > \frac{\partial\gamma_2}{\partial\lambda} > 0$). This result follows directly from the fact that the return of R&D investments is constrained by high intermediate business costs (low infrastructure capital) in the low-growth equilibrium. Besides, γ_1 is increasing in the share of infrastructure capital in the final output sector (β). Hence, γ_1 can potentially still be raised to a higher balanced growth path by an additional external financing source.[46] In contrast, the

[44] Note that the infrastructure provider does not internalize the static effect of an increase in G_t on the output level in a decentralized equilibrium.

[45] The exact derivatives are reported in Appendix A.

[46] Thus, the infrastructure externality outweighs the inefficiencies from the monopolies for the

impact of β on γ_2 is indeterminate and depends on the realizations of the parameter values.[47] Finally, an increase in the constant factor of the marginal investment costs (μ) causes a decline in γ_1. Again, the impact on γ_2 is indeterminate. Thus, under certain parameter realization the positive effect of μ on the level of the shadow price of infrastructure capital may outweigh its direct negative effects on the instantaneous profit function of the infrastructure monopolist.

Infrastructure subsidy

The equilibrium provision of infrastructure capital in our model is socially inefficient. The inefficiency results from the infrastructure externality as well as the monopolistic supplies of intermediate and infrastructure capital goods. Consequently, a government subsidy for infrastructure capital may potentially install the growth maximizing level of infrastructure capital. We have shown above that infrastructure is undersupplied in a decentralized equilibrium ($\frac{\partial \gamma}{\partial \beta} > 0$). It follows that a positive government subsidy for the infrastructure monopolist would be growth-enhancing. It might even induce a regime shift from the lower balanced growth rate to the higher one in the case of increasing marginal investment costs.

In general, we can compute the growth-maximizing subsidy (τ^*) given the different infrastructure investment cost functions. Therefore, we assume that the subsidy is financed by an income tax. The monopolist's period by period profit function changes to: $\pi_{G,t} = p_{G,t}G_t + \tau Y_t - \mu \mathcal{C}(I_t, t) - F$. Moreover, we refer to the special case of a Cobb-Douglas production function for final output by setting $\chi = 1 - \alpha - \beta$.[48] For the purpose of illustration, we focus on the case of constant marginal investment costs and assume that congestion eliminate scale effects. Following the procedure from above

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infrastructure capital stock belonging to γ_1. We discuss this result separately in the next section.

[47] Interestingly, the negative effect of β on the level of the shadow price of infrastructure capital may outweigh the positive direct effect on the instantaneous profit function of the infrastructure monopolist under certain parameter realizations.

[48] This specification implies constant returns to scale for the combination of labor, intermediates and infrastructure capital in the production of final output.

the equilibrium level of infrastructure (G_t^{ms}) and the growth rate (γ^{ms}) are:[49]

$$
\begin{aligned}
G_t^{ms} &= \frac{[(1-\tau)\beta^2 + \tau\beta]}{\mu(\rho+\delta)} Y_t \\
\gamma^{ms} &= \frac{\alpha(1-\alpha)[(1-\tau)^2\beta^2 + \tau(1-\tau)\beta]\lambda - (1-\alpha-\beta)\rho(1+\mu(\delta+\rho))}{\alpha(1-\alpha)[(1-\tau)^2\beta^2 + \tau(1-\tau)\beta] + (1-\alpha-\beta)\sigma(1+\mu(\rho+\delta))}
\end{aligned} \tag{1.24}
$$

Setting $\frac{\partial \gamma^{ms}}{\partial \tau} = 0$ and solving for τ yields the following growth-maximizing government subsidy: $\tau^* = \frac{1-2\beta}{2(1-\beta)}$. Not surprisingly, the growth-maximizing subsidy is decreasing in β. Moreover, τ^* internalizes the growth-enhancing infrastructure externality for a given level of the distortional income tax. For example, for $\beta = 0.3$, τ^* is approximately equal to 0.28. For $\beta \geq 0.5$ the growth-maximizing subsidy is 0. In this case, the negative growth effect from an additional income tax would outweigh the positive infrastructure externality. In general, the result shows that different market structures in the infrastructure capital sector have different implications for equilibrium growth.

1.6 Conclusion of Chapter 1

This article decomposes the growth effect of infrastructure investments. It suggests that infrastructure affects innovative investments and technological change instead of factor accumulation.

The empirical section provides evidence for a positive causal effect from infrastructure capital on TFP-growth from a dynamic panel estimation. We find that investments in (telecommunication) infrastructure cause an increase in R&D investments in subsequent periods. We control for a potential endogeneity of infrastructure by (i) including internal as well as exogenous instruments for infrastructure and (ii) analyzing the effect of macroeconomic aggregates on firm-level investment decisions. Moreover, we detect that infrastructure promotes TFP-growth via adjustments in ag-

[49]Notice that in the presence of an income tax rate the partial growth rate (2.20) amounts to: $\gamma' = \frac{(1-\tau)\alpha(1-\alpha)\lambda - (1-\alpha-\beta)\rho\phi(G)}{(1-\tau)\alpha(1-\alpha) + (1-\alpha-\beta)\sigma\phi(G/Y)}$.

gregate R&D. Finally, we are not able to detect a positive relationship between the provision of infrastructure and private investments in physical or human capital.

The empirical findings are striking since they challenge conventional growth theories which link growth-promoting effects of infrastructure investments to a stimulation of private capital investments. Our results reject this complementarity between public (infrastructure) and private capital investments. Instead, they suggest a direct effect of telecommunication infrastructure on technical change in relatively developed countries which is independent from private or human capital accumulation. Second, the impact of infrastructure on R&D features different policy implications. That is, the growth-effect of infrastructure investments depends on factors such as intellectual property rights, the degree of product market competition or tertiary education instead of factors that influence a household's saving decision.

In addition, we suggest a theoretical mechanism that complies with this empirical finding. In particular, we illustrate a positive link between the provision of infrastructure capital and the incentives to invest in R&D. This result is based on the assumption that infrastructure capital reduces costly distortions between the interactions of the final and intermediate sector (e.g. transportation and coordination costs). Moreover, the model implies crucial complementarities between infrastructure capital and other factors that influence the effectiveness of the R&D sector. Finally, we show that the link between infrastructure and R&D can lead to multiple balanced growth pathes if we endogenize the provision of infrastructure capital.

The connection between infrastructure and technical change refines the link between infrastructure and growth and helps to explore productivity differences across countries. The results suggest that future work on the link between infrastructure and growth should be devoted to its effect on innovative activities and technical change.

Chapter 2

Inflation, financial market incompleteness and long-run TFP-growth

This chapter demonstrates a negative relationship between inflation and long-run productivity growth. Inflation generates long-run real effects due to a link from the short-run interplay between nominal and financial frictions to a firm's qualitative investment portfolio. First, we employ country panel data to investigate the robustness of a negative causal effect of inflation on long-run TFP-growth. Second, we develop an endogenous growth model whose key ingredients are (i) a nominal short-run portfolio choice for households, (ii) an agency problem which gives rise to financial market incompleteness, (iii) a firm-level technology choice between a return-dominated but secure and a more productive but risky project. In this framework, inflation increases the costs of corporate insurance against productive but risky projects and hence a firm's choice of technology. It follows that economies (time periods) that feature a higher level of inflation are predicted to exhibit lower TFP-growth in the long-run. That is, each level of inflation is associated with a different long-run balanced growth path as long as financial markets are incomplete. Finally, we apply U.S. industry as well as firm-level dynamic panel data to examine the relevance of our specific microeconomic mechanism. We find that (i) firms insure systematically against risky R&D investments by means of corporate liquidity holdings, (ii) periods of higher inflation restrain firm-level R&D investments by reducing corporate liquidity holdings.

2.1 Introduction

Does inflation reduce long-run economic growth? If so, what is the key transmission mechanism relating inflation to long-run growth? To answer these questions, we provide empirical evidence - in accordance with Fischer (1993) and others - that the level of inflation reduces long-run productivity growth. Thereafter, we develop a novel theoretical explanation for a long-run relationship between the two variables in the context of an endogenous growth model with financial market frictions. Our transmission mechanism relates the qualitative composition of investments, instead of their quantity, to the level of inflation. Hence, we partly endogenize total factor productivity (TFP) by demonstrating that monetary policy is a relevant component of long-run TFP-growth. Finally, we present micro-econometric evidence from disaggregated U.S. sectoral and firm-level data that is consistent with our specific microeconomic mechanism underlying the macroeconomic monetary transmission channel.

Recent progress in development accounting have identified differences in total factor productivity (TFP), rather than physical or human capital accumulation, as the main factor generating cross-country income and growth differences.[1] Accordingly, variations in TFP explain about 2/3 of the variations in income across countries. However, TFP is measured as the component of output that is not explained by labor or (human) capital inputs. Therefore, Abramovitz (1956) refers to this residual measure as the "*measure of our ignorance*". Against this background, substantial efforts have been devoted to endogenize TFP.[2] The effect of nominal variables on real economic activities, on the other hand, has been mainly analyzed in a business cycle framework.

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[1]Caselli (2005) provides an exhaustive survey of recent contributions to development accounting and demonstrates the robustness of this result.

[2]The title of a contribution by Prescott (1998) anticipates recent developments in the endogenous growth literature: "Needed: A Theory of Total Factor Productivity". So far, the most prominent explanations for cross-country differences in TFP concentrate on the role of government regulations (Prescott, 1998), human capital (Benhabid and Spiegel, 2005), or institutions (Acemoglu et al. (2002)).

In this respect, it is well recognized that monetary policy can influence fluctuations in real variables in the short-run, but most theoretical contributions treat monetary policy shocks and TFP as orthogonal in the long-run. Accordingly, the determinants of growth and cycles are most often regarded as two separated entities.[3]

Our theoretical contribution takes a different route and combines elements of the growth and business cycle literature. Specifically, we analyze the interdependence between short-run nominal and financial frictions and its effect on long-run endogenous technological change. The standard endogenous growth model is supplemented in three dimensions. *First*, we incorporate a technology choice for producers. That is, intermediate firms can channel investments into two distinct projects: a safe, but return-dominated ("basic") and a superior ("advanced") project which yields higher expected returns, but is subject to idiosyncratic liquidity shocks. We attribute investments that enhance the stock of technologies available for a firm, e.g. R&D expenses, to the advanced projects since this type of investment is considered to be more productive, but also more risky. Thus, (part of the) expenses for advanced technologies generate a positive externality on the future stock of knowledge/technologies available in the economy. In contrast, investments in the basic technology reflect, e.g., expenses for machines of the same vintage relative to previous ones. Moreover, firms operating the advanced technology can insure themselves against the idiosyncratic liquidity risk by means of holding a precautionary stock of readily marketable assets; however, due to an entrepreneurial moral hazard problem, which is the *second* key building block of the model, the scope for insurance is limited. The consequence of this friction is that financial markets are incomplete in that scarce liquidity - along the lines of Holmstrom and Tirole (1998) - can not be efficiently provided to the productive sector. *Third*, we assume that households are required to hold cash in order

[3]This observation is well paraphrased by Aghion et al. (2005): *"The modern theory of business cycles gives a central position to productivity shocks and the role of financial markets in the propagation of these shocks; but it takes the entire productivity process as exogenous. The modern theory of growth, on the other hand, gives a central position to endogenous productivity growth and the role of financial markets in the growth process; but it focuses on trends, largely ignoring shocks and cycles."*

to consume at the end of a period. This short-run cash-in-advance constraint implies that households have to choose between cash holdings for consumption purposes and deposits with a financial intermediary that earn a net interest rate. It follows that the short-run supply of nominal assets (liquidity) is costly even in an environment of flexible prices. Taken together with the positive short-run demand for liquidity of firms operating the advanced technology this approach involves a positive short-run nominal interest rate that represents the cost of insurance against liquidity shocks. That is, the nominal interest rate constitutes an additional cost of production by means of the advanced technology relative to the basic one. This complementarity between corporate liquidity holdings and a firm's ability to invest in productive but risky projects leads to a type of *inflation tax* on productivity-enhancing investments. The short-run non-neutrality of monetary policy induces an investment composition effect that is found to be associated with changes in the aggregate stock of technologies in the long-run. Hence, the model postulates a novel aspect of monetary transmission in that differences in the level of inflation across countries or time periods induce long-run differences in TFP-growth as long as financial markets are incomplete.

Our empirical macroeconomic evidence demonstrates the robustness of this negative empirical relation. We apply a dynamic panel technique following Blundell and Bond (1998) which allows some inspection of causality. Accordingly, we find that inflation reduces long-run TFP-growth, whereby its exogeneity can not be rejected. Furthermore, the firm-level moral hazard problem results in a constrained-efficient contracting scheme between firms and financial intermediaries. This endogenous form of financial market incompleteness allows for a set of empirical implications which are specific to our model. We test these implications using disaggregated U.S. sectoral and firm-level panel data. The results demonstrate that firms with riskier cash-flows and higher R&D investments systematically adjust the composition of their asset and investment portfolios in periods of higher inflation. In particular, we find that (i) the sensitivity of TFP-growth with respect to inflation is significantly higher in more volatile and more productive sectors, (ii) periods of higher inflation restrain firm-level

R&D investments by reducing corporate liquidity holdings.

The rest of the chapter is organized as follows. In section 2, we review the literature on inflation and long-run economic growth. Section 3 examines the aggregate empirical relation between inflation and long-run TFP-growth. The next two sections describe the theoretical model as the basic structure to highlight the novel monetary transmission mechanism. In section 6, we test model-specific implications applying sectoral and firm-level panel data in order to identify the underlying microeconomic mechanism empirically. A final section concludes.

2.2 Literature review

A limited number of theoretical studies allow for an impact of changes in nominal variables on long-run economic growth. In this regard, King et al. (1998) incorporate constant returns to capital in a real business cycle model showing that temporary nominal shocks can have permanent effects due to a reduction in capital investments. Similarly, Aizenman and Marion (1993) develop a negative relation between nominal fluctuations and GDP-growth due to the existence of investment irreversibility. More recently, Fatas (2001) relates long-run growth to short-run business cycles. He embeds an aggregate demand externality in an endogenous growth model to show that the coordination of productive investments across different sectors may be an important prerequisite for aggregate economic development. In contrast to our contribution, the permanent effects in the above models are transmitted via the aggregate quantity of investments. However, Ramey and Ramey (1995) reveal that the negative empirical correlation between nominal macroeconomic fluctuations and the trend of GDP-growth is independent of the aggregate quantity of investments.

Aghion et al. (2005) and Angeletos (2006) focus on the link between financial market incompleteness and business cycle fluctuations. The former examine how (exogenous) credit constraints affect the cyclical behavior of productivity-enhancing investment. Specifically, they distinguish between a short-term and a long-term investment project which enhances future productivity. Survival of long-term projects is uncertain because they are subject to idiosyncratic liquidity shocks which - for reasons left unspecified - can only be imperfectly insured. The authors show that sufficiently tight credit constraints result in a procyclicality of long-term investment which amplify the business cycle. Similarly, Angeletos (2006) studies the effects of idiosyncratic investment risk on the aggregate level and the allocation of savings within the framework of a non-monetary neoclassical growth model. Their key result is that incomplete markets reduce TFP by shifting resources away from the more risky, but also more productive private equity investment. They focus on the impact of exogenous credit constraints on an economy's cyclical productivity dynamics and not on the evolution of the long-run trend. Moreover, Aghion et al. (2005) and Angeletos (2006) are concerned with real general equilibrium economies; they do not address a potential interplay between nominal and financial frictions. In order to better understand the determinants of the interdependence between nominal and financial frictions, it is important to carefully specify the source of market incompleteness which gives rise to uninsured idiosyncratic risk. Therefore, we embed the financial contracting problem discussed in Holmstrom and Tirole (1998) in our model. This endogenous form of financial market incompleteness makes it possible to derive a number of theoretical predictions which can be examined empirically.

Acemoglu and Zilibotti (1997), among others, develop a theoretical link between the degree of financial market development and long-term growth. Their reasoning is based on the ability of agents to share the risk of investment projects. Thus, capital investments in poor economies are constraint by risk diversification opportunities. The model explains why the level and volatility of output are high in less developed countries and decline with the degree of financial market development. Moreover, Levine et al. (2000) provide empirical evidence in favor of a causal link from financial development to economic growth. However, in contrast to these approaches, which are based on real economies, incomplete financial markets transmit short-run nominal constraints to long-run restrictions on the productivity trend in our model.

The empirical literature on inflation and growth employs cross-country (panel) regressions with low frequency data.[4] In this context, Bruno and Easterly (1998) and Easterly (2005) suggest that the negative relation between GDP-growth and inflation is mainly due to *inflation outliers*. Assuming different threshold levels (e.g. 20%, 40%) they detect that the robustness of the negative relation depends on high-inflation countries. In contrast, Fischer (1993) finds that the negative correlation between inflation and TFP-growth is, if anything, larger in low-inflation (OECD-) countries. Moreover, Fischer (1993) investigates the causal mechanism behind this correlation in several ways. First, he examines the potential endogeneity of inflation by considering sample variations across periods predominated by demand (1960-1972) or supply (1973-1988) shocks.[5] In line with the established literature, he starts from the presumption that adverse supply shocks are the main source of the endogeneity of inflation, i.e. while an adverse supply shock is inflationary, an adverse demand shock would be deflationary. However, he finds that the correlation between inflation and economic growth remains unchanged across periods of mainly demand or supply shocks and therefore is led to the conclusion that inflation is exogenous with respect to growth. Second, the author decomposes GDP growth into its components and detects a robust negative relation between inflation the growth rate of TFP. Thus, even after controlling for factor accumulation and employment, the negative effect of inflation on growth persists. Similarly, De Gregorio (1993) finds that inflation affects the productivity of investment rather than its level. It follows that there must be some inflation-driven mechanism which records in terms of decreased aggregate productivity growth.

[4]Important contributions in this branch of research include De Gregorio (1992), De Gregorio (1993), and Barro and Lee (1996).

[5]The difficulty in identifying a causal relation between inflation and growth stems from the lack of appropriate external instruments for inflation. For cross-country regressions, a possible instrumental variable approach is due to Cukierman et al. (1993) who incorporate measures of central bank independence as instrumental variables and detect negative correlations with economic growth. Our own approach in Section 2.3 circumvents the problem by applying dynamic panel regressions, thus relying on internal instruments whose validity is testable.

The structure of the model we develop suggests that the availability of corporate liquidity is a crucial determinant for firm-level qualitative investment decisions. To get some guidance on the potential power of this mechanism, we relate our analysis to the findings in Opler et al. (1999) who examine the determinants and implications of holdings of cash and marketable securities by publicly traded non-financial U.S. firms.[6] The authors establish that (i) firms with better outside financing opportunities tend to hold a lower fraction of their total assets in the form of liquid assets, and that (ii) firms with strong growth opportunities and riskier cash flows hold relatively high ratios of cash to total non-cash assets.[7] Moreover, there is evidence that firms retain a relatively high fraction of their earnings as liquid reserves and that these reserves are generally not used for capital investment, but rather tend to be depleted by operating losses, i.e. the corporate liquidity is held as a hedge against production risk. As to the quantitative importance of corporate cash holdings, the authors report the mean over the firms in their sample of the ratio of cash to net assets to be 18%, while the median amounts to 6.5%. Thus, corporate liquidity holdings are likely to constitute a quantitatively relevant expense factor in the presence of inflation.

2.3 Inflation- TFP-growth nexus

Data and methodology: In this section, we complement the work of Fischer (1993) and De Gregorio (1993) in that we apply a different econometric method and supplementary robustness tests to investigate the inflation TFP-growth nexus. The aggregate empirical analysis is based on an unbalanced panel data set consisting of 88

[6]The background for most theoretical and empirical studies of corporate cash holdings is the presumption that external finance is costly and that firms hold liquid assets in order to survive bad times and to have funds readily available if an investment opportunity arises. The benefits of corporate liquidity must then be balanced against its costs which arises as a consequence of a liquidity premium.

[7]We interpret these latter features - high growth potential and risky cash flows - as the identifying characteristics of what we label advanced technology.

countries from 1970-1999. We employ non-overlapping 5-year averages to smooth out business cycle effects which reduces the time dimension to six observations per country.[8] Inflation is measured by the first difference of the natural logarithm of the consumer price index from the World Development Indicator database (WDI). In addition, we include various institutional and financial control variables to minimize the potential of an omitted variable bias. In particular, we approximate a country's degree of financial market development by the amount of private credits relative to GDP (*credit*).[9] Furthermore, we account for the following control variables: the government and private investment shares from the Penn World Tables, the amount of trade in goods as % of GDP (WDI), the terms of trade (WDI), an index of overall property rights from the Fraser Institute of Economic Freedom database, and a measure of inflation uncertainty. We construct the TFP series following Caselli (2006). A detailed description of the growth accounting methodology is provided in Appendix B. In line with the empirical growth literature, we include the lagged level of TFP as a lagged dependent variable in the growth regression.[10] Accordingly, we apply a dynamic panel data model. Therefore, we employ the method developed by Blundell and Bond (1998) which is based on the general method of moments (GMM) and is constructed to yield consistent estimates in dynamic panels.[11] This procedure instru-

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[8]Specifically, we use the following time averages: 1970-1974, 1075-1979, ..., 1995-1999.

[9]The proxy is obtained from from Beck and Levine (1999). We note that all of our results are robust to the inclusion of alternative proxies from these authors such as the amount of liquid liabilities, the rate of stock market trade, or the amount of financial deposits. The results are available from the authors upon request.

[10]The corresponding coefficient is negative and significant on a 1% level in all estimation specifications. Compare e.g. Caldern and Servn (2005) or Barro and Sala-i-Martin (1995), and Aghion et al. (2005) for analogous approaches.

[11]In other words, considering the following dynamic panel data model in first differences:

$$y_{i,t} - y_{i,t-1} = \alpha(y_{i,t-1} - y_{i,t-2}) + \beta(X_{i,t} - X_{i,t-1}) + (\epsilon_{i,t} - \epsilon_{i,t-1}), \quad i = 1, 2, ..., N, t = 3, 4, ..., T,$$

the basic assumptions of Arellano and Bond (1991) are $E[y_{i,t-s}(\epsilon_{i,t} - \epsilon_{i,t-1})] = 0$, $E[X_{i,t-s}(\epsilon_{i,t} - \epsilon_{i,t-1})] = 0$ for $s \geq 2; t = 3, ...T$, where $y_{i,t}$ is the dependent variable, $X_{i,t}$ a vector of endogenous and ments predetermined and endogenous variables with the suitable corresponding lags of these variables. It allows to gain inspection of causality and provides a tests of autocorrelation and overidentifying restrictions to check for the validity of the instruments.

In Figure 2.1, we plot annual data for inflation and TFP-growth using the subset of 22 OECD countries from 1980-2000.[12] The scatter-plot illustrates a negative bivariate correlation between the two. However, this relation may be due to periods of excessive inflation rates above 20% or 40% as suggested by Bruno and Easterly (1998). Therefore, we focus on a smaller subset of 19 OECD countries from 1990-2000 in Figure 2.2. The highest observable inflation rate in this sample amounts to roughly 15%. Yet, the data still indicate a negative correlation between the two series. In this respect, the simple scatter-plots already suggest that the negative aggregate correlation between inflation and TFP-growth does not stem from inflation-outliers.

Results: In 2.1, we investigate the reduced-form relation between the two aggregate series controlling for spurious correlation and endogeneity of inflation. The first column reports a negative contemporaneous correlation between inflation and TFP-growth after controlling for the institutional and financial indicators. Correspondingly, this negative correlation does not simply capture an economy's degree of

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exogenous explanatory variables, N the number of cross-sections, T the number of time-periods, $\epsilon_{i,t}$ the error term and α and β parameters to be estimated. In addition, Blundell and Bond (1998) apply supplementary moment restrictions on the original model in levels, whereby lagged differences are used as additional instruments for the endogenous and predetermined variables in levels. Given that $E[y_{i,t}, \mu_i]$ is mean stationary, the Blundell and Bond (1998) estimator incorporates the additional moment restrictions $E[(y_{i,t-1} - y_{i,t-2})(\eta_i + \epsilon_{i,t})] = 0$, $E[(X_{i,t-1} - X_{i,t-2})(\eta_i + \epsilon_{i,t})] = 0$, which requires the additional assumption of no correlation between the differences of these variables and the country-specific effect. The authors show that this procedure is more efficient if explanatory variables are persistent.

[12]The informational value of the scatterplot is very limited if we exploit the entire panel of 88 countries since most inflation-observations are within the same range apart from some extreme outliers due to periods of hyperinflation.

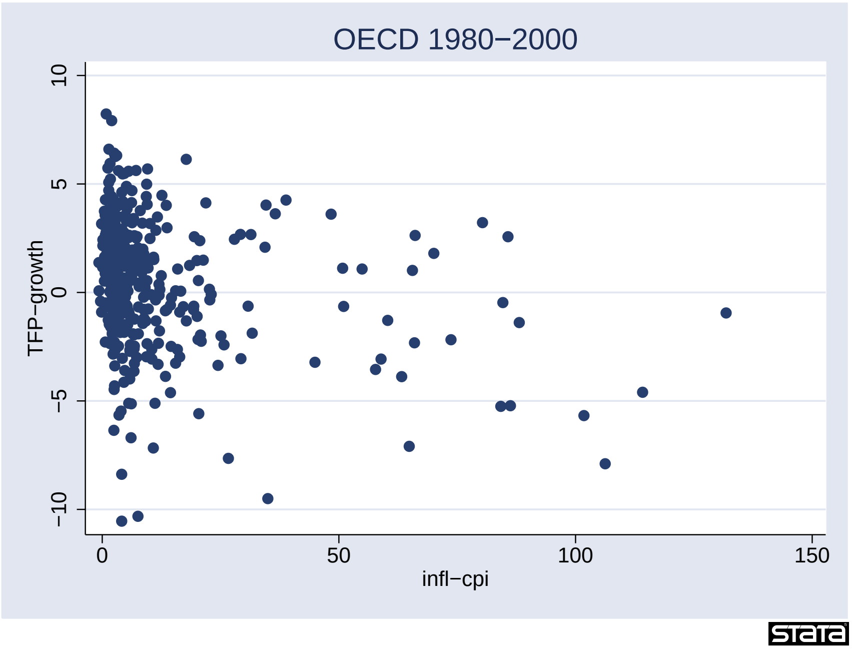

Figure 2.1: Scatter-plot: Panel of 22 OECD countries 1980-2000

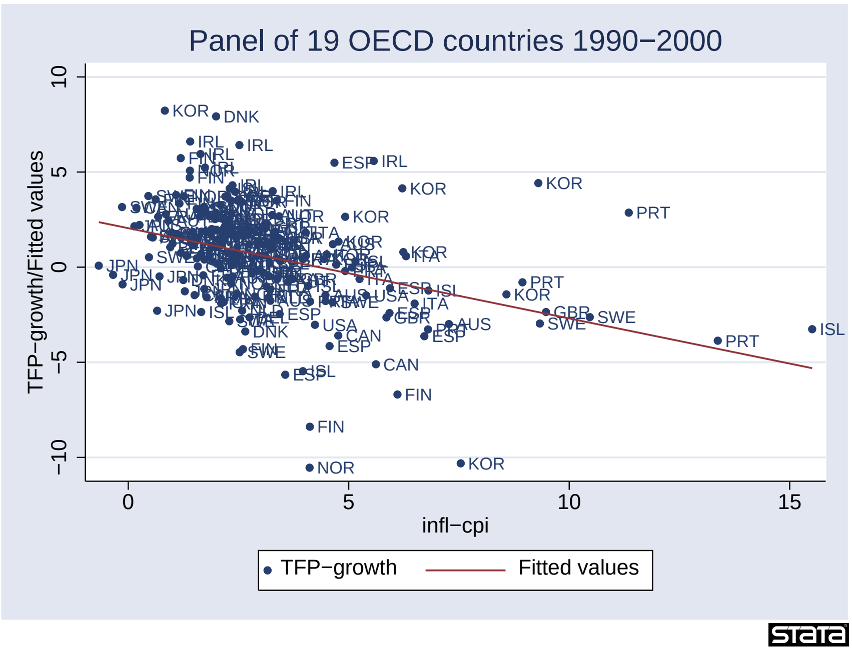

Figure 2.2: Scatter-plot: Panel of 19 OECD countries 1990-2000

financial or institutional development. In the next column, we apply the least square dummy variable estimator to additionally control for country fixed effects. The coefficient of inflation is still significant on a 1% level. Yet, the corresponding estimates are biased in the presence of a lagged dependent variable. Therefore, we present our preferred specification based on the method of Blundell and Bond (1998) in column three. Accordingly, inflation, which is instrumented by its suitable own lags, reduces TFP-growth. The corresponding coefficient is significant on a 1% level.[13] Thus, our results suggest that causation is running from inflation to TFP-growth. Moreover, TFP-growth is decreasing in the lagged level of TFP and increasing in the measure of overall property rights. The Hansen test and the test of second order autocorrelation signalize that the validity of the instruments can not be rejected.

In the remaining columns of 2.1, we conduct several robustness checks for our basic specification. Column four reveals that an increase in the private investment share enhances TFP-growth. However, the corresponding coefficient of inflation is still significant on a 5% level even after controlling for the fluctuations in aggregate investments. We infer that the transmission channel of inflation is independent from private factor accumulation. This result affirms our conjecture that inflation affects the quality (composition) of private investments instead of their quantity.[14] Column five shows that our results are robust to the inclusion of time fixed effects which control for aggregate shocks that are common for all countries in each time period. In column six and seven, we try to discriminate empirically between level and uncertainty effects of inflation. Therefore, we incorporate the standard deviation of inflation as a proxy

[13]We stress that the average effect of a 1% point increase is relatively small since some countries experienced excessive inflation rates. In particular, inflation varies from 0-6000% while TFP-growth varies from -10-10% in our sample. This reduces the average marginal effect of a 1% point increase substantially. We outline below that the average marginal effects are much larger if we focus on the OECD sub-sample or U.S. time series data.

[14]This result is in line with the earlier findings of Ramey and Ramey (1995) and Aghion et al. (2005) on (nominal) volatility and GDP-growth.

for inflation uncertainty.[15] The standard deviation significantly reduces TFP-growth if we abstract from level effects. Yet, we exclusively find a significant negative effect of the level of inflation if we account for both uncertainty and level effects. However, we note that the level and the standard deviation of inflation are highly correlated in our sample. Nevertheless, these results suggest that the distorting impact of inflation is due to movements in the level of inflation instead of changes in inflation uncertainty. Finally, the last column of 2.1 displays the results for the sub-sample of 22 OECD countries. Accordingly, a 5% increase in inflation reduces TFP-growth in this sub-set of developed economies, on average, by .35% in the same time period.[16] The negative coefficient is significant on a 1% level. The coefficient in the OECD sub-set is more pronounced since many countries suffered from periods of excessive inflation. This reduces the marginal effect of a 1% point increase in inflation if we consider the full sample. The result supports the hypothesis that inflation reduces TFP-growth even in regions/periods of moderate or low inflation. Summing up, the aggregate results highlight a negative empirical relation between inflation and TFP-growth in the data with causality running from the former to the latter.

2.4 The model

In this section, we introduce an endogenous growth model which accounts for short-run nominal and financial frictions to illuminate the long-run negative causation running from inflation to TFP-growth. The economy is populated by two sets of agents, households and entrepreneurs, each of unit mass. Moreover, there are a financial intermediation and a productive sector. The latter is organized in decentralized firms,

[15] Uncertainty is measured as the average annual standard deviation for a corresponding 5-year-interval.

[16] A 1% increase in inflation reduces the average annual U.S. TFP-growth by .4% if we exclusively focus on yearly U.S. time series data from 1975-2000. In this case, we employ the first two lags of inflation as instruments for the contemporaneous levels. The results are available from the authors upon request.

Table 2.1: Aggregate data: 5-year-averages: Inflation & TFP growth

	TFP growth							
	OLS	LSDV	GMM-sys	GMM-sys	GMM-sys	GMM-sys	GMM-sys	GMM-sys
infl	-.0014***	-.0009***	-.0020***	-.0016**	-.0022***		-.0059**	-.0646***
	(-7.33)	(-4.17)	(-2.74)	(-2.44)	(-2.96)		(-2.05)	(-2.85)
infl-vol						-.0009**	.0026*	
						(-2.01)	(1.66)	
credit	.2479	-.7932	.7770	-.5247	.8965	.7517	.0139	.4846
	(.54)	(-.93)	(.69)	(-.46)	(.81)	(.66)	(.01)	(.58)
trade	.0021	.0154	.0066	.0027	.0047	.0079	.0076	
	(.82)	(.96)	(1.05)	(.35)	(.87)	(1.22)	(1.38)	
ki				.1309***				
				(2.21)				
ppr	.3130***	.1759	.4452***	.3656**	.4182**	.4294**	.4779***	-.2293*
	(3.58)	(1.26)	(2.94)	(2.53)	(2.81)	(2.92)	(3.32)	(-1.71)
kg	-.0113	-.0687	-.0243	-.0145	-.0214	-.0257	-.0145	-.0606
	(-.59)	(-.79)	(-.87)	(-.54)	(-.81)	(-.95)	(-.54)	(-1.07)
tot	-.0066	-.0013	-.0055	-.0164	-.0058	-.0062	-.0047	.2247**
	(-.87)	(-.12)	(-.59)	(-1.54)	(-.66)	(-.67)	(-.51)	(2.18)
lag dep. var.	-.0049***	-.0229***	-.0180***	-.0183***	-.0162***	-.0171***	-.0151***	-.6202***
	(-3.24)	(-5.28)	(-5.53)	(-5.07)	(-5.52)	(-5.41)	(-5.65)	(-4.20)
time-FE	-	-	-	-	yes	-	-	
Cou./Obs.	86/363	86/363	86/363	86/363	86/363	86/362	86/362	22/107
2. auto-cor.	-	-	0.127	0.129	0.175	0.113	0.211	0.385
Hansen-test	-	-	0.122	0.287	0.161	0.108	0.195	0.939

We specify inflation, inflation-volatility, credit, trade and the investment share as endogenous and property rights, government share and terms of trade as exogenous variables in the GMM system estimation. Inflation volatility is measured by the average standard deviation of yearly inflation rates. Predetermined lagged level of TFP as lagged dependent variable.

which have access to two distinct technologies: a basic technology which is return-dominated but risk-free and a more productive but risky advanced technology.[17] There exist various interpretations of what the two types of investments represent. For example, the basic project might reflect investments in machines of the same vintage relative to previous ones, while the advanced project might represent investments in R&D, the learning a new skill, or the adoption of a new technology.[18] The timing structure underlying our model is as follows. Time is discrete, and within each period t, there are three points in time: one at the beginning of the period when government policy materializes and information about it is revealed, denoted t^-, one at an interim stage, and finally one at the end of the period, denoted t^+. Monetary policy, which is perfectly observable before individual decisions are realized each period, is the only source of aggregate uncertainty since we focus on the inflation-growth nexus. Apart, there exist purely idiosyncratic liquidity shocks ξ_t^i to the subset of firms operating the advanced technology. We now turn to a detailed description of the environment in which the economy's agents interact and define their relevant decision problems as well as the long-run balanced growth path of the economy.

2.4.1 Households

The economy is populated by a unit mass of infinitely-lived, risk averse households.[19] Households enter a given period t with a nominal wealth position M_t. At time t^-, households divide their nominal wealth into resources Q_t disposable for consumption later in the period and deposits $M_t - Q_t$ with a financial intermediary that earn a net

[17] As a general rule, variables pertaining to the basic sector are indicated by the variable/superscript k, while z is the relevant indicator for the advanced sector.

[18] Similarly, the basic project might be putting money into the current business, while the advanced reflects the start-up of a new business. See Aghion et al. (2005) for further discussion.

[19] Where necessary, variables pertaining to the household sector will be denoted with a superscript H.

interest rate $(\tilde{R}_t - 1)$.[20] Thus, there is a cash constraint on the goods market with the consequence that the household's current expenditure for consumption c_t^H must be covered by the resources Q_t. After aggregate shocks have unfolded, households rent out their sector-specific physical capital to the firms which operate a portfolio of projects using the basic and advanced technology, respectively. Moreover, they supply their labor inelastically. That is, each household is endowed with a constant amount of labor which can be used for either of the two intermediate sectors, whereby households are indifferent as to the sectoral composition of their labor supply. Hence, the constant aggregate supply of household labor amounts to: $\overline{h}^H = h_t^H = h_t^{k,H} + h_t^{z,H}$. Since households are indifferent as to where their labor is employed the sectoral wage rates must be identical in equilibrium, i.e. $W_t^{k,H} = W_t^{z,H} = W_t^H$. At time t^+, households receive the returns from labor $(W_t^{k,z})$ and capital $(R_t^{k,z})$ and make their consumption decisions. The household has preferences over sequences of consumption; hence, the household problem is to maximize lifetime utility:

$$E_{0^-} \sum_{t=0}^{\infty} \beta^t u(c_t^H) \tag{2.1a}$$

subject to the cash constraint:

$$Q_t \geq P_t \left[c_t^H + x_t \right], \tag{2.1b}$$

and an equation describing the evolution of nominal assets:

$$\begin{aligned} M_{t+1} &= Q_t - P_t c_t^H + \tilde{R}_t [M_t - Q_t + \mathcal{J}_t] + \Upsilon_t \\ &+ W_t^{k,H} h_t^{k,H} + W_t^{z,H} h_t^{z,H} + R_t^k k_t + R_t^z z_t, \end{aligned} \tag{2.1c}$$

[20]This timing convention is standard in monetary models which feature a cash-in-advance constraint on the household side; compare e.g. Lucas (1990). Our timing convention necessitates a careful treatment of the information sets relevant to the household when it takes decisions. Specifically, there is a distinction between expectation operators at the beginning of a period (time t^-) and at the end of a period (time t^+).

where $\mathcal{J}_t$ are cash injections into the financial market on behalf of the government and Υ_t are nominal resources redistributed in a lump sum fashion among the consumers at the end of the period, and subject to a law of motion for physical capital $x_t = k_t + z_t$, which accounts for depreciation:

$$x_t = (k_{t+1} + z_{t+1}) - (1 - \delta)(k_t + z_t) \tag{2.1d}$$

The solution to the household problem can be summarized by a set of optimality conditions which characterize the household's equilibrium behavior. The first one is the Euler equation describing the optimal inter-temporal allocation of nominal wealth:

$$E_{t^-} \left\{ \frac{u_c(c_t^H)}{P_t} - \beta \tilde{R}_t \frac{u_c(c_{t+1}^H)}{P_{t+1}} \right\} = 0 \tag{2.2}$$

Equation (2.2) implies a type of Fisher relation in that the nominal interest rate is a function of the rate of inflation and the real interest rate in equilibrium. The latter is in turn governed by the balanced growth rate of consumption and parameters of the utility function. Next, there are two Euler equations which determine the sequence of dynamic decisions between consumption and sector-specific investments; for $i = k, z$:

$$u_c(c_t^H) = \beta E_t \left\{ u_c(c_{t+1}^H) \left[(1 - \delta) + \frac{r_{t+1}^i}{\tilde{R}_{t+1}} \right] \right\}, \tag{2.3}$$

where $r_{t+1}^i = \frac{R_{t+1}^i}{P_{t+1}}$ is the real rental rate of capital in sector i in period $(t+1)$. An immediate implication of the two equations (2.3) is that the sector-specific rental rates must be equal in expectation, i.e. $E_t\{r_{t+1}^k\} = E_t\{r_{t+1}^z\} = E_t\{r_{t+1}\}$.

2.4.2 Entrepreneurs

Apart from households, there is a unit mass of risk neutral entrepreneurs, each one capable of running a specific project associated with the advanced production technology.[21] At the beginning of each period, a mass $(1 - \eta)$ of new-born entrepreneurs

[21]Apart from the fact that investments in the advanced project might represent investments in human capital, we do not consider limitations in that production factor. Yet, a straightforward

enters the economy without any initial wealth and replaces an equal measure of retiring entrepreneurs.[22] The remaining measure η of incumbent entrepreneurs stays active. An individual entrepreneur arrives in period t with an amount A_t^i of nominal wealth. Then, if she receives a random exit signal, she waits until the end of the period to simply consume her accumulated wealth such that $A_t^i = P_t c_t^{E,i}$. In contrast, new entrants and entrepreneurs who have not received the exit signal have no consumption motive; rather, each active entrepreneur inelastically supplies her (unit) labor endowment $h_t^E = h_t^{k,E} + h_t^{z,E} = 1$ and thus augments her nominal wealth A_t^i by her current wage earnings W_t^E. Hence, an individual entrepreneur's effective wealth position is $E_t^i = A_t^i + W_t^E$. This position E_t^i constitutes the entrepreneur's necessary private equity stake when she applies for funding of an advanced sector project with the financial intermediary.

2.4.3 Financial intermediary

The financial intermediary (equivalently, a perfectly competitive financial sector) receives the time t^- financial deposits $M_t - Q_t$ from the households as well as lump sum cash injections $\mathcal{J}_t$ from the monetary authority. These funds are supplied to the loan market at a gross nominal interest rate $\tilde{R}_t$. At the loan market, this supply meets the demand for nominal financial assets coming from the demand for liquidity D_t of firms operating the advanced technology. Hence, financial market clearing requires:

$$M_t - Q_t + \mathcal{J}_t = D_t \tag{2.4}$$

This condition simply stipulates that the equilibrium interest rate $\tilde{R}_t$ balances the supply of loans with the corporate demand for funds due to its need for liquidity. The financial intermediary operates after monetary policy is resolved and lends liquidity to

way to think about restrictions in the economy's endowment of human capital (in our model) is an endogenous mass of risk neutral entrepreneurs, which are capable of running the advanced project.

[22]Where necessary, variables pertaining to the entrepreneurial sector will be denoted with a superscript E.

the advanced sector firms. Yet, the provision of funds to advanced projects is complicated by an entrepreneurial moral hazard problem which is dealt with by a financial contract described in Section 2.4.5. Two key implication of that contracting scheme are that firm bankruptcy is an equilibrium phenomenon and that the intermediary must commit funds to individual advanced sector projects before these projects' respective liquidity needs are known. Therefore, it is important to recognize that the financial intermediary is able to pool idiosyncratic risks across the advanced sector firms. As a consequence, it is sufficient for the financial intermediary to break even on an individual credit relationship in expectation. At the end of the period, the intermediary receives the returns on its lending and financial investment activity and pays the amount $\tilde{R}_t[M_t - Q_t + \mathcal{J}_t]$ to the households in return for their deposits.

2.4.4 Firms

In our economy, production activities proceed in two different steps. First, investments in basic and advanced technologies results in two different types of intermediate goods (y_t^k, y_t^z). Second, the two types of intermediates are combined to produce the final market good (y_t) that is used for consumption purposes. In all three goods markets, firms face perfect competition.

Market good

The market good producers employ the following CES aggregation technology:

$$y_t = \left(\zeta^{\frac{1}{\rho}} {y_t^k}^{\frac{\rho-1}{\rho}} + (1-\zeta)^{\frac{1}{\rho}} {y_t^z}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}, \tag{2.5}$$

where the two parameters $0 < \zeta < 1$ and $\rho > 0$ determine the share of each intermediate good in producing the aggregate market good and the elasticity of substitution of the two factors.

Productive efficiency pins down the minimum cost combination of the final good firms' demands for intermediate input goods to be functions of the relative prices for the relevant intermediate input P_t^j, $j = k, z$ and for the final output P_t:

$$y_t^k = \zeta \left(\frac{P_t^k}{P_t} \right)^{-\rho} y_t \qquad \text{and} \qquad y_t^z = (1-\zeta) \left(\frac{P_t^z}{P_t} \right)^{-\rho} y_t \tag{2.6}$$

By perfect competition on the final goods market, the aggregate price level is determined by marginal costs, i.e. the intermediate good prices, which are constant from the final good firm's perspective. Consequently, zero profits imply:

$$P_t = \left(\zeta P_t^{k\,1-\rho} + (1-\zeta) P_t^{z\,1-\rho} \right)^{\frac{1}{1-\rho}} \tag{2.7}$$

Intermediate goods

There are two perfectly competitive sectors producing intermediate goods. Both sectors employ capital as well as labor as input goods, but are characterized by different technologies. On the one hand, there is a safe, but return-dominated (basic) technology; the other (advanced) technology yields a higher potential return, but is subject to idiosyncratic liquidity shocks. The scope for an individual advanced firm's insurance against this idiosyncratic liquidity risk is endogenously determined via the financial contract described in Section 2.4.5. The need for this insurance arises as a consequence of an entrepreneurial moral hazard problem which prevents the efficient refinancing of advanced projects and calls for the commitment of liquidity at an ex ante, rather than an ex post stage. A natural way to think about advanced technology projects are investments in R&D or the adoption of new (foreign) technologies. We assume, in accordance with the literature on endogenous growth, that investments in the advanced technology involve spill-overs to the future stock of knowledge ($\mathcal{T}_t$).[23] Consequently, aggregate productivity has two components: an exogenous and an endogenous one. The exogenous productivity parameters differ in both sectors, whereby the productivity of the advanced technology is strictly larger than the basic one by definition ($\mathcal{V} > \mathcal{A}$). We abstract from variations in the

[23] Compare Romer (1990) or Aghion and Howitt (1992). It does not matter in our framework if the spill-overs reflect actual investments in R&D or the scope of the advanced technology for accidental learning-by-doing.

exogenous productivity parameters over time since we focus on the growth-effect of short-run nominal fluctuations instead of technology-induced cycles. In addition to the exogenous components of productivity, there is an endogenous one. The endogenous component $\mathcal{T}_t$, which we call the level of knowledge, augments the productivity of both projects; the determination of $\mathcal{T}_t$ will be described later. Note that the advanced sector is characterized by perfect competition. Hence, investments in R&D take place not because of a monopolistic market structure, but due to the incentives for firms to optimize the composition of their investments. That is, the risk associated with R&D investments combined with the financial market incompleteness limit the capacity of R&D ex ante. Consequently, as opposed to the endogenous growth literature à la Romer (1990) or Aghion and Howitt (1992), the key feature of R&D is not the creation of monopoly rents, but its superior productivity combined with the risk associated to it.

Basic sector: Firms in the basic sector seek to maximize time t^+ profits by hiring labor and capital inputs $\{l_t^k, k_t\}$, whereby the vector of prices $\{P_t^k, W_t^k, R_t^k, \tilde{R}_t\}$ is taken as given. A Cobb-Douglas aggregator converts household and entrepreneurial labor inputs into their effective composite, and similarly agent-specific wages aggregate to a sectoral wage rate:

$$l_t^k = \frac{(h_t^{k,H})^{\Omega}(h_t^{k,E})^{(1-\Omega)}}{(\Omega)^{\Omega}(1-\Omega)^{(1-\Omega)}} \qquad \text{and} \qquad W_t^k = (W_t^{k,H})^{\Omega}(W_t^{k,E})^{(1-\Omega)}$$

The technology characterizing the basic intermediate sector is assumed to be homogenous of degree one. For simplicity, we employ the Cobb-Douglas form:

$$\varphi(k_t, l_t^k) = (k_t)^{\alpha}\left(l_t^k\right)^{1-\alpha}$$

Hence, the problem of a representative firm operating the basic technology is:

$$\max_{\{k_t, l_t^k\}} \Pi_t^k = P_t^k \left(\mathcal{T}_t \mathcal{A} \varphi(k_t, l_t^k) \right) - W_t^k l_t^k - R_t^k k_t$$
$$= P_t^k y_t^k - C(W_t^k, R_t^k; y_t^k) \tag{2.8}$$

By constant returns to scale, efficient factor employment implies that marginal costs are independent of the quantity produced, i.e. $C(W_t^k, R_t^k; y_t^k) = MC_t^k(W_t^k, R_t^k; 1) y_t^k$. Then, from the assumption of perfectly competitive intermediate goods markets, it follows that the price of the basic intermediate good equals marginal costs, i.e. $P_t^k = MC_t^k(W_t^k, R_t^k)$. Using the Cobb-Douglas specification of $\varphi(k_t, l_t^k)$, the optimal factor demands in the basic sector read:

$$k_t = \frac{\alpha P_t^k y_t^k}{R_t^k} \qquad \text{and} \qquad l_t^k = \frac{(1-\alpha) P_t^k y_t^k}{W_t^k} \tag{2.9}$$

Finally, the price for the basic intermediate good is:

$$P_t^k = \frac{1}{\mathcal{T}_t \mathcal{A}} \left(\frac{R_t^k}{\alpha} \right)^{\alpha} \left(\frac{W_t^k}{(1-\alpha)} \right)^{(1-\alpha)} \tag{2.10}$$

Advanced sector: The problem of firms operating the advanced technology is complicated by the risk that their production plan is hit by a liquidity shock[24] which may trigger the termination of productive projects before they yield any return. We assume that all advanced projects feature an ex post positive net present value if the entrepreneur has exerted effort. As in the basic sector, there is a Cobb-Douglas

[24]The liquidity shock admits a variety of interpretations. It can be thought of a simple cost overrun, as a shortfall of revenue at an interim stage which could have been used as an internal source of refinancing, as adverse information relating to the project's end-of-period profitability, an extra cost to familiarize the workers with the new technologies, or as an extra costs necessary for the new technology to be adapted to domestic market conditions once the new technology has been adopted. Hence, we stress that our notion of liquidity shock is consistent with what Opler et al. (1999) empirically summarize under the heading of operating losses.

aggregation of the respective labor inputs by households and entrepreneurs, and the technology in the advanced sector is also given by a Cobb-Douglas production function under constant returns to scale:

$$\phi(z_t, l_t^z) = (z_t)^{\alpha} (l_t^z)^{1-\alpha}$$

Each advanced firm is run by an individual entrepreneur who brings the amount E_t^i as private equity into the firm. The firm's production plan and its hedge against liquidity shocks ξ_t^i, which are distributed according to a continuous distribution function $G(\xi_t^i)$ with associated (strictly positive) density $g(\xi_t^i)$, are then determined as part of a constrained-efficient contract between the entrepreneur and the financial intermediary. In particular, the liquidity provision stipulated by the financial contract will be seen to pin down a threshold value $\hat{\xi}_t^*$ up to which liquidity shocks are covered; this threshold, in turn, determines an individual advanced firm's ex ante survival probability $G(\hat{\xi}_t^*)$. Since the financial contract, derived in Section 2.4.5, turns out to be linear in E_t^i, the distribution of equity across entrepreneurs does not matter and exact aggregation is possible.[25] Hence, we anticipate results and note in analogy to the basic sector that the price level for the intermediate goods produced in the advanced sector is:

$$P_t^z = \frac{1}{\tilde{R}_t \int_0^{\hat{\xi}_t^*} G(\xi_t) d\xi_t} \frac{1}{\mathcal{T}_t \mathcal{V}} \left(\frac{R_t^z}{\alpha} \right)^{\alpha} \left(\frac{W_t^z}{(1-\alpha)} \right)^{(1-\alpha)} \tag{2.11}$$

The details of the financial contract are described in the next section.

2.4.5 Financial contracting

Following Holmstrom and Tirole (1998), we now turn to a detailed analysis of the contracting problem which is specific to the advanced technology. In principle, all investment projects might face constraint financing opportunities. In this respect,

[25]From now on, we will therefore drop the superscript i.

the exact identifying assumption in our model is that the riskiness of an investment project is, on average, increasing in its productivity. However, we separate the technology choices into two classes according to their productiveness whereas the riskiness of less productive projects is normalized to zero to simplify the analysis of our model. The sequencing of events underlying an individual advanced firm's within-period contracting problem can be decomposed into three stages.[26]

At *stage one*, after information about monetary policy ($\mathcal{J}_t$) is unveiled, each advanced firm, run by an entrepreneur holding an equity position E_t in the firm, contracts with the financial intermediary to pin down its production plan and refinancing provisions.[27] In particular, the refinancing provisions determine the degree of insurance against idiosyncratic liquidity risk.[28] Thereafter, a contract between the financial intermediary (outside investor) and the entrepreneur (firm) holding equity E_t prescribes (i) the scale of production as determined by factor employment z_t, l_t^z, (ii) a state contingent continuation rule $\Gamma_t(\xi_t)$, and (iii) a state contingent transfer $\tau_t(\xi_t)$ from the firm to the investor. Hence, a generic contract takes the form $\mathcal{C}_t = \{z_t, l_t^z, \Gamma_t(\xi_t), \tau_t(\xi_t)\}$. A constraint on the contract is that it is written under limited liability, i.e. in case of project termination factors must be remunerated by the outside investor. At a subsequent interim stage (*stage two*) after the factor employment decisions have been made, the firm is hit by an idiosyncratic liquidity shock ξ_t. If the shock is met by appropriate refinancing to be provided by the intermedi-

[26]Although the firm's production plan is conditional on the predetermined entrepreneurial equity position E_t, the firm problem itself is not dynamic because entrepreneurial asset accumulation proceeds mechanically and there is no inter-temporal incentive provision.

[27]We assume that entrepreneurial self-financing is not possible; a sufficient condition for this to be the case is derived in Appendix B.

[28]It is important to realize that the financial contract is negotiated after fresh cash $\mathcal{J}_t$ has been injected into the economy. Consequently, the results of monetary policy that we will develop in the sequel do not stem from an implicit nominal rigidity. On the contrary, our concept of corporate liquidity is entirely real; what is affected by nominal fluctuations, however, is the price of such liquidity.

ary, the firm can continue; otherwise the firm is liquidated.[29] After the continuation decision, there is scope for moral hazard on the part of the entrepreneur in that she can exert effort to affect the distribution of production outcomes. Specifically, we define that, conditional on continuation, exerting effort guarantees a gross return of $P_t^z \mathcal{T}_t \mathcal{V} f(z_t, l_t^z) = P_t^z \tilde{y}_t^z$ to production activity, while shirking leads to zero output, but generates a private (non-monetary) benefit B_t. We assume that the private benefit is proportional to firm revenue conditional on survival; in particular, we have: $B_t = bP_t^z \mathcal{T}_t \mathcal{V} f(z_t, l_t^z) = bP_t^z \tilde{y}_t^z$ with $0 < b < 1$.[30] Finally, at *stage three*, the revenue from production accrues and payoffs are realized according to the rules stipulated in the financial contract. The financial intermediary engages in a continuum of contracts with advanced sector firms; hence, since liquidity risk is idiosyncratic, the intermediary is able to pool the risk inherent in the investments across individual firms' projects. As an implication, we can completely abstract from the effects of idiosyncratic uncertainty on the investor's evaluation of payoffs. Similarly, the entrepreneur who is exposed to her uninsured private equity risk is risk neutral and cares only about expected profits as long as she is active.

Hypothetically abstracting from both the entrepreneurial incentive constraint and the cost of obtaining liquidity at the interim stage, it is easy to see that there exists a unique cutoff value of one corresponding to a continuation policy which prescribes project continuation if and only if the liquidity shock is such that $\xi \leq 1$. The reason is that the stage one investment is sunk; hence, at the interim stage, it is optimal to refinance up to the full value of what can be generated in terms of revenue at the final stage. However, the need to take into account the incentive constraint and the costs of liquidity provision implies that the constrained-efficient continuation policy will take the form:

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[29]We assume that the liquidity shock is verifiable, but it is shown in Holmstrom and Tirole (1998) that nothing changes if only the firm observes the shock as long as the firm does not benefit from diverting resources.

[30]Note, however, that the specific value of $b > 0$ will not matter as long as the contract to be derived below delivers an interior solution.

$$\Gamma_t(\xi_t) = \begin{cases} 1, & \text{if } \xi_t \leq \hat{\xi}_t \\ 0, & \text{if } \xi_t > \hat{\xi}_t \end{cases}$$

for some cutoff value $\hat{\xi}_t < 1$. Hence, $\Gamma_t(\xi_t)$ is a simple indicator function with $\Gamma_t(\xi_t) = 1$ in case of continuation and $\Gamma_t(\xi_t) = 0$ in case of termination.

A constrained-efficient contract $\mathcal{C}_t = \{z_t, l_t^z, \Gamma_t(\xi_t), \tau_t(\xi_t)\}$ with (z_t, l_t^z) determining the scale of production, and $\Gamma_t(\xi_t)$ and $\tau_t(\xi_t)$ pinning down the state contingent policies for project continuation and transfers per unit of production costs $C\left(W_t^z, R_t^z; \tilde{y}_t^z\right)$, respectively, then solves the following second best program of maximizing the entrepreneur's net return:

$$\max_{\mathcal{C}_t} \int \left\{\Gamma_t(\xi_t) P_t^z \tilde{y}_t^z - \tau_t(\xi_t) C\left(W_t^z, R_t^z; \tilde{y}_t^z\right)\right\} dG(\xi_t) - E_t \tag{2.12a}$$

subject to a participation constraint for the investor that requires him to break even in expectation:

$$\int \left\{\tau_t(\xi_t) C\left(W_t^z, R_t^z; \tilde{y}_t^z\right) - \Gamma_t(\xi_t) \xi_t \tilde{R}_t P_t^z \tilde{y}_t^z\right\} dG(\xi_t) \geq C\left(W_t^z, R_t^z; \tilde{y}_t^z\right) - E_t \tag{2.12b}$$

and a state-by-state incentive compatibility constraint for the entrepreneur:

$$\Gamma_t(\xi_t) P_t^z \tilde{y}_t^z - \tau_t(\xi_t) C\left(W_t^z, R_t^z; \tilde{y}_t^z\right) \geq \Gamma_t(\xi_t) b P_t^z \tilde{y}_t^z \qquad \forall\, \xi_t, \tag{2.12c}$$

where:

$$\tilde{y}_t^z = \mathcal{T}_t \mathcal{V} \left(z_t\right)^{\alpha} \left(l_t^z\right)^{1-\alpha}$$

is firm-level output conditional on survival and:

$$C\left(W_t^z, R_t^z; \tilde{y}_t^z\right) = W_t^z l_t^z + R_t^z z_t$$

are the associated total costs which accrue when a output level of $\tilde{y}_t^z$ is targeted in case of survival.

Note how the specification of this problem, by means of the participation constraint (2.12b), incorporates the requirement that the investor who bears the risk of project failure be willing to finance the firm, whereby the outside investor commits both the factor remuneration and the interim resources needed to meet the liquidity shock. The cost of providing liquidity at the interim stage, which has to be obtained in the financial market at the financial rate $\tilde{R}_t$, will be key in shaping the solution to problem (2.12).

The algebraic solution to the optimal contract defined in (2.12) is provided in Appendix B. Intuitively, the constraint optimal contract implies that the firm is the residual claimer of the return of investment given that the outside investor breaks even in expectations. Thus, the firm wants to maximize the initial scale of investment. If we define $\hat{\xi}_t^0 = \frac{1-b}{\tilde{R}_t}$ as the cutoff value that maximizes the expected marginal return to outside investors, it follows that the optimal cutoff value, which defines the equilibrium provision of liquidity at the interim stage, must be in the interval $\hat{\xi}_t^* \in [\hat{\xi}_t^0, \hat{\xi}_t^{FB}]$. That is, if $\xi_t < \hat{\xi}_t^0$, then both parties prefer to continue ex post because both parties can realize gains on the investment in the sunk stage one; if $\xi_t > \hat{\xi}_t^{FB}$, then both parties prefer to abandon the project because the net social marginal return of continuing is negative. Within the interval $[\hat{\xi}_t^0, \hat{\xi}_t^{FB}]$, there emerges a trade-off: On the one hand, increasing $\hat{\xi}_t$ implies that continuation is possible in more contingencies, and thus the marginal net social return $\lambda_t(\hat{\xi}_t)$ on each unit of initial investment is increased. On the other hand, decreasing $\hat{\xi}_t$ allows to increase the amount of initial investment $MC_t^z(\cdot)\tilde{y}_t^z$.

The solution of the constraint efficient contract results in an the optimal continuation value $\hat{\xi}_t^*$ that satisfies the optimality condition:

$$\int_0^{\hat{\xi}_t^*} G(\xi_t) d\xi_t = \frac{MC_t^z(\cdot)}{P_t^z} \frac{1}{\tilde{R}_t} \tag{2.13}$$

This condition reflects that the maximum equilibrium provision of liquidity must coincide with the adjusted markup on advanced sector output prices, whereas the adjustment represents the cost of providing liquidity which is given by the nominal interest rate ($\tilde{R}_t$).

Hence, second best contracting is indeed consistent with liquidity holdings at the firm-level, whereby the nominal interest rate $\tilde{R}_t$ reflects the shadow price for such scarce liquidity. Moreover, we can derive a measures of aggregate liquidity demand under financial intermediation by aggregating over the advanced sector firms:

$$D_t^* = \left[\int_0^{\hat{\xi}_t^*} \xi_t g(\xi_t) d\xi_t \right] P_t^z \tilde{y}_t^z < \bar{D}_t \tag{2.14}$$

Thus, the second best liquidity demand under financial intermediation, which efficiently economizes on the use of scarce liquidity by pooling liquidity risk across firms, falls below the demand that results from a policy which disregards the scope for risk sharing across firms.

2.4.6 Empirical implications

As an immediate consequence of optimal financial contracting as derived in Section 2.4.5 and B.1, we put on record the following empirical implications of optimal financial contracting as governed by equation (2.13), which will be subject of our later empirical analysis of industry and firm-level panel data.

- $\mathcal{H}1$: *Ceteris paribus*[31], an increase in $\tilde{R}_t$ leads to a lower cutoff $\hat{\xi}_t^*$:

$$\frac{d\hat{\xi}_t^*}{d\tilde{R}_t} = -\frac{\int_0^{\hat{\xi}_t^*} G(\xi_t) d\xi_t}{\tilde{R}_t G(\hat{\xi}_t^*)} < 0, \tag{2.15}$$

[31] The claimed result obtains if, to a first approximation, $\frac{MC_t^z(\cdot)}{P_t^z}$ remains constant. That is, the results derived in the following are valid from a partial equilibrium perspective; taking into account general equilibrium effects does not change the qualitative (sign) properties of the relevant derivatives. However, to obtain a closed-form solution, we have to determine a functional form of $G(\xi)$. It is shown in Appendix B that the general equilibrium effect is negative if $G' > 0$.

which follows from total differentiation of condition (2.13).

Thus, quite intuitively, higher nominal interest rates $\tilde{R}_t$ lead to smaller hedging against idiosyncratic liquidity shocks because the intermediary's participation constraint gets tighter in line with the increased costs of providing liquidity. In order to examine the effects of other changes in the economic environment on firms' liquidity demand, we establish two auxiliary results.

First, increased volatility of the liquidity shock distribution $G(\cdot)$ in the sense of a mean-preserving spread implies a lower cutoff value $\hat{\xi}_t^*$; formally $\frac{d\hat{\xi}_t^*}{d\sigma_\xi} < 0$.[32] The intuition behind this result is that increased risk makes the option to terminate the project more valuable. The empirical prediction therefore is that firms operating in a more volatile environment are insured to a smaller degree.

- $\mathcal{H}2$: Increased production risk (in the form of a mean-preserving spread of the distribution $G(\cdot)$) accentuates the negative effect of $\tilde{R}_t$ on the cutoff $\hat{\xi}_t^*$:

$$\frac{d}{d\sigma_\xi}\left(\frac{d\hat{\xi}_t^*}{d\tilde{R}_t}\right) = \frac{d\hat{\xi}_t^*}{d\sigma_\xi}\frac{d}{d\hat{\xi}_t^*}\left(\frac{d\hat{\xi}_t^*}{d\tilde{R}_t}\right) < 0, \tag{2.16}$$

where the inequality follows from the fact that $\hat{\xi}_t^*$ is decreasing in the volatility of the shock distribution and differentiation of expression (2.15) with respect to $\hat{\xi}_t^*$.

Second, situations where production by means of the advanced technology is more profitable, i.e. situations characterized by lower ratios $\frac{MC_t^z(\cdot)}{P_t^z}$, are predicted to feature a lower $\hat{\xi}_t^*$; formally $\frac{d\hat{\xi}_t^*}{d(MC_t^z/P_t^z)} > 0$.[33] The reason for the poorer insurance of more profitable projects is the contracting trade-off underlying the choice of $\hat{\xi}_t^*$: While a more generous provision with liquidity has the advantage of withstanding larger

[32] Variations in the standard deviation σ_ξ need to be restricted to mean-preserving spreads, the result then obtains by partial integration; compare Mas-Colell, Whinston and Green (1995), chapter 6.

[33] This follows from total differentiation of condition (2.13), for given $\tilde{R}_t$.

shocks, it necessarily implies a lower stage one investment volume. Thus, for highly profitable projects, both contracting parties prefer to cut $\hat{\xi}_t^*$ in order to expand the project size. Based on these results, we can derive two additional hypotheses relating to the sensitivity of specific firms (or industries) to fluctuations in the nominal interest rate.

- $\mathcal{H}3$: Increased profitability accentuates the negative effect of $\tilde{R}_t$ on the cutoff $\hat{\xi}_t^*$:

$$\frac{d}{d(MC_t^z/P_t^z)}\left(\frac{d\hat{\xi}_t^*}{d\tilde{R}_t}\right) = \frac{d\hat{\xi}_t^*}{d(MC_t^z/P_t^z)}\frac{d}{d\hat{\xi}_t^*}\left(\frac{d\hat{\xi}_t^*}{d\tilde{R}_t}\right) > 0, \tag{2.17}$$

where the inequality follows from the fact that $\hat{\xi}_t^*$ is increasing in the marginal-cost-to-price ratio and differentiation of expression (2.15) with respect to $\hat{\xi}_t^*$.

2.4.7 Endogenous technical change

In this section, we describe the endogenous part of the productivity processes - the dynamics of $\mathcal{T}_t$. As mentioned above, we assume that the advanced projects (y_t^z) generate spill-overs on the future stock of knowledge since they embody investments in R&D, skills or the adoption of new technologies. Thus, the stock of knowledge/technologies is characterized by the difference equation:

$$\begin{aligned} \mathcal{T}_{t+1} &= \mathcal{T}_t\left(1+\epsilon\int_0^1 y_{t,i}^z di\right) \\ &= \mathcal{T}_t\left(1+\epsilon\int_0^1 G(\hat{\xi}_t^*)\tilde{y}_{t,i}^z di\right) \end{aligned} \tag{2.18a}$$

where $0 < \epsilon \leq 1$ represents the fraction of investments in the advanced technology that involve knowledge spill-overs.

The law of motion specifies that productivity growth is increasing in productivity-enhancing investments, whereby we suppose that only successful advanced investment projects create productivity spill-overs proportional to the contemporaneous stock of knowledge.[34] Note that the specification in (2.18a) is essentially the same as the corresponding ones in the endogenous growth literature: the rate of technical change is governed by investments in R&D, which, in our model, are part of the investments in the advanced sector.[35] In particular, we suppose that investments in R&D consist of expenses for research labor and capital (e.g. research lab) which are combined in a Cobb-Douglas fashion. Hence, given $\mathcal{V}$, $\mathcal{A}$ and an initial level $\mathcal{T}_0$, the current realization of the TFP-level depends on all successful past realizations of advanced investment projects. Consequently, it depends on past realizations of inflation if financial markets are incomplete.

Note that an increase in the stock of knowledge/technology ($\mathcal{T}$) enhances the productivity in both sectors since we suppose that the new technology is not *skill biased* - it can be adopted for both types of projects.

2.4.8 Government policy

In order to close the model, a specification for government policy is needed. We suppose that government policy is governed by an exogenous process which consists of periodic injections $\mathcal{J}_t$ of money in the financial market. $\mathcal{J}_t$ is implicitly defined as $\mathcal{J}_t = (e^{mg_t} - 1)(M_t + A_t)$, where mg_t is the gross rate of money growth. Hence, the aggregate of nominal wealth held by households and entrepreneurs is updated according to:

$$(M_{t+1} + A_{t+1}) = e^{mg_t}(M_t + A_t).$$

[34]Note that terminated advanced projects are liquidated before the entrepreneur exerts any effort (moral hazard). Thus, it is assumed that these *failed* projects do not cause any knowledge externality.

[35]Compare, e.g., Romer (1990) or Aghion and Howitt (1992).

2.5 Long-run balanced growth path

In this section, we demonstrate that the equilibrium growth rate along the long-run balanced growth path is negatively related to the inflation rate. The important result of the analysis shows that this is due to a compositional effect between investment into the basic sector and investment into the advanced project.

Our setup allows to define a set of aggregate relations characterizing a competitive equilibrium in each period. The definition of a competitive equilibrium in our economy and the corresponding equilibrium relations are reported in Appendix B. Moreover, (2.18a) concatenates a sequence of competitive equilibria. The long-run dynamics of the model are fully governed by the law of motion of the endogenous stock of technologies in (2.18a) because technological progress is the only source of endogenous growth in this model:

$$\gamma = \epsilon \int_0^1 G(\hat{\xi}^*)\tilde{y}_i^z di = \epsilon y^z, \tag{2.20}$$

where $y^z = \widetilde{y}^z G(\hat{\xi}^*)$ is the aggregate level of (realized) output in the advanced sector.[36] As a consequence, we need to solve for the impact of the variables in our model on the scale of successful advanced investment projects in order to analyze the determinants of the long-run balanced growth path. The analysis of the impact of inflation on the growth rate is carried out in three steps: First, we show that a drop in the cutoff value for the optimal liquidity provision $\hat{\xi}^*$ leads to a compositional change of aggregate output towards the good produced in the basic sector. Second, as already emphasized by hypothesis ($\mathcal{H}1$), an increase in the nominal interest rate reduces the optimal cutoff value and hence the insurance provided against idiosyncratic liquidity risk in the advanced sector. Moreover, because the real rental rate of capital is increasing in the nominal interest rate, the aggregate output level in the advanced sector is strictly falling in the nominal interest rate. Third, it is shown that

[36] In the discussion of the balanced growth path, we leave out time subscripts for notational convenience.

the equilibrium level of the nominal interest rate itself is increasing in the inflation rate.

Along the balanced growth path, the rental rates of capital and the wages in both sectors must be equal. Consequently, since both the basic technology and the advance technology employ the identical composition of capital and labor as input factors, the associated total costs in the advanced sector, which accrue when an output level of $\widetilde{y}^z$ is targeted in case of survival, amount to $V \cdot \widetilde{MC}^z = A \cdot MC^k$. Making use of the optimal input factor demands and noting that $MC^k = P^k$ in the basic sector, we obtain:

$$\frac{y^z}{y^k} = \frac{V}{A} G(\hat{\xi}^*) \tag{2.21}$$

In other words, the markup of prices over marginal costs in the advanced sector is zero due to perfect competition if we abstract from the liquidation risk in the advanced sector. Hence, the productivity adjusted marginal costs in both sectors are equal in this case. If we differentiate (2.21) with respect to the cutoff-value ($\hat{\xi}^*$), we obtain the responsiveness of the intermediate output ratio with respect to changes in the insurance of corporate liquidity shocks in the advanced sector:

$$\frac{d\left(\frac{y^z}{y^k}\right)}{d\hat{\xi}^*} = \frac{V}{A} g(\hat{\xi}^*) > 0 \tag{2.22}$$

Hence, the equilibrium ratio of investments in the advanced sector relative to the basic sector is increasing in corporate liquidity holdings ($\hat{\xi}^*$). Intuitively, lower corporate liquidity holdings induce, on average, relatively more failure of advanced investment projects. In addition, this also leads to a reduction of investment into the advanced technology as the advanced projects loose attractiveness in terms of expected revenues as compared to the basic technology. Moreover, it follows from $\mathcal{H}1$ that this ratio is decreasing in the nominal interest rate $\tilde{R}$. That is, less liquidity is devoted to the insurance of the advanced projects since the costs of liquidity holdings increase.

Finally, we know that the aggregated output level (y) is decreasing in the financial rate ($\tilde{R}$) since on the one hand the real rental rate of capital increases in the financial rate $\tilde{R}$ and on the other hand labor is constant.[37] Because the nominal interest rate $\tilde{R}$ reduces both, the ratio ($\frac{y^z}{y^k}$) and the aggregate output level, it immediately follows that it reduces production in the advanced sector, i.e.:

$$\frac{dy^z}{d\tilde{R}} < 0 \tag{2.23}$$

Therefore, taken together with (2.20), we infer that the equilibrium balanced growth rate is strictly increasing in the provision of liquidity according to the financial contract. An increase in the amount of corporate liquidity holdings enhances economic growth ($\frac{d\gamma}{d\hat{\xi}^*} > 0$). It follows from ($\mathcal{H}1$) that the long-run balanced growth rate is decreasing in the nominal interest rate ($\tilde{R}$). In fact, each equilibrium level of the nominal interest rate implies a different long-run balanced growth rate: $\gamma = \gamma(\tilde{R})$. Importantly, this link between a nominal variable and TFP-growth in the case of incomplete financial markets is due to firm-level heterogeneity of investment projects. The highlighted tradeoff between risk and productivity in our framework yields an investment composition effects that results lower aggregate growth rates for higher levels of the nominal interest rate as emphasized in the following implication:

- $\mathcal{I}1$: An increase in $\tilde{R}$ leads to a lower long-run balanced growth rate γ by reducing the liquidity holdings of firms in equilibrium:

$$\frac{d\gamma}{d\tilde{R}} = \epsilon \frac{dy^z}{d\tilde{R}} < 0 \tag{2.24}$$

Moreover, (2.2) implies a type of Fisher equation in equilibrium between the nominal interest rate and the level of inflation. In particular, we can re-write (2.2) as follows if the economy is in a balanced growth equilibrium:

[37] This can be easily demonstrated by making use of the two inter-temporal Euler equations for nominal wealth (2.2) and physical capital accumulation (2.3).

$$\tilde{R} = \pi\phi(\gamma) \tag{2.25}$$

In (2.25), $\pi = \frac{P'}{P}$ where P' denotes the price level in the next period. The deterministic function $\phi(\gamma) = \frac{u_c(c^H)}{\beta u_c(c'^H)}$ depicts the marginal rate of substitution along the long-run balanced growth path. For a standard (strictly concave) utility function $u(c^H)$, $\phi_\gamma > 0$. Total differentiation of condition (2.25) yields:

$$\frac{d\tilde{R}}{d\pi} = \frac{\phi}{1 - \epsilon\phi_\gamma \frac{dy^z}{d\tilde{R}}} > 0, \tag{2.26}$$

which is strictly positive by $\mathcal{I}1$. It follows that higher rates of inflation induce a higher nominal interest rate if the economy is in a long-run balanced growth equilibrium. Consequently, economies that feature a higher level of (trend) inflation suffer from reduced long-run productivity growth. Similarly, periods of high inflation within a country reduce productivity growth while low-inflation periods cause a transition to a higher balanced growth path.

- $\mathcal{I}2$: An increase in the inflation rate π leads to a lower long-run balanced growth rate γ:

$$\frac{d\gamma}{d\tilde{\pi}} = \epsilon\frac{dy^z}{d\tilde{R}}\frac{d\tilde{R}}{d\pi} < 0 \tag{2.27}$$

Note that (2.20) implies that there exists a single long-run balanced growth rate in the (first-best) case of complete financial markets ($b = 0$). In this case, the ex ante pledgeable unit return complies with the ex post pledgeable unit return ($\hat{\xi}_t^{FB} = \hat{\xi}_t^*$), so that all investments projects in the advanced sector are re-financed: $\int_o^{\hat{\xi}_t^*} G(\xi)d\xi = 1$. Not surprisingly, it follows that the long-run balanced growth rate in a complete financial market economy dominates the growth rate in an economy that is characterized by incomplete markets. Yet, the empirical firm-level evidence from Opler et al. (1999) suggests that firms require liquidity holdings in order to invest in productive and risky projects even in the U.S. economy.

2.6 Empirical analysis

In this section, we employ disaggregate U.S. data to examine the specific microeconomic mechanism underlying our model. We do so in two steps, first exploiting industry-level data and then firm-level data.

2.6.1 Sectoral level

Data and methodology: Our model provides a set of firm-level predictions ($\mathcal{H}1$ - $\mathcal{H}3$). It is straightforward to extend our one-sector model to a multi-sector setup, whereby each individual industrial sector is a replica of the representative production structure described in Section 4. The economy-wide TFP measure $\mathcal{T}$ can then be interpreted as industry-specific productivity measures, and the contracting implications $\mathcal{H}1$ - $\mathcal{H}3$ do apply not only for individual firms, but also for industrial sectors. Hence, we can empirically test our hypotheses by means of industry-level data. As an implication of $\mathcal{H}2$, we hypothesize that the response in terms of the cutoff $\hat{\xi}^*$ to movements in the nominal interest rate is stronger for firms operating in more volatile industries. A positive correlation between the rate of inflation and nominal interest rates in equilibrium (compare equation 2.26) and the fact that a lower $\hat{\xi}^*$ ceteris paribus leads to lower TFP-growth (compare equation (2.23)) then together imply that the negative relation between TFP-growth and inflation is expected to be stronger in more volatile sectors. In addition, we presume that firms operating in more productive sectors in terms of their historically realized TFP-growth have had access and are more exposed to superior investment opportunities. For given $\tilde{R}$, inspection of equation (B.2) reveals a link between the technology $\mathcal{V}$ available to a firm and its profitability $\frac{P^z}{MC^z}$ in case of survival; the intuitive implication is that high productivity growth goes along with high potential profitability. Hence, from $\mathcal{H}3$, profitable firms operating in industries with high realized productivity growth are expected to react more sensitively to higher inflation.

We apply 3-digit industry-level data for the U.S. to investigate these hypotheses. The productivity of U.S. industrial sectors is measured by the yearly growth rate of real value added per industry from the UNIDO (2002) industrial statistics database. The yearly data are available for 28 industries from 1963-2000.[38] The classification of 3-digit U.S. industries with respect to average volatility (standard deviation) and average growth of productivity in our sample are reported in *Table* 2.2. The correlation coefficient between these two rankings is positive 0.23 (s.e.=0.03) and significantly different from zero at a 1% level according to Spearman's rank correlation test. Hence, an independence of both rankings is rejected confirming that more volatile sectors are characterized by higher average productivity growth.[39] Therefore, identifying (i) volatile and (ii) strongly growing sectors with industries that are highly exposed to the advanced technology, we divide the sample according to the median, the first and the fourth quartile of both measures. According to our theoretical model, the differential impact of inflation on TFP-growth across the relevant sub-samples should result from the different sensitivity of corporate liquidity holdings in response to higher inflation and is expected to be more pronounced in the 14 (7) industries whose volatility/average productivity growth is above the median (in the first quartile).

We control for industry specific fixed effects in all estimations. Since the first lag of the growth rate (or level) of value added is not significant at conventional levels in any specification, we employ a static panel estimation. That is, we estimate the following model:

$$y_{i,t} = \alpha + \beta_1 \Pi_{t-1} + \beta_2 (\Pi_{t-1} * DV_i) + \beta_3 X_t + \eta_i + \epsilon_{i,t}, \qquad i = 1, 2, ..., N, t = 1, 2, ..., T \tag{2.28}$$

where $y_{i,t}$ is the growth rate of real value added per industry, Π_{t-1} the first lag of inflation, DV_i a dummy which amounts to one for industries with an above median (first quartile) volatility/mean, X_t a vector of aggregate control variables, $N = 28$

[38]We deflate the value added series in each sector with the economy-wide GDP-deflator.

[39]Among the ten most volatile sectors, we find industries such as professional & scientific equipment, petroleum refineries, plastic products, industrial chemicals, iron and steel or non-ferrous metals. In contrast, the four least volatile sectors are food products, other chemicals, beverages and printing and publishing.

the number of cross-sections, $T = 38$ the number of time-periods, η_i industry specific fixed effects, ϵ the error term, and α and β parameters to be estimated.[40]

We cluster the error terms at the industry level so that the standard errors are robust to within group (serial) correlation.[41] Inflation is measured by the first difference of the natural logarithm of the economy-wide consumer price index. We include the first lag of inflation ($L.infl$) due to the potential endogeneity of contemporaneous measures. Apart, we include the contemporaneous level and the first lag of the growth rate of GDP ($GDP - growth$), the private investment share ($inv - share$) and the amount of overall credit ($credit$) as control variables. The latter variable is often used as a proxy for the degree of financial market development in the literature.

Results: The first column in 2.3 reports the correlation between the first lag of inflation and the growth rate of real value added for the full sample. We find that an 1% increase in the economy-wide rate of inflation triggers, on average, a drop in the sectoral growth rate of real value added by .96% after controlling for changes in (lagged) GDP-growth, the private investment share and the overall supply of credits. The next two columns, contrast the sensitivity of value added growth with respect to inflation in high and low volatility sectors (above/below median). In accordance with $\mathcal{H}2$, we detect that the negative impact of inflation is significant in both sub-samples, but on average 40% higher in the 14 highly volatile sectors. In order to test for a statistical significance of the difference between both coefficient, we interact the lag of inflation with a dummy variable which amounts to one for high volatility industries (according to the median) and zero otherwise. Column four reveals that the interaction is negative and significant on a 10% level. That is, the distorting impact of an 1% increase in inflation aggravates, on average, by .32% if we focus on high volatility as opposed to low volatility sectors. This effect is even more pronounced if we compare the sensitivity in the seven most volatile sectors with the

[40]We also included a linear time trend, but it is not significant at conventional levels.

[41]Consequently, our results are not subject to the caveat raised by Moulton (1990).

Table 2.2: USA: Sectoral volatility and mean of growth in value added per worker

Industries	volatility	ranking	average growth	ranking
Petroleum refineries	22.41135418	1	8.718858009	4
Non-ferrous metals	14.82056985	2	6.70920077	14
Iron and Steel	13.20761732	3	4.28101271	26
Wood products, except furniture	12.33161156	4	7.080945619	13
Professional & scientific equipment	11.82739193	5	9.520253349	3
Leather products	10.80728372	6	3.355740195	28
Industrial chemicals	9.80919931	7	6.565964224	17
Tobacco	9.466520079	8	9.765847611	2
Plastic products	9.047342577	9	11.40471846	1
Misc. Petroleum and coal products	8.966026705	10	7.523389904	8
Transport equipment	8.93003486	11	6.708187212	15
Pottery, china, earthenware	8.753001453	12	6.344808742	18
Machinery, except electrical	8.447901686	13	7.217618028	11
Footwear, except rubber or plastic	7.94506906	14	0.592402327	29
Machinery, electric	7.771043776	15	7.865959786	6
Furniture, except metal	7.139279992	16	7.311662001	10
Paper and products	7.022639071	17	7.458034007	9
Other non-metallic mineral products	6.880040345	18	5.97226836	23
Textiles	6.602291836	19	5.229363677	25
Rubber products	6.212744352	20	5.399295643	24
Other manufacturing products	5.895932472	21	6.204043301	20
Glass and products	5.803579219	22	6.009918041	22
Wearing apparel, except footwear	5.515015898	23	3.865111854	27
Fabricated metal products	5.513984278	24	6.108224644	21
Total manufacturing	5.035217269	25	7.183158099	12
Printing and publishing	4.634205085	26	8.18032749	5
Beverages	4.122690753	27	6.238331092	19
Other chemicals	3.660652642	28	7.535671621	7
Food products	2.840748937	29	6.661717672	16

one in the residual 21 sectors. In particular, the sensitivity of value added growth per industry with respect to inflation is, on average, 76% higher in the seven most volatile sectors (.62/.81). The difference is significant on a 5% level. Thus, we are able to link the inflation-sensitivity of sectoral TFP-growth to the average sectoral volatility of productivity growth per industry. This systematic variation in the data is consistent with the prediction of our model summarized in $\mathcal{H}2$. Columns six to seven of 2.3 classify the impact of inflation on productivity growth according to the median and first quartile of the observed average productivity growth of a given industry in the sample. In accordance with $\mathcal{H}3$, column six reports that the negative impact of inflation is more pronounced in industries whose average productivity growth is above the sample median. Yet, the difference is not significant at conventional levels. Moreover, the coefficient not significant and even positive if we focus on the seven sectors that experienced the highest average productivity increase in the sample.

Overall, the results emerging from the analysis of industry-level corroborate our theoretical predictions that the negative effect of inflation on TFP-growth varies systematically with the riskiness as measured by the sectoral volatility of value added growth ($\mathcal{H}2$) of investment portfolios across sectors. In particular, we interpret these findings as supportive for our theoretical model's distinction between the basic technology, which is normalized to be free of liquidity risk, and the advanced technology, where idiosyncratic liquidity shocks give rise to a corporate demand for (partial) insurance against such risk. In the next subsection, we will revisit the specific implications arising from this setup on the basis of firm-level data.

2.6.2 Firm-level

Data and methodology: Microeconomic data on firm-level behavior allow for a straightforward test of our specific theoretical mechanism. That is, our model predicts that corporate liquidity holdings are associated with investments in superior technologies. Moreover, firms react to an increase in inflation (the nominal interest rate) by reducing their liquidity holdings and by shifting their portfolio towards more

Table 2.3: Inflation-sensitivity in volatile/high-growth vs. non-volatile/low-growth sectors

	Growth rate of value added						
	full sample	vol>med	vol<1.qua	full sample	full sample	full sample	full sample
inflation	-.9632***	-1.19**	-.7390***	-.8014***	-.8107***	-.8700***	-1.02***
	(-4.20)	(-2.69)	(-5.83)	(-3.84)	(-3.73)	(-3.51)	(-4.25)
infl∗dvol				-.3235*	-.6167**		
				(-1.65)	(-2.58)		
infl∗dmean						-.1981	.2379
						(-.97)	(1.14)
GDP-growth	1.20***	1.29**	1.10***	1.19***	1.19***	1.20***	1.19***
	(4.36)	(2.67)	(3.92)	(4.36)	(4.34)	(4.36)	(4.35)
L.GDP-growth	-.7851***	-.8938*	-.6764***	-.7851***	-.7869***	-.7839***	-.7858***
	(-2.92)	(-1.71)	(-4.11)	(-2.92)	(-2.93)	(-2.92)	(-2.92)
credit	-11.46***	-15.01**	-7.91***	-11.46***	-11.52***	-11.42***	-11.49***
	(-3.26)	(-2.23)	(3.86)	(-3.26)	(3.27)	(3.52)	(-3.27)
inv-share	.5734**	.8181	.3287	-.6305	.5734**	.5720**	.5741**
	(2.04)	(1.55)	(1.64)	(2.04)	(2.05)	(2.03)	(2.04)
Ind./Obs.	28/946	14/473	14/473	28/946	28/946	28/946	28/946

The correlation coefficient between the volatility- and mean rankings amounts to .23 (s.e. 0.03) according to Spearman's rank correlation test. 1963-2000 yearly data. Always include a constant. Heteroscedasticity- and serial correlation robust s.e. t-statistics in parenthesis. ***,**,* significant at 1%, 5%, 10%.

secure investments ($\mathcal{H}1$). In order to test these hypotheses we employ U.S. firm-level data from Compustat. The data relate to the balance sheets of U.S. nonfinancial firms and cover the time period 1970-2000. We consider annual data since we expect that firms frequently adjust their liquidity and investment portfolios to changes in the cost of insurance.[42] Overall, we have an unbalanced panel consisting of over 8000 firms. We include the following firm-level data: R&D expenses, the amount of cash and marketable securities (*corp.liquidity*), the amount of total assets (*assets*), the operating income (*opincome*), and the amount of retained earnings (*reearn*). All variables are measured in millions of dollars. Corporate R&D investments are used as a proxy for investments in superior technologies. The amount of cash and marketable securities approximate a firm's corporate liquidity holdings. The other measures serve as control variables. In particular, we expect that investments in advanced technologies increase with the size of a firm (*assets*), its operating income and its retained earnings. In addition, we use the rate of inflation measured by the first difference of the natural logarithm of the economy-wide consumer price index to investigate the effect of this macroeconomic variable on firm-level liquidity and investment portfolios.[43] We employ the GMM system estimator following Blundell and Bond (1998). Note that the mix of macro- and microeconomic data allows for a direct inspection of causality. In particular, the coefficient of inflation reflects the causal impact on (marginal) R&D expenses of a single firm since the latter has no feedback-effect on the aggregate level of inflation.

We point out that the empirical evidence provided by Opler et al. (1999), which

[42] As our model demonstrates, these frequent corporate portfolio adjustments have long-run empirical implications for the relationship between inflation and TFP-growth which we confirm in our aggregate empirical analysis in section 2.3. Moreover, we obtain qualitatively similar firm-level results if we focus on longer or shorter time horizons by applying 5-year averages or quarterly data, respectively. The results are available from the authors upon request.

[43] We stress that our results based on the GMM system estimator do not suffer from an aggregation bias, as outlined by Moulton (1990), since we employ heteroscedasticity- and serial correlation robust standard errors to avoid within-group correlation.

we outlined in section 2.2, already supports part of our specific microeconomic mechanism. That is, the authors reveal that U.S. firms with higher growth opportunities, which are approximated by a firm's market-to-book value as well as its R&D expenses, hold on average more liquid assets (cash and marketable securities) relative to total assets. We see these empirical findings as strongly supportive of the relevance of corporate liquidity holdings for the purpose of insuring superior production activities. In this regard, we extend the analysis in Opler et al. (1999) by investigating the impact of inflation on corporate cash holdings and firm-level R&D expenses.

Results: The first two columns of 2.4 confirm $\mathcal{H}1$ which states that inflation reduces corporate liquidity holdings. Accordingly, a 1% point increase in inflation reduces corporate liquidity holdings, on average, by 2.4 million US dollar in the same year. The corresponding coefficient is significant on a 1% level if we employ the GMM system estimator. Note that the long-run effect is even more pronounced in this dynamic model since a reduction in the lagged dependent variable further reduces future realization of corporate liquidity holdings. The corresponding long-run effect of a 1% point increase in inflation amounts to -9.74 million US dollar.[44] The negative effect of an increase in inflation is independent of variations in total assets, operating income, retained earnings or firm fixed effects. Column three and four of 2.4 display a negative correlation between inflation and firm-level R&D expenses after controlling for the other firm-level variables. Note that the coefficient of inflation declines substantially if we additionally control for corporate liquidity holdings. Column five and six report our preferred estimation specification following Blundell and Bond (1998). We find that firms reduce their investments in R&D significantly in years of higher inflation. Accordingly, a 1% point increase in inflation reduces corporate R&D expenses, on average, by .19 million US dollar in the same year and by 8.8 million US dollar in the long-run. This distorting impact declines, on average, by

[44]If $\beta_1 = 2.36$ denotes the coefficient of inflation and $\rho = .7578$ the one of the lagged dependent variable the long-run effect approximately amounts to $\frac{\beta_1}{1-\rho}$.

Table 2.4: U.S. firm-level yearly data: R&D versus investments

	Corporate liquidity		R&D				inv	
	OLS	GMM-sys	OLS	OLS	GMM-sys	GMM-sys	GMM-sys	GMM-sys
inflation	-1.73***	-2.36***	-.1692***	-.1291***	-.1919*	-.0612	.1771	-.5942
	(-7.45)	(-4.88)	(-3.82)	(-3.03)	(-1.69)	(-.66)	(.14)	(-.40)
corp. liquidity				.0173***		.0470***		-.1099
				(3.65)		(2.95)		(-.66)
assets	.0056	.0055	-.0009**	-.0011***	-.0018*	-.0019**	-.0109	-.0063
	(1.56)	(.74)	(-2.05)	(-2.79)	(-1.84)	(-1.95)	(-.40)	(-.25)
opincome	.0034	-.0003	.0115***	.0109***	.0298***	.0225***	.5931***	.6211***
	(.09)	(-.03)	(3.65)	(3.36)	(3.39)	(2.90)	(4.27)	(4.07)
reearn	.0213	.0749**	.0009	-.0001	.0011	-.0033	-.0418	-.0257
	(1.49)	(2.14)	(.72)	(-.09)	(.48)	(-1.03)	(-.47)	(-.32)
lag-dep.-var.	.898***	.7578***	1.03	1.00	.9782	.9248	.9773	.9634
	(29.11)	(9.44)	(75.78)	(59.16)	(21.1)	(14.8)	(12.7)	(13.6)
Firms	8285	8285	8287	8287	8287	8287	8276	8276
Observations	64681	64681	64708	64703	64708	64703	64494	64494
2. auto-cor.		.479			.899	.854	.743	.771
Hansen-test		.160			.046	.272	.109	.100

The maximum lag is restricted to 10 years in order to reduce the size of the IV matrix. 1970-2000 yearly data.

Heteroscedasticity robust s.e. t-statistics in parenthesis. ***,**,* significant at 1%, 5%, 10%.

68% if we additionally control for corporate liquidity holdings. The resulting inflation coefficient is no longer significant at conventional levels. Thus, the negative effect of inflation disappears once we control for changes in corporate liquidity holdings. This finding reveals that the negative impact of inflation on firm-level R&D investments is transmitted via fluctuations in corporate liquidity holdings just like our theoretical mechanism suggest, compare $\mathcal{H}1$ and $\mathcal{I}2$. Moreover, in accordance with Opler et al. (1999), we detect a strong positive correlation between corporate liquidity holdings and R&D which is significant at a 1% level. We reject the presence of second order autocorrelation in all estimation specifications and the Hansen test of overidentifying restrictions supports the validity of the instruments. Hence, the estimation specifications appears to be well specified.[45] In the last two columns of 2.4, we include the corporate level of overall capital investments instead of specific R&D investments as the dependent variable. Recall that our model predicts that only investments in the advanced technology are negatively affected by inflation or a reduction in corporate liquidity holdings. Indeed, the results show that inflation does not influence the overall quantity of corporate investments. Similarly, they are also not affected by the level of corporate liquidity holdings. Thus, the distorting impact of inflation is specific to investments in advanced technologies. Finally, note that the systematic pattern of correlation between R&D specific corporate investments and inflation after controlling for other firm characteristics clearly suggests that the negative inflation coefficient is not just picking up time effects.[46] Instead, there appears to be a systematic variation in the data supporting our hypotheses.

Summing up, the firm-level results show that inflation has a negative impact on firm-level R&D expenses. However, this effect disappears if we correctly control for corporate holdings of cash and marketable securities. Thus, the impact of inflation on firm-level investments in superior technologies is due to variations in corporate

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[45] Inflation is considered as an exogenous variable (see above). The microeconomic variables are considered as (potentially) endogenous.

[46] We also included a linear time trend, but it is not significant at conventional levels.

liquidity holdings. This empirical result directly approves the microeconomic mechanism underlying our theoretical derivations of a negative aggregate relation between inflation and long-run TFP-growth.

2.7 Conclusion of Chapter 2

The present chapter presents an endogenous growth model that combines elements of the growth and business cycle literature: it considers financial markets frictions and their interaction with short-run nominal constraints and endogenizes the productivity process via an endogenous technology choice which is catalyzed by these frictions. We demonstrate that inflation reduces long-run productivity growth in this framework. Thus, TFP-growth is partially endogenized by relating changes in the long-run balanced growth path of TFP to changes in monetary policy. The model replicates the negative empirical long-run relationship between inflation and TFP-growth as observed by Fischer (1993) and others adequately. In the empirical analysis, we present micro-econometric evidence from disaggregated sectoral and firm-level data that is consistent with our specific microeconomic mechanism underlying the macroeconomic monetary transmission channel. In particular, we detect at the industry level that the negative effect of inflation on productivity-growth per sector varies systematically with the riskiness (volatility) of investments in a sector ($\mathcal{H}2$). The firm-level data reveal that an increase in inflation is associated with reduced corporate liquidity holdings in the U.S. economy ($\mathcal{H}1$). In addition, aggregate inflation has a negative impact on firm-level R&D expenses, whereas we are able to show that the effect is due to fluctuations in corporate liquidity holdings just as the theoretical model suggests. Therefore, the general equilibrium implications of the constraint optimal financial contracting scheme are consistent with micro-econometric empirical evidence. In fact, the disaggregated empirical results confirm the relevance of our specific monetary transmission channel even in developed countries such as the USA. These microeconomic interactions lead to the key insight: the short-run interplay between inflation, the financial market friction and a firm's compositional investment decision involve long-run consequences for TFP-growth. Hence, the model postulates a novel aspect of monetary transmission in that movements in inflation are associated with changes in the long-run growth path of TFP. Since differences in TFP explain roughly 2/3 of cross-country income fluctuations, differences in trend inflation across countries represent an important factor to account for these fluctuations. This result entails strong policy implications for some (emerging) economies since changes in monetary policy regimes represent a relatively inexpensive way to catch up in terms of TFP and to encourage private sector development.

Chapter 3

Distributional effects of capital and labor on economic growth

In the following, we propose a growth model for an economy consisting of firms which are heterogeneous in technologies and input demands. We show that the growth rate in this economy depends not only on changes in the aggregate level of capital and labor, but also on changes in the allocation of these inputs across firms. As the latter effects are neglected in conventional growth models, they are misleadingly captured by the residual TFP measure. In contrast, we are able to quantify the influence of these components. Our empirical analysis, which is based on structural estimation from firm-level data, reveals that changes in allocation of capital and labor have pronounced effects on GDP-growth for most European countries. Further, we take cross-country differences in the distributional effects into account to improve conventional growth accounting exercises. In particular, we find that they explain additionally up to 17% of growth differences among 19 European countries. Consequently, allowing for heterogeneity in firm-level technologies and input demands increases the explanatory power of the inputs.

3.1 Introduction

In the following, we propose a growth model for an economy consisting of firms which are heterogeneous in technologies and input demands. We show that the growth rate in this economy depends not only on changes in the aggregate level of capital and labor, but also on changes in the allocation of these inputs across firms. As the latter effects are neglected in conventional growth models, they are misleadingly captured by the residual measure, referred to as total factor productivity (TFP). In contrast, we are able to quantify the influence of these components by structural estimation from firm-level data. Further, we take cross-country differences in the distributional effects into account to improve conventional growth accounting exercises.

Why do some countries grow and others stagnate?[1] This question initiated the growth accounting literature, which assigns cross-country differences in growth or income to differences in physical and human capital as well as the unobservable efficiency with which input factors are combined. The consensus view in this literature is that only approximately one third of the cross-country growth or income differences is explained by differences in input factors. The residual two thirds are left unexplained and attributed to differences in the unobservable efficiency which is referred to as total factor productivity (TFP).[2] In this context, Abramovitz (1956) refers to TFP as the *measure of our ignorance.*

The fact that TFP is unobservable and at the same time explains the major part of cross-country differences triggered tremendous efforts to identify its determinants in recent years.[3] However, we show in this chapter that the above growth accounting results have to be revised if one consistently aggregates over heterogeneous firms. In order to illustrate the relevance of aggregation for growth models we briefly discuss fundamental results of the aggregation literature.

The pillar of every macroeconomic growth model is an aggregate production function F, which relates aggregate capital $\bar{K}$ and labor $\bar{L}$ to aggregate output $\bar{Y}$, i.e., $\bar{Y} = F(\bar{K}, \bar{L})$. However, although there exists a well developed microeconomic theory of production for a single firm, there is no corresponding theoretical foundation for the entire economy. In fact, the aggregate production function suffers from two

[1] The Science magazine considers this question as one of the 125 "most compelling puzzles and questions facing scientists today" (Science, 2005).

[2] See, for example, Caselli (2005), Hall and Jones (1999) or Jorgenson (2005).

[3] This issue is best summarized by the title of a recent paper by Prescott (1998) "Needed: A Theory of Total Factor Productivity."

types of aggregation problems. The first, often referred to as the "measurement problem," involves the aggregation of different types of capital, labor, and output within a firm into one capital and labor input and one output. The second is concerned with aggregation of heterogeneous technologies and input demands across firms into their aggregate counterpart. These problems have been dealt with extensively in the aggregation literature. Early works by Nataf (1948), Gorman (1953), and a series of papers by Franklin Fisher (collected in Fisher (1993))[4] have shown that in the absence of perfect competition and perfect factor mobility the aggregate production function F cannot be linked to microeconomic production functions unless all firms operate according to identical and constant returns to scale technologies.

A frequent short-cut that circumvents the problem of aggregation over heterogeneous technologies is the assumption that the production function of an entire economy complies with the one of a single *representative firm*. Although the above theoretical results show that this link is only possible under very restrictive assumption, it is often applied in theoretical and empirical analysis due to its simplicity. However, from a practical point of view, growth models that ignore consistent aggregation over heterogeneous firms will suffer from serious drawbacks:[5] they neglect growth effects of (i) changes in the allocation of inputs[6] and (ii) changes in the pattern of economic interactions between firms. Yet, it is reasonable to expect that these factors affect

[4]For a comprehensive survey on aggregation of production functions, see Felipe and Fisher (2003).

[5]Hopenhayn (1992) initiated a literature on the effect of firm heterogeneity on industry dynamics. His approach was extended, e.g., by Melitz (2003) to analyze the impact of trade liberalization on the aggregate productivity of an economy. In these models firms are heterogeneous in productivity which is included in a way such that the impact of the productivity distribution on aggregate demand for inputs is fully determined by the average productivity. Consequently, under this parsimonious aggregation rule, aggregate output depends on average productivity and average input demands but not on the allocation of inputs across firms. That is, once the average productivity level is determined the model yields identical aggregate outcomes as a model based on a representative firm.

[6]Empirical studies document that these changes are substantial in developed and developing countries. For example, Roberts and Tybout (1997) quantify the rate of labor reallocation among manufacturing firms between 25 and 30 percent.

growth substantially, since they represent changes in growth due to changes in the market structure. For example, differences in the degree of competition in different industries as well as different incentives to innovate for small, medium, and large firms are found to affect technological change (see, e.g., Aghion and Griffith (2005)). Where are these effects in the growth literature? As they are not assigned to the levels of aggregate capital or labor, they are assigned to the unobserved efficiency. Therefore, they are misleadingly captured by the residual TFP measure.

In order to assess the impact of changes in the allocation of capital and labor on growth, we apply the aggregation procedure established by Hildenbrand and Kneip (2005). Our main result is that the growth rate of aggregate output depends on changes in the levels of aggregate capital and labor as well as changes in the distribution of capital and labor in the economy. We quantify the growth effect of each component by means of structural estimation based on firm-level data. These effects are estimated separately for each of 20 European countries. Our main findings are that distributional effects are significant in all countries. Further they are as large as the corresponding level effects in most countries. Finally, we exploit the information on the different distributional changes across countries to conduct a growth accounting exercise. More precisely, we assess the explanatory power of the distributional changes with respect to cross-country growth differences. It turns out that these effects explain additionally up to 17%. Accordingly, an aggregation approach that consistently accounts for firm heterogeneity can help explain the growth path of a single country as well as cross-country growth differences. Hence, the role of capital and labor in explaining the growth path of a single country or growth differences across countries is understated.

In the next section, we present our growth model for an economy consisting of heterogeneous firms. In Section 3, we describe the data, the empirical strategy, and discuss our results. Section 4 presents the growth accounting exercise, whereas the final section concludes.

3.2 The Model

Assume that in period t each firm j from a heterogeneous population of firms J_t produces according to the firm-specific production function $f_t^j(\cdot)$ defined by:

$$Y_t^j = f_t^j(K_t^j, L_t^j),$$

where Y_t^j denotes the output level, K_t^j the capital stock and L_t^j the labor demand.[7] Further, we assume that the heterogeneity in production functions f_t^j, i.e., in technologies and input demands, can be parameterized by a vector of parameters V_t^j. In general, V_t^j is unobservable. Then one can write:

$$Y_t^j = f(K_t^j, L_t^j, V_t^j) \tag{3.1}$$

Hence, technological changes over time translate into changes in the distribution of V_t^j across J_t. The function f can therefore, without loss of generality, be regarded as time-invariant and equal for all individuals. In the simplest scenario, f could be a Cobb-Douglas production function with $V_t^j = (V_{1,t}^j, V_{2,t}^j)$ such that $Y_t^j = V_{1,t}^j \cdot {K_t^j}^{V_{2,t}^j} \cdot {L_t^j}^{1-V_{2,t}^j}$. However, in order to establish our main result at the aggregate level, an explicit parametric specification of f is not required.

In the above setup, we define aggregate output $\bar{Y}_t$ in period t as:

$$\bar{Y}_t = \int f(K, L, V)\, dG_{t,KLV}, \tag{3.2}$$

where K, L, and V are generic random variables corresponding to capital, labor, and unobservable productivity parameters of a randomly chosen firm, respectively, and $G_{t,KLV}$ is the joint distribution of (K, L, V) across the population J_t. Thus, G_{KLV} is the explanatory variable for aggregate output. However, we do not need to model G_{KLV} but only its changes over time, since our objective is to determine the growth rate instead of the level of aggregate output.

In order to impose a structure on the evolution of the unobservable distribution of V, we introduce a set of observable firm specific attributes A_t^j with the corresponding

[7]One can easily extend the model to the case of multiple capital and labor inputs.

random variable A, which are expected to be correlated with V: the age of a firm, the region or industry in which it operates, its ownership structure, and its legal form.

Further, we use A to decompose $G_{t,KLV}$ into the distributions $G_{t,V|KLA}$, $G_{t,A|KL}$, and $G_{t,KL}$. The first term is the conditional distribution of V given (K, L, A), the second is the conditional distribution of A given (K, L), and the third is the joint distribution of (K, L). We write:

$$\bar{Y}_t = \int\Big[\int \Big(\int f(K,L,V)\, dG_{t,V|KLA}\Big)\, dG_{t,A|KL}\Big]\, dG_{t,KL} = \int \Big(\int \bar{f}_t(K,L,A)\, dG_{t,A|KL}\Big)\, dG_{t,KL}, \tag{3.3}$$

where $\bar{f}_t(K, L, A)$ is the conditional mean of output Y given (K, L, A) in period t. Thus, it is a regression function of Y on (K, L, A), which can be estimated from a cross-section of firms in period t.

From (3.3) we infer that assumptions on changes in $G_{V|KLA}$, $G_{A|KL}$, and G_{KL} are required in order to model output growth. It is easier to model the evolution of a distribution if it is symmetric, because a symmetric distribution can be well-described by its first few moments, like its mean and variance. Since the distributions of capital and labor are right-skewed in all countries, we formulate the model assumptions in terms of log capital $k_t^j := \log K_t^j$ and log labor $l_t^j := \log L_t^j$ with the corresponding random variables k and l. Further, we define $\bar{k}_t$ and $\bar{l}_t$ as the mean of k and l across J_t and σ_t^k and σ_t^l as the corresponding standard deviations. By analogy to $G_{V|KLA}$, $G_{A|KL}$, and G_{KL}, we define $G_{V|klA}$, $G_{A|kl}$, and G_{kl}, respectively. In addition, G_k and G_l represent marginal distributions of log capital and log labor. Finally, let $G_{\tilde{k}\tilde{l}}$ denote a component-wise standardized joint distribution of (k, l), which is defined as a joint distribution of $(\tilde{k}, \tilde{l})$, where $\tilde{k} := \frac{k-\bar{k}}{\sigma^k}$ and $\tilde{l} := \frac{l-\bar{l}}{\sigma^l}$.

In line with the aggregation approach of Hildenbrand and Kneip (2005), we impose the following assumptions.

Assumption 1: ("Structural stability"[8] of G_{kl}) *The component-wise standardized*

[8]The concept of structural stability of a distribution relies on an empirical regularity that dis-

joint distribution of log capital and log labor $G_{\tilde{k}\tilde{l}}$ is approximately equal for two consecutive periods t and $t-1$, i.e., $G_{t,\tilde{k}\tilde{l}} \approx G_{t-1,\tilde{k}\tilde{l}}$.

It is important to note that $G_{\tilde{k}\tilde{l}}$ refers to a standardized distribution. That is, if Assumption 1 holds, the entire change in G_{kl} over two consecutive periods is fully captured by the changes in means and the variances of k_t^j and l_t^j.[9]

In order to impose the assumption on the evolution of $G_{A|kl}$ we define $k_{t,\tau}$ as the τ-quantile of the distribution $G_{t,k}$ and $l_{t,\eta}$ as the η-quantile of the distribution $G_{t,l}$, respectively.

Assumption 2: *The conditional distribution of A given $k = k_\tau$ and $l = l_\eta$ denoted by $G_{A|k_\tau l_\eta}$ is approximately equal for two consecutive periods t and $t-1$, i.e., $G_{t,A|k_\tau l_\eta} \approx G_{t-1,A|k_\tau l_\eta}$.*

---

tributions of individual variables across large populations of economic agents change very slowly over time. It has been first noticed by Pareto (1896) and introduced into macroeconomic models by Malinvaud (1993). More precisely, for a distribution of a certain parametric form, for example, the normal distribution, structural stability holds, if its normal structure prevails and its entire evolution is captured by changes in its mean and its variance. However, this concept of structural stability cannot be applied to distributions which are poorly approximated by a parametric form. In this context, Hildenbrand and Kneip (2005) proposed a nonparametric counterpart of Malinvaud's idea. Instead of keeping the parametric structure constant and allowing for changes over time in few parameters, one can keep these parameters constant and allow the shape of the distribution to vary over time. This can be achieved by simple transformations of the distribution like centering (constant mean) or standardizing (constant mean and variance). Accordingly, structural stability as defined by Hildenbrand and Kneip (2005) holds, if a centered or standardized distribution does not change over two consecutive periods.

[9]To be more precise, Hildenbrand and Kneip (2005) model the evolution of G_{kl} in terms of a distribution which is standardized by a full covariance matrix $\Sigma_t := \begin{pmatrix} (\sigma_t^k)^2 & \sigma_t^{kl} \\ \sigma_t^{kl} & (\sigma_t^l)^2 \end{pmatrix}$, instead of a component-wise standardized one, which uses the matrix $\tilde{\Sigma}_t = \begin{pmatrix} (\sigma_t^k)^2 & 0 \\ 0 & (\sigma_t^l)^2 \end{pmatrix}$. Our version of the assumption is more stringent, as it requires that the correlation between log capital and log labor does not change significantly over two consecutive periods. The main advantage of our formulation (see Proposition and Appendix C) is the possibility to separate growth effects of changes in σ^k from growth effects of changes in σ^l.

Assumption 2 refers to the distribution of A across firms with log capital and log labor in the *same quantile position* (τ, η) of G_{kl} in period t and $t-1$, instead of firms with the *same values* of k and l. We employ the former specification since it increases the likelihood that we condition on the same group of firms in both periods. That is, if G_{kl} shifts over time due to a common trend, we refer to the same group of firms in both periods by conditioning on the quantile position as opposed to conditioning on the same values of k and l.

Note that one is able to verify Assumptions 1 and 2, since G_{kl} and $G_{A|kl}$ are observable in firm-level data. We document in the Appendix C that both assumptions are supported by our data. In contrast, one is not able to falsify the following two assumptions on $G_{V|klA}$ as they concern a distribution of unobservable variables.

Let $J_t(k,l,A)$ denote the subpopulation of firms with capital k, labor l, and attributes A and $\bar{V}_t(k,l,A)$ denote the mean of V across $J_t(k,l,A)$. Further, $G_{\tilde{V}|klA}$ denotes the centered distribution of V across $J_t(k,l,A)$, whereby $\tilde{V}$ corresponds to the centered variable $\tilde{V} := V - \bar{V}_t(k,l,A)$.

Assumption 3: *The distribution $G_{\tilde{V}|klA}$ is approximately equal for two periods t and $t-1$, i.e., $G_{t,\tilde{V}|klA} \approx G_{t-1,\tilde{V}|klA}$.* Note that Assumption 3 is a very mild assumption since we allow for any form of heterogeneity in V across firms with different capital stocks, labor stocks, or firm characteristics, i.e. Assumption 3 refers to the conditional distribution of $\tilde{V}$ given k, l, and A. Furthermore, we even allow for heterogeneity in V across firms with the same capital stock, labor stock, and firm characteristics, as long as changes in $G_{V|klA}$ are captured by changes in the conditional mean $\bar{V}(k,l,A)$. In this case, we assume that $\bar{V}_t(k,l,A)$ is additively separable in (k,l) and t. More precisely,

Assumption 4: *$\bar{V}_t(k,l,A)$, can be additively factorized by $\bar{V}_t(k,l,A) = \varphi(k,l,A) + \psi(t,A)$, where the function φ is continuously differentiable in k and l.*

Proposition: (Hildenbrand and Kneip (2005)) *If Assumptions 1-4 hold, the growth rate of aggregate output in the economy, $g_t := \frac{\bar{Y}_t - \bar{Y}_{t-1}}{\bar{Y}_{t-1}}$, is given by:*

$$
\begin{aligned}
g_t &= \beta^k_{t-1}(\log \bar{K}_t - \log \bar{K}_{t-1}) + \beta^l_{t-1}(\log \bar{L}_t - \log \bar{L}_{t-1}) && (3.4)\\
&+ \gamma^k_{t-1}\Big(\frac{\sigma^k_t - \sigma^k_{t-1}}{\sigma^k_{t-1}}\Big) + \gamma^l_{t-1}\Big(\frac{\sigma^l_t - \sigma^l_{t-1}}{\sigma^l_{t-1}}\Big) && (3.5)\\
&+ \text{(effects due to changes in } \bar{V}_{t-1}(k,l,A))\\
&+ \text{(second order terms of the Taylor expansion).}
\end{aligned}
$$

The coefficients β^k_{t-1}, β^l_{t-1}, γ^k_{t-1}, and γ^l_{t-1} are defined in terms of partial derivatives of the regression function $\bar{f}_{t-1}(k,l,A)$. For $s = \{k,l\}$ and $S = \{K,L\}$, β^s_{t-1}, γ^s_{t-1} are defined by

$$
\beta^s_{t-1} = \frac{1}{\bar{Y}_{t-1}} \int \partial_s \bar{f}_{t-1}(k,l,A)\, dG_{t-1,klA}, \tag{3.6}
$$

$$
\gamma^s_{t-1} = \frac{1}{\bar{Y}_{t-1}} \int (s - \bar{s}_{t-1}) \partial_s \bar{f}_{t-1}(k,l,A)\, dG_{t-1,klA} - \frac{\beta^s_{t-1}}{\bar{S}_{t-1}} \int (s - \bar{s}_{t-1}) \exp(s) dG_{t-1,s} \tag{3.7}
$$

Remark 1: The proof is given in Hildenbrand and Kneip (2005). However, the above Proposition differs from the one in Hildenbrand and Kneip (2005) in two aspects. First, our Assumption 1 relies on a component-wise standardization which makes it possible to separate growth effects of changes in σ^k from growth effects of changes in σ^l. Second, we model the aggregate relation in terms of the logarithm of aggregate variables, i.e., $\log \bar{K}$ and $\log \bar{L}$ and not the aggregates of the logarithms of individual variables, i.e., $\bar{k}$ and $\bar{l}$. This distinction yields different definitions of γ^k_{t-1} and γ^l_{t-1} and is essential to compare our model with conventional growth models, which are based on (the logarithm of) aggregate variables. See Appendix C for the corresponding derivations.

From the above representation we infer that the growth rate g of aggregate output does not only depend on changes in aggregate capital and aggregate labor (term (3.4)). It also depends on changes in the allocation of inputs (term (3.5)) measured by the standard deviation of log capital and log labor across firms.

The aggregate coefficients $(\beta^k_{t-1}, \gamma^k_{t-1})$ and $(\beta^l_{t-1}, \gamma^l_{t-1})$ depend on the derivatives of the regression function $\bar{f}_{t-1}$ with respect to k and l, respectively. All other variables in (3.7) are observable. The derivatives $\partial_k \bar{f}_{t-1}(k, l, A)$ and $\partial_l \bar{f}_{t-1}(k, l, A)$ can be estimated using a cross-section of firms in period $t-1$. Hence, they can be estimated independently of each other in each time period. It is important to note that in the estimation of our representation of the growth rate *no time-series model* fitting takes place, which would require to include all potential growth determinants. Our estimation procedure does not require information on the growth rate of aggregate capital and labor nor the corresponding standard deviations, since the computation of aggregate coefficents is based on the estimation from a single cross-section of firms. In contrast, we are able to quantify the growth effect of changes in the distribution of inputs without specifying an exhaustive model for the aggregate growth rate. We describe the estimation methodology for these coefficients in more detail in Section 3.3.2.

Remark 2: Under Assumption 1 coefficients β^k_{t-1} and β^l_{t-1} can be interpreted as elasticities of aggregate output with respect to aggregate capital and aggregate labor, respectively. Accordingly, γ^k_{t-1} and γ^l_{t-1} are elasticities of aggregate output with respect to σ^k and σ^l, respectively.[10] One expects β^k_{t-1} and β^l_{t-1} to be positive. However, to draw conclusions on the expected sign of γ^k_{t-1} and γ^l_{t-1} one needs to impose additional assumptions on the impact of changes in the market structure on the standard deviation of inputs. For example, if a higher degree of product market competition leads to more similarity in firm size, negative γ^k_{t-1} and γ^l_{t-1} indicate a positive relationship between growth and competition. Alternatively, we outlined above that changes in the standard deviation represent changes in the pattern of economic interactions between firms. These interactions comprise, for instance, technology spill-overs between firms. If technology diffusion is stronger among more similar firms, we expect a negative relation between spill-overs and the standard deviation of inputs and, hence,

[10]See Hildenbrand and Kneip (2005) for a detailed discussion on the interpretation of the coefficients.

negative γ_{t-1}^k and γ_{t-1}^l.

Our theoretical result has an important implication for growth accounting. To illustrate this point, let us hypothetically claim that all variables in our model other than capital and labor do not change over time. Then, in a classical growth model, changes in $\bar{Y}$ would be in part attributed to changes in the mean of capital and labor ($\bar{K}$ and $\bar{L}$). However, a part of the change in $\bar{Y}$, which is not captured by the effect of changes in $\bar{K}$ and $\bar{L}$, would be attributed to changes in aggregate TFP. Such a conclusion, however, would be misleading, since we assumed that TFP did not change. From the Proposition we know that it is the effect of changes in the distribution of inputs, which is erroneously attributed to changes in TFP. Obviously, the correct conclusion in this framework is only possible in models which allow for input heterogeneity of firms.

3.3 Empirical Analysis

In the following, we structurally estimate the effects of changes in the level and allocation of capital and labor on growth separately for each of 20 European countries in our sample.

3.3.1 Data

The analysis is based on European firm-level data from 2002 until 2004.[11] The data stem from the Bureau van Dijk's AMADEUS database. It contains information from firm balance sheets and covers all firms in each country. We measure output as real[12] value added. Capital and labor are measured as real fixed tangible assets and the real

[11] We estimate the corresponding coefficients exclusively for 2003. Yet, we need additional observations in 2002 for the Olley and Pakes (1996) estimation procedure and in 2004 for the growth accounting exercise.

[12] Real variables are obtained by deflating by the national output price deflators. Unfortunately, price deflators were not available at the industry level for most of the 20 European countries.

total cost of employees, respectively.[13] Our procedure requires that the firms have non-missing observations in 2003. Moreover, we only include countries in which data for at least 200 firms are available.

Furthermore, we include firm's age and other control variables to control for differences in economic environment across firms. In particular, we account for industry-specific and region-specific fixed effects, in that we distinguish sectors by means of two digit NACE codes and include regional dummies. Moreover, we incorporate dummy variables that capture the ownership status of a firm: (i) `quoted` takes value 1 if a firm is publicly quoted and 0 if not, while (ii) `indep1- indep9` correspond to independence indicators (defined in the AMADEUS database) which represent different shareholder structures. Finally, we include gross investment, measured by the change in the capital stock plus depreciation, which is employed as an instrument for the unobservable technology shock in the estimation procedure of Olley and Pakes (1996).

The descriptive statistics of the variables for each country in 2003 and 2004 are listed in *Table* 3.1. The first column indicates that the number of observations used for estimation varies substantially across countries in our sample. These differences can be attributed to different filing regulations of individual countries. For example, German companies are not legally obliged to reveal some information from their balance sheets. Hence, although the full sample for Germany covers over 800,000 firms in 2003, joint information on value added, fixed tangible assets and the number of employees is available for only roughly 6,000 German firms. In contrast, the corresponding information is available for most companies in the Spanish or Italian sample which contain about 360,000 and 117,000 observations in 2003, respectively. Analog,

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[13] We define labor in this way in order to account, to a certain extent, for differences in the quality of employees, i.e., human capital, across firms. These differences are captured by the total cost of employees, as long as firms that are characterized by the same capital stock, number of employees, and the same attribute profile A, (that is, the same industry, region, age, ownership structure, etc.) but a higher human capital stock pay higher wages. We emphasize that the qualitative results do not change if we define labor as the number of employees. These results are available from authors upon request.

means and variances of the variables differ noticeably across countries. We observe relatively large firms in Germany, the Netherlands, Austria, Great Britain and Portugal, whereas the sample covers many small firms in Romania, Spain, Italy, and Sweden. Accordingly, we also observe analog differences in the standard deviations. In all, the date reveals a substantial amount of heterogeneity both across firms within a country as well as across countries.

Table 3.1: Descriptive statistics of AMADEUS data

country	n_{2003}	$\bar{Y}_{2003}$	$\bar{K}_{2003}$	$\bar{L}_{2003}$	n_{2004}	$\bar{Y}_{2004}$	$\bar{K}_{2004}$	$\bar{L}_{2004}$
Austria	1071	23.766 (112.158)	27.059 (127.479)	18.098 (62.713)	1364	23.883 (113.935)	27.296 (130.298)	14.039 (43.775)
Belgium	10980	12.159 (123.637)	6.708 (32.035)	4.652 (13.922)	11036	12.146 (123.736)	6.720 (31.395)	5.156 (15.683)
Bosnia & H.	2573	0.420 (2.806)	1.358 (9.766)	0.118 (0.353)	2862	0.399 (2.643)	1.215 (7.586)	0.132 (0.380)
Bulgaria	5818	0.311 (2.734)	0.755 (4.083)	0.156 (0.591)	5955	0.308 (2.738)	0.776 (4.029)	0.175 (0.658)
Czech R.	11494	1.258 (14.420)	1.995 (9.655)	0.622 (1.614)	15799	1.270 (13.455)	2.003 (9.833)	0.615 (1.671)
Denmark	20426	2.915 (78.919)	1.359 (7.839)	1.173 (4.930)	21782	2.981 (77.818)	1.370 (7.804)	1.181 (4.778)
Estonia	7666	0.232 (1.799)	0.239 (0.966)	0.097 (0.243)	8083	0.235 (1.811)	0.257 (1.060)	0.112 (0.299)
Finland	32401	1.695 (39.112)	0.795 (5.318)	0.673 (2.848)	30328	1.700 (39.318)	0.730 (4.813)	0.785 (3.215)
France	157141	1.914 (49.716)	0.739 (4.914)	1.154 (4.081)	168079	2.045 (52.413)	0.731 (4.788)	1.214 (4.354)
Germany	6076	71.486 (840.303)	61.754 (273.698)	45.140 (188.750)	7623	68.272 (778.787)	62.813 (296.033)	34.938 (130.982)
Great Britain	41649	18.927 (263.407)	13.435 (88.357)	8.671 (34.791)	37666	19.163 (269.775)	14.751 (98.518)	11.578 (46.104)
Italy	117111	2.385 (86.508)	1.462 (6.618)	1.059 (3.622)	75392	1.976 (24.330)	1.561 (7.379)	1.984 (6.541)
Netherlands	7365	24.505 (329.132)	19.989 (109.564)	16.695 (71.049)	7375	25.337 (347.447)	20.302 (115.710)	17.977 (78.165)
Norway	12051	1.416 (45.918)	1.792 (9.647)	0.540 (1.295)	14299	1.432 (46.209)	1.747 (9.624)	0.679 (1.981)
Poland	10571	2.612 (26.125)	3.338 (13.321)	0.920 (2.119)	11188	2.551 (25.342)	3.823 (14.851)	1.101 (2.535)
Portugal	1451	9.958 (84.895)	19.793 (147.204)	6.114 (25.616)	1487	9.325 (84.477)	21.399 (154.907)	6.003 (25.167)
Romania	49018	0.102 (2.354)	0.102 (0.446)	0.046 (0.164)	66230	0.102 (2.403)	0.120 (0.505)	0.042 (0.141)
Slovakia	2042	1.626 (11.354)	4.157 (30.283)	0.842 (2.302)	2557	2.413 (22.984)	3.231 (23.581)	0.828 (2.489)
Spain	357410	0.956 (34.631)	0.492 (2.250)	0.313 (1.071)	360517	1.003 (37.231)	0.519 (2.374)	0.340 (1.175)
Sweden	123058	1.555 (42.467)	0.731 (5.522)	0.401 (1.776)	125725	1.474 (38.704)	0.735 (5.553)	0.437 (1.906)

All values in millions of EUR.

3.3.2 Estimation strategy

The aggregate coefficients β_t^s and γ_t^s, $s \in \{k, l\}$ can be estimated as (suitably weighted) average derivatives in the regression of value added Y_t^j on log capital k_t^j, log labor l_t^j, and a vector of firm specific attributes A_t^j, i.e., in the model:

$$Y_t^j = \bar{f}_t(k_t^j, l_t^j, A_t^j; \zeta) + u_t^j, \tag{3.8}$$

where ζ is the vector of parameters to be estimated and u_t^j is the error term with $E(u_t^j) = 0$. Hence, according to (3.6) and (3.7), once consistent estimates $\partial_s \bar{f}_t\widehat{(k, l, A}; \zeta)$, $s \in \{k, l\}$, are obtained, one can estimate aggregate coefficients by:

$$\hat{\beta}_t^k = \frac{\sum_{j \in J_t} \partial_k \bar{f}_t\widehat{(k_t^j, l_t^j, A_t^j)}}{\sum_{j \in J_t} Y_t^j}, \quad \hat{\beta}_t^l = \frac{\sum_{j \in J_t} \partial_l \bar{f}_t\widehat{(k_t^j, l_t^j, A_t^j)}}{\sum_{j \in J_t} Y_t^j}, \tag{3.9}$$

$$\hat{\gamma}_t^k = \frac{\sum_{j \in J_t} (k_t^j - \hat{\bar{k}}_t) \partial_k \bar{f}_t\widehat{(k_t^j, l_t^j, A_t^j)}}{\sum_{j \in J_t} Y_t^j} - \frac{\hat{\beta}_t^k}{\bar{K}_t} \sum_{j \in J_t} (k_t^j - \hat{\bar{k}}_t) K_t^j, \text{ and} \tag{3.10}$$

$$\hat{\gamma}_t^l = \frac{\sum_{j \in J_t} (l_t^j - \hat{\bar{l}}_t) \partial_l \bar{f}_t\widehat{(k_t^j, l_t^j, A_t^j)}}{\sum_{j \in J_t} Y_t^j} - \frac{\hat{\beta}_t^l}{\bar{L}_t} \sum_{j \in J_t} (l_t^j - \hat{\bar{l}}_t) L_t^j \tag{3.11}$$

Our empirical strategy is focused on the model specification and estimation for $\bar{f}_t$. However, our analysis revealed that a regression of $y_t^j := \log Y_t^j$ on (k_t^j, l_t^j, A_t^j) provides a significantly better model fit and stability of results, as compared to the regression of Y_t^j on (k_t^j, l_t^j, A_t^j). Consequently, we estimate derivatives of $\bar{f}_t$ from the model:

$$y_t^j = \bar{h}_t(k_t^j, l_t^j, A_t^j; \theta) + \varepsilon_t^j, \tag{3.12}$$

where θ is the vector of parameters to be estimated and ε_t^j is the error term with $E(\varepsilon_t^j) = 0$. In doing so, we use the fact that $\partial_s \bar{f}_t(k_t^j, l_t^j, A_t^j; \hat{\zeta}) = Y_t^j \partial_s \bar{h}_t(k_t^j, l_t^j, A_t^j; \hat{\theta})$, if $\hat{\zeta}$ and $\hat{\theta}$ are consistent estimates of ζ and θ, respectively. Our basic specification for $\bar{h}_t$ is linear in (k, l, A) and can be estimated using OLS. Further, we analyze the robustness of our results in two ways. First, we control for possible simultaneity between ε_t^j and (k, l) using the Olley and Pakes (1996) method. Second, we extend our analysis to a partially linear specification of $\bar{h}_t$, in which the relationship between y and (k, l) is modelled nonparametrically. The latter procedure avoids a parametric misspecification of $\bar{h}_t$.

The loglinear model

Our basic specification for $\bar{h}_t$ is the loglinear model, i.e.:

$$y_t^j = \theta_0 + \theta^k k_t^j + \theta^l l_t^j + \theta_A' A_t^j + \varepsilon_t^j, \tag{3.13}$$

which implies that $\widehat{\partial_k \bar{f}_t(k_t^j, l_t^j, A_t^j)} = \hat{\theta}^k Y_t^j$ and $\widehat{\partial_l \bar{f}_t(k_t^j, l_t^j, A_t^j)} = \hat{\theta}^l Y_t^j$.[14] These quantities are then imputed into (3.9) - (3.11), in order to calculate aggregate parameters.

In the simplest case, (3.13) can be estimated by the OLS method from a single cross-section in 2003. However, the vast literature on estimation of production functions from firm-level data points out that OLS may suffer from a simultaneity problem. This problem arises if there is a contemporaneous correlation between the demand for inputs k_t^j, l_t^j and the realization of the unobservable technology shock contained in ε_t^j. In such a case, estimates $\hat{\theta}^k$ and $\hat{\theta}^l$, and, hence, $\hat{\beta}^k$ and $\hat{\beta}^l$ would be biased. There are several approaches to correct for simultaneity between (k_t^j, l_t^j) and ε_t^j and all of them put additional restrictions on the data. For instance, Olley and Pakes (1996) propose a method, which uses changes in firm's investment decision as a proxy for the productivity shock. However, only firms with non-missing data for 2002 and 2003 on value added, capital, labor, and investment can be used for estimation. Depending on the country, this requirement involves an elimination of up to 70% of the companies from our sample of firms with non missing data on value added, capital, and labor in 2003. Following the same idea, Levinsohn and Petrin (2003) suggest the use of intermediate inputs instead of the investment variable as a proxy.[15] Finally, as described

[14]Note that in this model, $\hat{\beta}^k = \hat{\theta}^k$ and $\hat{\beta}^l = \hat{\theta}^l$.

[15]They motivate their choice by weaker data requirements and argue that an adjustment in intermediate inputs is likely to have better properties as an instrument for a technology shock than an adjustment in investment. Interestingly, the approach of Levinsohn and Petrin (2003) requires even

in Blundell and Bond (2000), the simultaneity problem in estimation of production function can also be bypassed by a GMM system estimator, though it requires a long time-series of cross-sections and is therefore not attractive for our analysis. Moreover, OLS may introduce a sample selection bias, if dropping out of the sample between 2002 and 2003 is non-random.

Being aware of the problems mentioned above, we consistently estimate (3.13) following Olley and Pakes (1996) in controlling for both simultaneity bias and sample attrition. The method is based on a two-step procedure and requires the following assumptions: (i) labor is the only input which contemporaneously responds to a technology shock, (ii) the capital stock is predetermined and hence uncorrelated with a contemporary technology shock, (iii) changes in corporate investment decisions depend on the contemporaneous technology shock, the age and the capital stock of a firm, (iv) investments are monotonically increasing in the technology shock for a given value of age and capital. Under these assumptions, the technology shock can be instrumented as a function of capital, age, and investment. The estimation of this function is carried out by a series estimator.

Semiparametric model

In order avoid a misspecification of the relationship between y and (k, l, A) we model $\bar{h}_t$ semiparametrically and include an interaction term, i.e.:

$$y_t^j = \theta_0 + \bar{h}_t^k(k_t^j) + \bar{h}_t^l(l_t^j) + \theta^{kl} k_t^j l_t^j + \theta'_A A_t^j + \varepsilon_t^j, \tag{3.14}$$

where $\bar{h}_t^k$ and $\bar{h}_t^l$ are differentiable in k and l, respectively. We model $\bar{h}_t^k$ as a quadratic splines function with D^k knots $d_1^k < d_2^k < \cdots < d_{D^k}^k$. Defining basis functions $b_i^k(k) = \max\{0, k - d_i^k\}^2$, we obtain $\bar{h}_t^k(k) = \theta_1^k k + \theta_2^k k^2 + \sum_{i=1}^{D^k} \theta_{3,i}^k b_i^k(k)$. Analog, we model $\bar{h}_t^l$ as $\bar{h}_t^l(l) = \theta_1^l l + \theta_2^l l^2 + \sum_{i=1}^{D^l} \theta_{3,i}^l b_i^l(l)$. All coefficients in (3.14) can

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more firms to be eliminated from our sample due to the very large number of firms with missing data on the use of materials.

be estimated by the OLS method. Accordingly, $\partial_k \bar{f}_t(k_t^j, l_t^j, A_t^j)$ can be estimated as:

$$\partial_k \bar{f}_t \widehat{(k_t^j, l_t^j}, A_t^j) = \Big(\hat{\theta}_1^k + 2\hat{\theta}_2^k k_t^j + \hat{\theta}^{kl} l_t^j + 2\sum_{i=1}^{D^k} \hat{\theta}_{3,i}^k \max\{0, k_t^j - d_i^k\}\Big) Y_t^j$$

Similarly, one obtains $\partial_l \bar{f}_t \widehat{(k_t^j, l_t^j}, A_t^j) = (\hat{\theta}_1^l + 2\hat{\theta}_2^l l_t^j + \hat{\theta}^{kl} k_t^j + 2\sum_{i=1}^{D^l} \hat{\theta}_{3,i}^l \max\{0, l_t^j - d_i^l\}) Y_t^j$. The optimal number of knots and their position is obtained by the minimization of the Mallows' C_p criterion (see Mallows (1973)) using the knot deletion method as described by Fan and Gijbels (1996).[16]

Statistical significance of the aggregate coefficients

Condifence intervals for the aggregate coefficients as well as standard errors of the estimates are determined by bootstrap. For i.i.d. bootstrap resamples $(Y_t^{j*}, k_t^{j*}, l_t^{j*}, A_t^{j*})$, the distribution of $(\hat{\beta}_t^k - \beta_t^k)$ is approximated by the conditional distribution of $(\hat{\beta}_t^{k*} - \hat{\beta}_t^k)$ given $(Y_t^j, k_t^j, l_t^j, A_t^j)$, where $\hat{\beta}_t^{k*}$ is the estimate of β_t^k based on the bootstrap sample. We asses the significance of β_t^k on the basis of the 95% confidence interval, $[\hat{\beta}_t^k - q_{0.975}^*, \hat{\beta}_t^k - q_{0.025}^*]$, where q_α^* is the α-quantile of the distribution of $(\hat{\beta}_t^{k*} - \hat{\beta}_t^k)$. Analog, we compute confidence intervals for β_t^l, γ_t^k, and γ_t^l. Distributional effects are statistically significant, if the condifence interval for γ_t^k or γ_t^l does not include zero. The consistency proof of such a naive bootstrap in the context of average derivative estimation can be found in Härdle and Hart (1992).

[16]Knot deletion is an iterative procedure. We start with a large number $\bar{D}^k$ of initial knots for k, i.e., $d_1^k < d_2^k < \cdots < d_{\bar{D}^k}^k$, which divide the domain of k into intervals $[d_i^k, d_{i+1}^k]$ with approximately equal number of observations. Similarly, we determine the corresponding $\bar{D}^l$ initial knots for l. In step 0, we estimate (3.14) by the OLS method and obtain $\bar{D} = \bar{D}^k + \bar{D}^l$ estimated spline coefficients $\hat{\theta}_{3,1}^k, \ldots, \hat{\theta}_{3,\bar{D}^k}^k, \hat{\theta}_{3,1}^l, \ldots, \hat{\theta}_{3,\bar{D}^l}^l$ with the corresponding t-values, $t := \hat{\theta}/SE(\hat{\theta})$. At step 1, we delete the knot with the lowest absolute t-value at step 0 and reestimate (3.14) using $\bar{D} - 1$ knots. We repeat this process $\bar{D}$ times until no knots are left. At each step r, $0 \leqslant r \leqslant \bar{D}$, we compute the *residual sum of squares* $RRS_r = \sum_{j=1}^n (\hat{\varepsilon}_t^j)^2$. Finally, we choose the model with the lowest value for Mallows' C_p defined by $C_r := RSS_r + 3(\bar{D} + 6 + n_A - r)\hat{\sigma}_0^2$, where n_A is the number of attributes in A_t^j and $\hat{\sigma}_0$ is the estimated standard deviation of ε_t^j at the 0^{th} model.

Table 3.2: Aggregate coefficients based on OLS production function estimation

country	$\hat{\beta}^k$	$\hat{\beta}^l$	$\hat{\gamma}^k$	$\hat{\gamma}^l$
Austria	0.151 (0.016)	0.788 (0.025)	-0.190 (0.034)*	-0.037 (0.054)
Belgium	0.140 (0.006)	0.749 (0.008)	-0.293 (0.020)*	-0.250 (0.030)*
Bosnia & H.	0.212 (0.011)	0.581 (0.015)	-0.351 (0.039)*	-0.166 (0.036)*
Bulgaria	0.234 (0.009)	0.639 (0.010)	-0.268 (0.027)*	-0.190 (0.063)*
Czech R.	0.140 (0.004)	0.811 (0.007)	-0.183 (0.011)*	0.035 (0.026)
Denmark	0.116 (0.004)	0.747 (0.006)	-0.181 (0.012)*	-0.149 (0.024)*
Estonia	0.185 (0.008)	0.715 (0.009)	-0.278 (0.019)*	-0.210 (0.029)*
Finland	0.147 (0.002)	0.778 (0.003)	-0.299 (0.014)*	-0.090 (0.011)*
France	0.111 (0.001)	0.854 (0.002)	-0.232 (0.005)*	-0.038 (0.007)*
Germany	0.136 (0.007)	0.803 (0.011)	-0.130 (0.017)*	-0.107 (0.037)*
Great Britain	0.132 (0.003)	0.783 (0.004)	-0.248 (0.010)*	-0.057 (0.016)*
Italy	0.131 (0.002)	0.732 (0.002)	-0.179 (0.004)*	-0.058 (0.007)*
Netherlands	0.119 (0.007)	0.832 (0.010)	-0.171 (0.017)*	-0.158 (0.035)*
Norway	0.091 (0.003)	0.804 (0.006)	-0.210 (0.011)*	-0.123 (0.018)*
Poland	0.152 (0.006)	0.774 (0.009)	-0.213 (0.012)*	-0.077 (0.021)*
Portugal	0.130 (0.017)	0.818 (0.022)	-0.170 (0.032)*	0.132 (0.060)*
Romania	0.252 (0.003)	0.667 (0.004)	-0.241 (0.008)*	-0.319 (0.010)*
Slovakia	0.156 (0.013)	0.743 (0.020)	-0.193 (0.037)*	0.136 (0.086)
Spain	0.115 (0.001)	0.841 (0.001)	-0.181 (0.003)*	-0.103 (0.006)*
Sweden	0.148 (0.001)	0.766 (0.002)	-0.351 (0.008)*	-0.089 (0.012)*

Bootstrapped standard errors in parentheses. Asterisks denote statistical significance of distributional effects at 5% level.

3.3.3 Empirical results

In the following, we present the results for the estimation of β^k, β^l, γ^k, and γ^l. We report results based on the OLS estimation of (3.13) in *Table* 3.2. The first two columns reveal that, as expected, changes in the levels of aggregate capital and labor have a positive significant effect on growth in all countries. Further, the capital coefficient appears to be higher for transition than for developed countries. Overall, the estimated aggregate output elasticities with respect to aggregate capital and labor, i.e., $\hat{\beta}^k$ and $\hat{\beta}^l$, are comparable with those obtained by other studies.[17] More interestingly, we find that distributional effects of capital or labor, associated with γ^k and γ^l, are significant at 1% level in all countries. These coefficients are displayed in the last two columns of *Table* 3.2. Further, the distributional effects of capital are negative and generally higher (in absolute value) than the corresponding level effects associated with β^k. As for distributional effects of labor, they turn out to be negative and significant at 1% level for all countries except from Austria, Czech Republic, Portugal and Slovakia. For Portugal they are positive and significant at the 5% level. Summing up, distributional effects of capital and labor, which have been overlooked in the growth literature so far, are statistically and economically significant.

We investigate the robustness of this finding, in that we control for potential simultaneity and misspecification of the functional form. *Table* 3.3 reports the estimation results according to the Olley and Pakes (1996) method. Overall, the estimates are similar to the OLS estimates but exhibit higher standard errors. We infer that the simultaneity problem is of less importance in our sample. In particular, γ^k is still negative and significant for all countries. Moreover, apart from Germany and Romania, the distributional effects of capital are again stronger (in absolute value) than the corresponding level effect. The distributional effects of labor are negative and significant in 13 out of 20 countries. The results for the semiparametric estimation are reported

[17] Recall that under this specification $\hat{\beta}^k = \hat{\theta}^k$ and $\hat{\beta}^l = \hat{\theta}^l$. Hence, we can compare our estimates with those obtained in studies on production function estimation from the firm-level data, e.g., Olley and Pakes (1996), Levinsohn and Petrin (2003), and Blundell and Bond (2000).

in *Table* 3.4. We observe that the estimates of β^k exceed the corresponding OLS estimates in most countries. In contrast, $\hat{\beta}^l$ are comparable to the OLS counterparts. At least one of the distributional effects, i.e., γ^k or γ^l, is significant in all countries apart from the Czech Republic and Slovakia. Interestingly, accounting for a more flexible functional form yields positive significant distributional effect of capital in Denmark, Italy and Norway. In contrast, γ^k is negative significant for eleven countries. Besides, the distributional effects of capital are lower than the ones resulting from the loglinear model. As opposed to previous models, they are also lower than the corresponding level effects. As for distributional effects of labor, they are negative significant in ten countries and positive significant in Portugal. Summing up, the importance of the distributional effects, which are the main focus of this chapter, is robust to simultaneity and parametric misspecification.

The negative impact of changes in the standard deviation of inputs in most countries supports the intuition outlined in Remark 2. First, under the assumption that a higher degree of product market competition among firms is associated with more similarity in firm size, i.e., smaller standard deviations of capital and labor, we find a positive relationship between competition and economic growth. This positive relation is also found in the literature, for instance, by Nicoletti and Scarpetta (2003).

Second, changes in the distribution of inputs capture changes in the pattern of economic interactions between firms. In particular, the literature on economic growth emphasizes the importance of technology spill-overs among firms in developed economies. A standard assumption in the literature is that technology spill-overs are more likely between firms that are more similar in terms of the inputs they use in the production process.[18] Accordingly, an increase in the standard deviation of capital or labor corresponds to less intensive technology spill-overs and, hence, to lower growth rates.

[18]Theoretical models by Basu and Weil (1998) and Acemoglu and Zilibotti (2001) show that international technology diffusion is stronger if firms employ more similar capital-labor ratios in production. An empirical evidence in favor of this result is provided by Keller (2004).

Table 3.3: Aggregate coefficients based on Olley and Pakes (1996) method

country	$\hat{\beta}^k$	$\hat{\beta}^l$	$\hat{\gamma}^k$	$\hat{\gamma}^l$
Austria	0.165 (0.067)	0.795 (0.087)	-0.240 (0.127)*	-0.010 (0.062)
Belgium	0.159 (0.029)	0.715 (0.009)	-0.298 (0.057)*	-0.184 (0.037)*
Bosnia & H.	0.266 (0.076)	0.509 (0.020)	-0.195 (0.86)*	-0.260 (0.068)*
Bulgaria	0.286 (0.042)	0.560 (0.017)	-0.304 (0.062)*	-0.089 (0.072)
Czech R.	0.111 (0.045)	0.752 (0.014)	-0.124 (0.051)*	0.029 (0.040)
Denmark	0.121 (0.039)	0.760 (0.008)	-0.166 (0.053)*	-0.095 (0.017)*
Estonia	0.185 (0.020)	0.685 (0.012)	-0.209 (0.025)*	-0.080 (0.034)*
Finland	0.156 (0.017)	0.763 (0.005)	-0.282 (0.035)*	-0.067 (0.013)*
France	0.119 (0.009)	0.829 (0.003)	-0.228 (0.018)*	-0.031 (0.008)*
Germany	0.117 (0.038)	0.744 (0.016)	-0.081 (0.035)*	-0.020 (0.044)
Great Britain	0.155 (0.035)	0.782 (0.005)	-0.285 (0.067)*	-0.038 (0.019)*
Italy	0.163 (0.017)	0.705 (0.003)	-0.173 (0.018)*	-0.061 (0.007)*
Netherlands	0.180 (0.031)	0.758 (0.013)	-0.213 (0.041)*	-0.051 (0.034)
Norway	0.064 (0.007)	0.835 (0.008)	-0.109 (0.012)*	-0.059 (0.006)*
Poland	0.123 (0.046)	0.741 (0.011)	-0.164 (0.065)*	-0.091 (0.032)*
Portugal	0.126 (0.051)	0.832 (0.041)	-0.236 (0.101)*	0.007 (0.062)
Romania	0.147 (0.044)	0.629 (0.006)	-0.101 (0.030)*	-0.252 (0.014)*
Slovakia	0.158 (0.053)	0.682 (0.028)	-0.186 (0.072)*	0.234 (0.135)
Spain	0.121 (0.010)	0.817 (0.002)	-0.173 (0.015)*	-0.063 (0.007)*
Sweden	0.154 (0.007)	0.759 (0.002)	-0.353 (0.018)*	-0.070 (0.012)*

Bootstrapped standard errors in parentheses. Asterisks denote statistical significance of distributional effects at 5% level.

Table 3.4: Aggregate coefficients based on semiparametric specification

country	$\hat{\beta}^k$	$\hat{\beta}^l$	$\hat{\gamma}^k$	$\hat{\gamma}^l$
Austria	0.171 (0.030)	0.779 (0.035)	-0.095 (0.045)*	-0.212 (0.061)*
Belgium	0.142 (0.011)	0.813 (0.014)	-0.097 (0.018)*	-0.231 (0.041)*
Bosnia & H.	0.240 (0.047)	0.729 (0.040)	-0.340 (0.057)*	0.109 (0.077)
Bulgaria	0.295 (0.036)	0.725 (0.041)	-0.095 (0.053)*	-0.050 (0.087)
Czech R.	0.257 (0.025)	0.793 (0.020)	-0.024 (0.039)	0.067 (0.038)
Denmark	0.174 (0.015)	0.796 (0.013)	0.038 (0.022)*	-0.220 (0.034)*
Estonia	0.187 (0.016)	0.775 (0.020)	-0.119 (0.025)*	-0.109 (0.043)
Finland	0.160 (0.010)	0.833 (0.010)	-0.095 (0.017)*	-0.090 (0.021)*
France	0.119 (0.003)	0.870 (0.004)	-0.059 (0.006)*	-0.024 (0.011)*
Germany	0.178 (0.013)	0.815 (0.016)	-0.006 (0.020)	-0.100 (0.044)*
Great Britain	0.211 (0.008)	0.797 (0.009)	-0.066 (0.012)*	-0.125 (0.021)*
Italy	0.153 (0.007)	0.820 (0.006)	-0.027 (0.021)	-0.063 (0.013)*
Netherlands	0.170 (0.019)	0.829 (0.022)	-0.002 (0.038)	-0.115 (0.050)*
Norway	0.141 (0.010)	0.856 (0.011)	0.060 (0.016)*	-0.050 (0.027)
Poland	0.156 (0.017)	0.856 (0.017)	-0.130 (0.031)*	-0.024 (0.033)
Portugal	0.231 (0.058)	0.805 (0.074)	-0.045 (0.037)	0.149 (0.084)*
Romania	0.209 (0.009)	0.693 (0.008)	-0.264 (0.018)*	-0.206 (0.014)*
Slovakia	0.309 (0.060)	0.730 (0.053)	-0.082 (0.089)	0.141 (0.103)
Spain	0.164 (0.004)	0.831 (0.003)	-0.001 (0.006)	-0.142 (0.009)*
Sweden	0.173 (0.004)	0.820 (0.005)	-0.095 (0.008)*	-0.047 (0.014)*

Bootstrapped standard errors in parentheses. Asterisks denote statistical significance of distributional effects at 5% level.

3.4 Growth Accounting

We exploit the economic significance of the distributional effects outlined above to refine conventional growth accounting exercises. That is, we explore whether cross-country growth differences can be explained by differences in changes in the allocation of capital and labor. Their explanatory power depends on the cross-country heterogeneity in γ^k and γ^l as well as the heterogeneity in the growth rates of the standard deviations of the inputs.

To measure the success of a model in explaining cross-country growth differences we follow the tradition of variance decomposition. That is, analog to Caselli (2005), we compute the explanatory power of the changes in the aggregate input levels as:

$$\texttt{S1} = \frac{var(\hat{g}_{1,t})}{var(g_t)} \tag{3.15}$$

where

$$\hat{g}_{1,t} = \hat{\beta}^k_{t-1}(\log \bar{K}_t - \log \bar{K}_{t-1}) + \hat{\beta}^l_{t-1}(\log \bar{L}_t - \log \bar{L}_{t-1}).$$

The residual of this indicator, $1 - \texttt{S1}$, is the explanatory power of changes in TFP. However, we know from the above Proposition that part of the residual changes should not be associated to changes in the production technology (TFP), but instead, to changes in the higher moments of the distribution of capital and labor across firms. Accordingly, our approach which takes firm-level heterogeneity in the inputs into account leads to a different growth accounting model:

$$\texttt{S2} = \frac{var(\hat{g}_{2,t})}{var(g_t)}, \tag{3.16}$$

where

$$\hat{g}_{2,t} = \hat{\beta}^k_{t-1}(\log \bar{K}_t - \log \bar{K}_{t-1}) + \hat{\beta}^l_{t-1}(\log \bar{L}_t - \log \bar{L}_{t-1}) + \hat{\gamma}^k_{t-1}\Big(\frac{\sigma^k_t - \sigma^k_{t-1}}{\sigma^k_{t-1}}\Big) + \hat{\gamma}^l_{t-1}\Big(\frac{\sigma^l_t - \sigma^l_{t-1}}{\sigma^l_{t-1}}\Big).$$

In addition to the estimated aggregate coefficients, growth accounting requires data on the growth rate of aggregate output, aggregate capital, aggregate labor, and the standard deviations of log capital and log labor. Since the estimation of coefficients relies on data in 2003 (corresponding to $t-1$) we focus on growth rates from 2003 to 2004. All of the required information is available in the AMADEUS database. However, the computation of aggregate output and inputs from the cross-section of firms yields implausibly high growth rates in some countries as is displayed in *Table* 3.1. Therefore, we employ information on aggregate growth rates from the standard cross-country data sets. In particular, we employ Penn World Tables and follow Caselli (2005) in measuring output as real GDP per capita in PPP and computing the aggregate capital stock from the corresponding investment series using the perpetual inventory method by assuming a yearly depreciation rate of 6%. Since aggregate labor in 2004 is not available in the Penn World Tables, we measure aggregate labor as the total number of employees from the Eurostat database. Obviously, the information on the standard deviations of log capital and log labor has to be obtained from the firm-level database. Unfortunately, required aggregate data for Bosnia and Herzegovina are not available and we are forced to omit this country in our analysis. The growth rates of the variables employed in the growth accounting exercise are reported in *Table* 3.5.

We derive S1 and S2 based on the three different estimators outlined in the last section. In particular, we find that the aggregate capital and labor explain 28% of the cross-country growth differences based on the OLS estimates ($\texttt{S1}_{OLS} = 0.28$), 29% based on the Olley and Pakes (1996) method ($\texttt{S1}_{OP} = 0.29$), and 40% based on the semiparametric model ($\texttt{S1}_{SP} = 0.40$). These results are consistent with the corresponding findings in the conventional growth accounting literature. If we additionally take the distributional effects into consideration, we are able to explain an additional 17%, 13%, and 6% of the growth differences across countries, respectively ($\texttt{S2}_{OLS} = 0.45$, $\texttt{S2}_{OP} = 0.42$, $\texttt{S2}_{SP} = 0.46$). Recall that our aggregate coefficients are not estimated by fitting changes in aggregate levels and standard deviations to output growth rates, but are computed from a structural estimation based on firm-level data. Hence, in contrast to standard goodness-of-fit measures, the explanatory power could drop if we additionally account for distributional effects. This would be the

Table 3.5: Growth accounting: growth rates in 2004 (in %)

country	g_{04}	$\log \frac{\bar{K}_{04}}{\bar{K}_{03}}$	$\log \frac{\bar{L}_{04}}{\bar{L}_{03}}$	$\frac{\sigma^k_{04}-\sigma^k_{03}}{\sigma^k_{03}}$	$\frac{\sigma^l_{04}-\sigma^l_{03}}{\sigma^l_{03}}$
Austria	2.14	-1.31	0.57	-2.46	-1.89
Belgium	2.46	3.52	0.65	0.61	-0.76
Bosnia & H.	-	-	-	-5.14	-6.20
Bulgaria	5.02	10.02	2.59	-0.62	-1.38
Czech R.	3.10	4.73	-0.28	-0.43	2.33
Denmark	1.71	2.22	0.00	0.79	-1.00
Estonia	7.73	-0.54	0.25	1.24	0.48
Finland	3.47	2.75	0.41	-3.33	-0.22
France	1.97	5.03	0.05	0.46	0.38
Germany	1.66	1.13	0.42	1.22	0.27
Great Britain	2.75	1.93	1.00	1.52	0.56
Italy	1.09	0.28	0.37	3.78	10.14
Netherlands	1.23	2.25	-1.42	-0.21	1.79
Norway	2.20	9.26	0.47	0.83	1.39
Poland	5.31	6.36	1.31	-0.28	0.66
Portugal	0.38	1.26	0.09	0.22	3.50
Romania	8.68	1.64	0.39	-5.42	1.86
Slovakia	3.50	9.25	0.27	-10.04	-4.29
Spain	1.61	1.95	3.42	0.06	-0.92
Sweden	3.58	-1.27	-0.57	1.61	1.04

case if the changes in σ^k and σ^l were negatively correlated with omitted factors that explain GDP-growth. Consequently, distributional effects of capital and labor across firms help to explain a significant part of variation in growth across the 19 European countries.

We analyze the robustness of the above result in two different ways. First, we redo the growth accounting exercise by excluding one country at a time. We repeat this procedure for all countries. Doing this, we obtain very similar results as the ones from the unrestricted sample. Second, we extend the sample period to 2002-2004, which virtually does not change our results. In all, the growth accounting results are robust to variations in the cross-section as well as in the time-series dimension.

Overall, we conclude that accounting for distributional effects of capital and labor helps explain an additional 6-17% of the cross-country variation in output growth among the 19 European countries. Thus, a growth accounting model which is based on the correct treatment of firm heterogeneity improves the explanatory power of the production inputs and reduces the relevance of the residual TFP measure.

3.5 Conclusion of Chapter 3

In this chapter, we propose a growth model to examine the effect of distributional changes of capital and labor on economic growth. We show that the growth rate of an economy depends not only on changes in the aggregate level of capital and labor, but also on changes in the allocation of these inputs across firms, which we measure by standard deviations of capital and labor. Our empirical analysis, based on European firm-level data, reveals that changes in the allocation of capital and labor due to firm-level heterogeneity have economically and statistically significant effects on GDP-growth in almost all of the 20 European countries. This striking result revises the rather unimportant role of capital and labor distributions in explaining income and growth differences across countries as documented, for instance, by Caselli (2005). Moreover, it suggests that conventional TFP measures misleadingly capture growth effects stemming from changes in the standard deviations of capital and labor. In fact, our framework allows to assess the explanatory power of higher moments of the input distributions and, therefore, reassess the explanatory power of TFP. In this regard, we refine conventional growth accounting exercises by controlling for cross-country differences in aggregate input levels *and* input allocations.

We find that higher standard deviations in labor and capital have negative effects on output growth. This finding is consistent with a positive relationship between competition and growth if more competition is associated with more similarity in firm size and, hence, lower standard deviations in capital and labor among firms. Our findings are also consistent with the hypothesis that technology spill-overs are more intensive if firms are becoming more similar.

Finally, in a growth accounting exercises we show that distributional effects of capital and labor help explain an additional 6-17% of cross-country growth differences among the 19 European countries.

Concluding remarks

This dissertation contributes to the explanation of differences in total factor productivity growth across countries or over time. It presents new mechanisms that help explain firm-level technology choices by taking the interdependence between different micro- and macroeconomic factors into account. In the following, we briefly summarize the most important results particularly with regard to their implications for policymakers in developed or emerging economies.

The first chapter demonstrates that the provision of infrastructure capital influences corporate investments in R&D if one accounts for the effect of infrastructure on the costs of using a large variety of intermediate goods in final production. Therefore, the model is able to explain the positive empirical relationship between infrastructure and R&D investments which we detect in the panel of 36 relatively developed countries as well as a panel of U.S. firms. Instead, we do not find a positive relationship between the provision of infrastructure and private capital investments at the country- or firm-level. The empirical findings are striking since they challenge conventional growth theories which are based on a complementarity between infrastructure and private capital investments. Moreover, we define relatively mild conditions which involve the existence of multiple strictly positive balanced growth pathes if one considers an endogenous financing of infrastructure investments. The interdependence of R&D and infrastructure investments in relatively developed countries refines our understanding of the link between infrastructure and growth. It implies that the growth-effect of infrastructure investments depends on factors such as intellectual property rights, the degree of product market competition, or tertiary education instead of factors that influence a household's saving decision. Thus, policymakers in the 36 countries of our sample are recommended, on average, to invest in infrastructure in regions with high R&D investments. Otherwise, the financing or subsidizing of regional infrastructure projects should be accompanied by simultaneous support of local R&D activities. We emphasize that our analysis represents only a first step to explain the relation between infrastructure and growth and future work should be devoted to its effect on innovative activities and technical change.

The second chapter reveals that the interdependence between the degree of financial development and the level of inflation affects the composition of corporate investments in an economy. It follows that the level of inflation influences long-run aggregate TFP-growth in a world of incomplete financial markets as long as more productive investments are also more risky. We underpin the general equilibrium implications of our model with sound empirical evidence based on dynamic panel estimations at the country-, industry-, and firm-level. This novel aspect of monetary transmission entails strong policy implications. In particular, a low inflation policy represents a relatively inexpensive way to foster long-run TFP-growth and to encourage private sector innovations. This policy implication is the more important for some emerging economies that suffer from underdeveloped financial markets and high inflation. Moreover, the potential long-run impact of the level of inflation on TFP-growth implies that monetary authorities should be cautious to use expansionary monetary policy as a tool to stimulate the economy in the short-run. In this regard, there exists up to a certain extend a tradeoff between short-run stabilization policy and long-run productivity growth.

The third chapter presents an endogenous growth model that accounts for a heterogeneity in firm-level technologies and input demands. This framework makes it possible to account for growth-effects stemming from (higher moments of) the distribution of input factors across firms. It is shown that up to 17% of the differences in TFP-growth across countries have to be attributed to differences in the distribution of capital and labor. A reduction in the standard deviation of capital or labor induces, on average, a positive growth effect in most of the 20 European countries in our sample. This effect is consistent with a positive relationship between competition and growth if more competition is associated with more similarity in input demands among firms. It is also consistent with the empirical prediction that technology spill-overs are more intensive among more similar firms. Policymakers can potentially affect the distribution of capital and labor across firms by means of industrial policies, i.e. competition policy or asymmetric regulations for different firm sizes. We emphasize, however, that the main purpose of this chapter of the dissertation is to demonstrate the impact of distributional effects on economic growth and to refine conventional growth accounting methods. A more pronounced policy evaluation requires a separate analysis of distributional growth effects at the industry level. The above model is well-suited to aggregate among heterogenous firms in each sector separately for a given country. This approach would accentuate differences in distributional effect across different industries and thus allow for appropriate industry-specific policy measures. Therefore, we consider the aggregation across heterogenous firms at the industry level as important future research.

In sum, this dissertation addresses several new determinants of total factor productivity growth. Thereby, it refines the scope for macroeconomic or industrial policies to foster long-run economic growth and development and to reduce income differences across countries.

A Appendix

A.1 Proof of Proposition II

Given the assumptions underlying Proposition I, we know that the balanced growth rate is a continuous, monotonic, increasing function of the stock of infrastructure capital (assuming $\lambda > \lambda^{**} = \frac{\rho\beta^2+\rho\chi\mu(\rho+\delta)}{\alpha(1-\alpha)\mu(\delta+\rho)}$). Since we assume $\phi'(G) < 0$, $\phi''(G) > 0$ and $\lambda > \lambda^{**}$, we can infer from (2.20):

$$\frac{\partial\gamma}{\partial G} = \frac{\partial\gamma}{\partial\phi(G)}\frac{\partial\phi(G)}{\partial G} = \left(\frac{-\chi\rho[a+\chi\sigma\phi(G)] - \chi\sigma\hat{\lambda}}{[a+\chi\sigma\phi(G)]^2}\right)\phi'(G) > 0$$

$$\frac{\partial^2\gamma}{\partial^2 G} = \frac{\partial^2\gamma}{\partial^2\phi(G)}\frac{\partial^2\phi(G)}{\partial^2 G} = \left(\frac{\chi^2\rho\sigma[a+\chi\sigma\phi(G)]^2 + 2\chi^2\sigma^2[a+\chi\sigma\phi(G)]\hat{\lambda}}{[a+\chi\sigma\phi(G)]^3}\right)\phi''(G) > 0$$

where $\hat{\lambda} = a\lambda - \chi\sigma\phi(G) > 0$ and $a = \alpha(1-\alpha) > 0$.

Hence, the balanced growth rate is a strictly convex function of the stock of infrastructure capital: $\gamma = \gamma(G)$, $\gamma'(G) > 0$, $\gamma''(G) > 0$.

The equilibrium provision of infrastructure capital is given in (1.20). The marginal variable investment costs are a continuous, monotonic, increasing function of time ($\frac{\partial\mathcal{C}_{I_t}}{\partial t}$¿0). In order to sustain (positive) balanced growth, we assume that marginal infrastructure investment costs increase proportional to the GDP-level in the economy ($I_t = \delta G_t$), but can not exceed it.[19] It follows from (1.17) that infrastructure capital is a continuous, monotonic function of the balanced growth rate in equilibrium. This

[19]Note that this is a necessary but not a sufficient condition for the existence of a balanced growth equilibrium. In order to obtain a sufficient condition, we would need to impose quantitative assumptions on $\phi(G_t)$ and $\mathcal{C}(I_t, t)$ relative to Y_t.

allows us to define $N(t) = \frac{Y_t}{\mathcal{C}_{I_t}}$, where $N'(t) \geq 0$, $N''(t) \geq 0$. We also defined $\frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}t} = M(t)$, where $M'(t) > 0$ and $M''(t) = 0$ in a balanced growth equilibrium. Thus, we can infer from (1.20):

$$
\begin{aligned}
\frac{\partial G}{\partial \gamma} &= \frac{\beta^2 N'[\delta + \rho - M(\gamma)] + \beta^2 N(\gamma) M'}{[\delta + \rho - M(\gamma)]^2} > 0 \\
\frac{\partial^2 G}{\partial^2 \gamma} &= \frac{[\beta^2 N''[\delta + \rho - M(\gamma)] - \beta^2 N' M'][\delta + \rho - M(\gamma)] + [\beta^2 N'[\delta + \rho - M(\gamma)] M']}{[\delta + \rho - M(\gamma)]^3} \\
&+ \frac{[\beta^2 N' F' + \beta^2 N(\gamma) M''][\delta + \rho - M(\gamma)] + \beta^2 N(\gamma) M' M'}{[\delta + \rho - M(\gamma)]^3} > 0
\end{aligned}
$$

The first derivative is always positive. A sufficient condition for the second derivative to be positive is $\delta + \rho - M(\gamma) > 0$, which we assume. Hence, we do not allow that the growth rate of the marginal (variable) infrastructure investment costs exceeds the summation of the depreciation rate for infrastructure capital and the intertemporal elasticity of substitution. A violation of this condition is empirically irrelevant so that the restriction is rather technical. Hence, the infrastructure capital stock is a strictly convex function of the balanced growth rate: $G = G(\gamma)$, $G'(\gamma) > 0$, $G''(\gamma) > 0$.

In addition, we know that $\gamma = \gamma(0) = 0$ since $\lim_{G \to 0} \phi(G) \to \infty$ and $G = G(0) = G_0 > 0$ holds by assumption. Consequently, given a balanced growth path exists, it features two strictly positive balanced growth rates γ_1 and $\gamma 2$ with $\gamma_1 > \gamma 2$.

A.2 Marginal investment costs increase in Y_t:

In the following, we report the partial derivatives of γ_1 and γ_2 (from (1.22) and (1.23)) with respect to λ, β and μ:

$$\begin{aligned}
\frac{\partial\gamma_1}{\partial\lambda} &= a\mu\left(1+\frac{a\mu(\delta+\rho-\lambda)+\chi(\mu(\rho+\sigma(\delta+\rho))-\beta\sigma)}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_2}{\partial\lambda} &= a\mu\left(1-\frac{a\mu(\delta+\rho-\lambda)+\chi(\mu(\rho+\sigma(\delta+\rho))-\beta\sigma)}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_1}{\partial\beta} &= 2\beta\chi\left(\sigma+\frac{a\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho))}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_2}{\partial\beta} &= 2\beta\chi\left(\sigma-\frac{a\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho))}{Z^{1/2}}\right)<>0\\
\frac{\partial\gamma_1}{\partial\mu} &= -\frac{\beta^2\chi(\alpha\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma(\beta^2\sigma\chi+\chi\mu(\rho+\sigma(\delta+\rho))-\sigma Z^{1/2}))}{2\mu^2(a+\sigma\rho)Z^{1/2}}<0\\
\frac{\partial\gamma_2}{\partial\mu} &= \frac{\beta^2\chi(\alpha\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho)))+Z^{1/2})}{2\mu^2(a+\sigma\rho)Z^{1/2}}<>0
\end{aligned}$$

where $Z=[a\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)]^2-4\mu[a+\chi\sigma][a\lambda\mu(\delta+\rho)-\rho(\beta^2+\chi\mu(\delta+\rho))]>0$ and $a=\alpha(1-\alpha)$.

B Appendix

B.1 Financial contract

In the following, we provide the algebraic solution of the financial contract $\mathcal{C}_t = \{z_t, l_t^z, \Gamma_t(\xi_t), \tau_t(\xi_t)\}$ defined in (2.12).

Optimal factor input ratio and the cost function: Obviously, part of the optimal contract must be to use factor inputs in a cost minimizing combination. However, since factor demands are determined via the contract $\mathcal{C}_t$, they will not only reflect the firm's profit maximization objective, but also the intermediary's need to break even in expectation. With our Cobb-Douglas specification, the possibility of project failure then requires that factors earn constant shares not of firm revenue, but of the total costs $C\left(W_t^z, R_t^z; \tilde{y}_t^z\right)$ associated with a targeted production scale $\tilde{y}_t^z$. Hence, the demands for capital and labor are:

$$z_t = \frac{\alpha^z P_t^z \tilde{y}_t^z}{R_t^z} \qquad \text{and} \qquad l_t^z = \frac{(1 - \alpha^z P_t^z \tilde{y}_t^z)}{W_t^z} \tag{B.1}$$

Furthermore, from constant returns to scale and the Cobb-Douglas specification of the technology, we can write:

$$C\left(W_t^z, R_t^z; \tilde{y}_t^z\right) = MC_t^z\left(W_t, R_t^z\right)\tilde{y}_t^z = \frac{1}{\mathcal{T}_t\mathcal{V}}\left(\frac{R_t}{\alpha}\right)^{\alpha}\left(\frac{W_t^z}{(1-\alpha)}\right)^{(1-\alpha)}\tilde{y}_t^z \tag{B.2}$$

where $MC_t^z(\cdot)$ are the per unit costs of producing a targeted output level $\tilde{y}_t^z$; since the technology displays constant returns to scale, these per unit costs coincide with marginal costs. Note that, as a consequence, the program to find the optimal contract is linear in the project size $\tilde{y}_t^z$.

First best - the socially optimal contract: First look at the first best contract where $b = 0$ such that the entrepreneurial moral hazard problem plays no role (but liquidity is scarce and has an opportunity cost $\tilde{R}_t$). The questions asked here are, what is the maximum overall return on investment, and how does the corresponding socially optimal contract look like? Suppose for the moment a binding participation constraint for the investor; indeed, we will later verify that this is the case in a well-specified problem.[20] Substituting from the binding participation constraint (2.12b) into the entrepreneur's net return (2.12a) yields:

$$\Pi_t^F = \left[\int \Gamma_t(\xi_t) \frac{P_t^z}{MC_t^z(\cdot)} \left(1 - \xi_t \tilde{R}_t\right) dG(\xi_t) - 1 \right] MC_t^z(\cdot) \tilde{y}_t^z$$

Let $\hat{\xi}_t$ denote the cutoff value for the liquidity shock such that the project is continued if and only if $\xi_t \leq \hat{\xi}_t$; using this rule for the indicator function then allows to rewrite the entrepreneur's net return as:

$$\Pi_t^F(\hat{\xi}_t) = \lambda_t(\hat{\xi}_t) MC_t^z(\cdot) \tilde{y}_t^z, \tag{B.3a}$$

where:

$$\lambda_t(\hat{\xi}_t) \equiv \left[\int_0^{\hat{\xi}_t} \frac{P_t^z}{MC_t^z(\cdot)} \left(1 - \xi_t \tilde{R}_t\right) dG(\xi_t) - 1 \right] \tag{B.3b}$$

In definition (B.3b), $\lambda_t(\hat{\xi}_t)$ denotes the net social marginal return on one unit invested in an individual advanced sector project, given a cutoff value $\hat{\xi}_t$. Since $\frac{P_t^z}{MC_t^z(\cdot)} > 0$, $\lambda(\hat{\xi}_t)$ is maximized at the socially optimal cutoff value $\hat{\xi}_t^{FB} = \frac{1}{\tilde{R}_t}$. Moreover, from (B.3a), it is clear that the entrepreneur is the residual claimant and receives the full social surplus from the project.

Second best - entrepreneurial moral hazard: Now consider the case where $b > 0$. First of all note that general equilibrium considerations imply that the marginal net social return under both the first and the second best solution must be positive.[21] Then, given a positive value for $\lambda_t(\hat{\xi}_t)$, the entrepreneur will seek to maximize $\Pi_t^F(\hat{\xi}_t)$

[20]By well-specified, we mean (i) that there is no self-financing by the firms, and (ii) that the solution to the constrained-optimal contract features a finite investment level.

[21]To see this, suppose to the contrary that $\lambda(\hat{\xi}_t^{FB}) \leq 0$ such that the optimal contract would prescribe $z_t = l_t^z = 0$, i.e. zero investment for any level of entrepreneurial equity E_t. However, this implies $\tilde{y}_t^z = 0$ which contradicts a general equilibrium with positive consumption and investment,

by choosing the maximum investment volume $MC_t^z(\cdot)\tilde{y}_t^z$ that still guarantees investor participation. But from (2.12b), this is achieved by maximizing the state contingent per unit transfer $\tau_t(\xi_t)$ to the investor. Accordingly, the second best contract prescribes to retain the minimum amount of profits in the firm that is still consistent with incentive compatibility. Hence, the entrepreneur's incentive compatibility constraint (2.12c) is binding at the maximum pledgeable unit return:

$$\tau_t(\xi_t) = \frac{\Gamma_t(\xi_t)(1-b)P_t^z\tilde{y}_t^z}{MC_t^z(\cdot)\tilde{y}_t^z} \tag{B.4}$$

We can now solve for the largest investment volume $MC_t^z(\cdot)\tilde{y}_t^z$ that is compatible with both the investor's participation constraint and the entrepreneur's incentive constraint by substituting the maximum pledgeable unit return (B.4) into the investor's participation constraint (2.12b) to obtain:

$$\left[1 - \int \Gamma(\xi_t)\left((1-b) - \xi_t\tilde{R}_t\right)\frac{P_t^z}{MC_t^z(\cdot)}dG(\xi_t)\right] MC_t^z(\cdot)\tilde{y}_t^z = E_t \tag{B.5}$$

Here, the expression in squared brackets represents the difference between marginal cost of investment to an outside investor and the expected marginal return to such outside investment. Let $\hat{\xi}_t^0 \equiv \frac{(1-b)}{\tilde{R}_t}$ denote the cutoff value that maximizes the expected marginal return to outside investors, and note that equation (B.5) implies that, given some $E_t > 0$, the expected (subject to idiosyncratic liquidity shocks) marginal return on outside investment is strictly smaller than one.[22]

and the price of the advanced intermediate good would adjust such as to guarantee a positive marginal net social return. By the same token, the second best solution must also involve a cutoff rule $\hat{\xi}_t$ with positive marginal net social return.

[22] Indeed, if this was not the case, investment would be self-financing and there would be no demand for liquidity at all in that the investor's participation constraint would be non-binding. A sufficient condition for ruling out self-financing is:

$$\int_0^{\hat{\xi}_t^0}\left((1-b) - \xi_t\tilde{R}_t\right)\frac{P_t^z}{MC_t^z(\cdot)}dG(\xi_t) < 1$$

Solving equation (B.5) for the maximum investment volume conditional on a given cutoff value $\hat{\xi}_t$, allows to write the firm's investment capacity as:

$$MC_t^z(\cdot)\tilde{y}_t^z \quad = \quad \mu_t(\hat{\xi}_t)E_t, \tag{B.6a}$$

where:

$$\mu_t(\hat{\xi}_t) \quad \equiv \quad \frac{1}{1 - \int_0^{\hat{\xi}_t} \left((1-b) - \xi_t \tilde{R}_t\right) \frac{P_t^z}{MC_t^z(\cdot)} dG(\xi_t)} \tag{B.6b}$$

is an equity multiplier, whose denominator specifies the amount of internal funds that the firm has to contribute per unit of investment in order to compensate the outside investor for the shortfall implied by the expression in squared brackets in (B.5). Finally, using (B.3a) and (B.6a), the entrepreneur's expected net payoff becomes:

$$\Pi_t^F(\hat{\xi}_t) = \lambda_t(\hat{\xi}_t)\mu_t(\hat{\xi}_t)E_t \tag{B.7}$$

It now remains to determine the second best continuation threshold, to be denoted $\hat{\xi}_t^*$. Given an entrepreneurial equity position E_t, the second best cutoff $\hat{\xi}_t^*$ maximizes (B.7). It is clear that $\hat{\xi}_t^* \in [\hat{\xi}_t^0, \hat{\xi}_t^{FB}]$. Within this interval there emerges a trade-off since, on the one hand, increasing $\hat{\xi}_t$ implies that continuation is possible in more contingencies and, on the other hand, decreasing $\hat{\xi}_t$ allows to increase the amount of initial investment $MC_t^z(\cdot)\tilde{y}_t^z$ by increasing the equity multiplier $\mu_t(\hat{\xi}_t)$. After substitution from the definitions (B.3b) and (B.6b) into (B.7), it is straightforward to show that the optimal continuation value $\hat{\xi}_t^*$ can be found as the solution to the following problem:

$$\min_{\hat{\xi}_t} \frac{\tilde{R}_t \int_0^{\hat{\xi}_t} \xi_t dG(\xi_t) + \frac{MC_t^z(\cdot)}{P_t^z}}{G(\hat{\xi}_t)} \tag{B.8}$$

Observe that rewriting this condition yields $\lambda_t(\hat{\xi}_t^0) < b\frac{P_t^z}{MC_t^z(\cdot)}G(\hat{\xi}_t^0)$; then, it is apparent that $\hat{\xi}_t^{FB} = \hat{\xi}_t^0$ if $b = 0$, which leads to the conclusion that, in order to rule out self-financing, a positive wedge $\hat{\xi}_t^{FB} - \hat{\xi}_t^0 > 0$ and therefore $b > 0$ are essential.

which has the interpretation that the second best cutoff value minimizes the expected unit cost of total expected investment. The first order condition to this problem is:

$$\int_0^{\hat{\xi}_t^*} G(\xi_t) d\xi_t = \frac{MC_t^z(\cdot)}{P_t^z} \frac{1}{\tilde{R}_t} \tag{B.9}$$

Finally, using the optimality condition for the cutoff value allows to rewrite the entrepreneur's expected net return in the following compact form:

$$\Pi_t^F(\hat{\xi}_t^*) = \frac{\frac{1}{\tilde{R}_t} - \hat{\xi}_t^*}{\hat{\xi}_t^* - \frac{(1-b)}{\tilde{R}_t}} E_t = \frac{\hat{\xi}_t^{FB} - \hat{\xi}_t^*}{\hat{\xi}_t^* - \hat{\xi}_t^0} E_t \tag{B.10}$$

Observe how this expression reflects the trade-off underlying the choice of $\hat{\xi}_t^* \in [\hat{\xi}_t^0, \hat{\xi}_t^{FB}]$. For future reference, we define the expected net return per unit of entrepreneurial equity E_t as:

$$\tilde{\Pi}_t^F(\hat{\xi}_t^*) \equiv \frac{\frac{1}{\tilde{R}_t} - \hat{\xi}_t^*}{\hat{\xi}_t^* - \frac{(1-b)}{\tilde{R}_t}}$$

Implementation and aggregate liquidity demand: In order to cover liquidity shocks up to the second best cutoff $\hat{\xi}_t^*$, it is necessary that outside investors commit funds at the initial contracting stage (*stage one*). The reason is that, by issuing corporate claims at the interim stage (*stage two*), it is not possible to raise enough funds because the entrepreneurial commitment problem limits the maximum return pledgeable to outside investors at $\hat{\xi}_t^0 < \hat{\xi}_t^*$. It is then an natural question to ask how the second best policy can actually be implemented at the initial contracting stage; moreover, in view of our modelling hypothesis that an economy's physical investment portfolio is affected by the degree to which firms can insure their activities by means of holding corporate liquidity, there arises the related question of whether there is a second best policy that features firms (rather than the intermediary) holding liquidity.

Aggregating over the advanced sector firms, we can derive two measures of aggregate liquidity demand. The first one is relevant if the second best policy should be feasible for each individual firm, but liquidity provision is organized in a way that disregards the scope for risk sharing across firms:

$$\bar{D}_t = \hat{\xi}_t^* P_t^z \tilde{y}_t^z \tag{B.11a}$$

In contrast, the second measure of overall liquidity demand is relevant if liquidity risk can be pooled across firms:

$$D_t^* = \left[\int_0^{\hat{\xi}_t^*} \xi_t g(\xi_t) d\xi_t \right] P_t^z \tilde{y}_t^z < \bar{D}_t \tag{B.11b}$$

It is clear that this latter concept requires some form of financial intermediation.

Now, drawing on Holmstrom and Tirole (1998), we turn to the institutional details supporting the implementation of the second best policy derived in Section 2.4.5. One possibility is to have the financial intermediary initially extend the amount $MC_t^z(\cdot)\tilde{y}_t^z - E_t$ to the entrepreneur together with an *irrevocable line of credit* of maximum size $\hat{\xi}_t^* P_t^z \tilde{y}_t^z$ to be drawn from as needed at the interim stage. Given our assumptions on the details of the moral hazard problem which does not envisage distraction of resources on the part of the entrepreneur, this line of credit implements the second best solution as long as the credit line, irrespective of the amount $\xi_t P_t^z \tilde{y}_t^z \leq \hat{\xi}_t^* P_t^z \tilde{y}_t^z$ of liquidity actually requested, is provided free of charge. Since the firms' liquidity shocks are independent, the aggregate amount of resources needed to cover the advanced sector's refinancing needs at the interim stage is then given by D_t^*. At the level of an individual advanced sector firm, an alternative would be via a *liquidity covenant* which involves the financial intermediary initially extending the amount $[1 + (P_t^z / MC_t^z(\cdot))\hat{\xi}_t^*] MC_t^z(\cdot)\tilde{y}_t^z - E_t$ to the entrepreneur, whereby the requirement is imposed that the amount $\hat{\xi}_t^* P_t^z \tilde{y}_t^z$ is not sunk in the project but kept in the form of readily marketable assets. However, at the aggregate level across all advanced sector firms, implementation of the second best policy via liquidity covenants is seen to require strictly more resources $\bar{D}_t > D_t^*$ because liquidity is kept separately at each firm, thus forgoing the potential to pool liquidity across firms.[23]

Given our empirical interest, the question arises whether there is a second best policy that features firms (rather than the intermediary) holding liquidity. We now give an example for such a policy. For that purpose, first define a number $\check{\xi}_t$ which is implicitly given by $D_t^* = \check{\xi}_t P_t^z \tilde{y}_t^z$; then, a policy of the desired kind is constructed as follows: At stage one, the intermediary extends the amount $[1+(P_t^z/MC_t^z(\cdot))\check{\xi}_t]MC_t^z(\cdot)\tilde{y}_t^z - E_t$ to the entrepreneur. The financial contract further stipulates that the amount $\check{\xi}_t P_t^z \tilde{y}_t^z$ must be held in the form of liquid assets. The firm will then invest up to the maximum admissible scale $MC_t^z(\cdot)\tilde{y}_t^z - E_t$ and deposit its liquid assets with the intermediary (at zero interest). Now, at stage two, when hit by a liquidity shock ξ_t, the firm must first use up its own asset position of $\check{\xi}_t P_t^z \tilde{y}_t^z$; only then can it approach the intermediary for additional funds, which the latter will residually provide up to the second best quantity $\hat{\xi}_t^* P_t^z \tilde{y}_t^z$. The intermediary is able to provide this liquidity by calling idle funds from those firms who receive shocks $\xi_t < \check{\xi}_t$. Obviously, this policy replicates the second best in terms of both the initial investment scale and the cutoff $\hat{\xi}_t^*$. Thus, it only remains to check whether above arrangement is feasible, which is the case since, from the definition of $\check{\xi}_t$, the supply of and demand for liquidity are equal at the aggregate level: $P_t^z \tilde{y}_t^z \check{\xi}_t = D_t^* = P_t^z \tilde{y}_t^z \int_0^{\hat{\xi}_t^*} \xi_t g(\xi_t) d\xi_t$. Further variations on the institutional structure implementing the second best, involving advanced sector firms holding assets other than cash (e.g. corporate debt issued by the basic sector firms) as well as liquid assets earning non-zero rates of return, are possible.

[23] In the benchmark section of their paper which features an exogenous supply of liquidity, Holmstrom and Tirole (1998) establish equivalence of the two methods of providing liquidity. This result stems from the fact that their economy allows for a technology ("cash") to transfer wealth across the stages of the financial contracting problem and the additional assumption that cash is not scarce. Conversely, in our economy cash is available, but its (limited) supply is determined in general equilibrium via households' financial deposits and monetary policy. Importantly then, liquidity is costly (it has a price $\tilde{R}_t > 1$), and agents have an incentive to economize on its usage. The consequence is that intermediated credit lines and liquidity holdings on behalf of the firms are no longer equivalent.

B.2 Competitive equilibrium relations

We can derive a set of relations that characterize a competitive equilibrium at the aggregate level. Specifically, for $\tilde{R}_t > 1$, the household's cash constraint (2.1b) is binding and we can aggregate over households and entrepreneurs to obtain a condition relating aggregate consumption and investment to agents' nominal asset holdings:

$$Q_t + (1-\eta)A_t = P_t c_t, \tag{B.12}$$

where $c_t = c_t^H + (1-\eta)c_t^E$. Then, the evolution of nominal wealth held by households is determined via the nominal budget constraint (2.1c) and the binding cash constraint (2.1b):

$$M_{t+1} = \tilde{R}_t[M_t - Q_t + J_t] + \Upsilon_t + R_t^k k_t + R_t^z z_t + W_t^{k,H} h_t^{k,H} + W_t^{z,H} h_t^{z,H}, \tag{B.13}$$

where we note that $\Upsilon_t = D_t + E_t$. This relation stipulates that, at the end of any given period, the nominal resources $D_t + E_t$ lost due to liquidity shocks are re-channelled to the household sector. Accordingly then, while the termination of projects implies that the production of real output is curbed, the amount of nominal resources ("money") circulating is unaffected by liquidity shocks. Now, making use (i) of a zero-profit condition for firms in the basic sector, firms in the advanced sector (net of entrepreneurial rents $\tilde{\Pi}_t^F(\hat{\xi}_t^*)E_t$) and the financial intermediary, (ii) of the financial market clearing condition (2.4), and (iii) of the aggregate cash constraint (B.12), one obtains:

$$M_{t+1} = M_t + \mathcal{J}_t + \Big\{(1-\eta)A_t - [W_t^{k,E} h_t^{k,E} + W_t^{z,E} h_t^{z,E} + (\tilde{\Pi}_t^F(\hat{\xi}_t^*) - 1)E_t]\Big\} \tag{B.14}$$

This relation has the intuitive interpretation that the evolution of nominal household wealth is governed by cash injections $\mathcal{J}_t$ and the net cash flow from the entrepreneurial sector (entrepreneurial consumption expenditure minus retained earnings) to the household sector. The evolution of nominal wealth in the entrepreneurial sector itself follows:

$$A_{t+1} = \tilde{\Pi}_t^F(\hat{\xi}_t^*)E_t + W_t^{k,E}h_t^{k,E} + W_t^{z,E}h_t^{z,E}, \tag{B.15}$$

where $E_t = \eta A_t$. In order to derive a convenient expression for the evolution of aggregate wealth, we add equations (B.13) and (B.15) and employ the zero-profit condition mentioned above as well as condition (2.4) to obtain:

$$M_{t+1} + A_{t+1} - (D_t + E_t) = P_t y_t, \tag{B.16}$$

which gives immediately rise to a modified quantity relation:

$$P_t = \frac{M_{t+1} + A_{t+1} - (D_t + E_t)}{y_t} \tag{B.17}$$

Again, this equation allows for an intuitive interpretation, namely that the contemporaneous price level P_t is determined as the ratio of nominal resources channelled through the goods market to aggregate output.[24]

B.3 Equilibrium

Definition 1. (Competitive Equilibrium) *Given initial conditions* $\{k_0, z_0, A_0, M_0\}$ *and realizations of monetary policy* $\{\mathcal{J}_t\}_{t=0}^{\infty}$ *and idiosyncratic shocks* $\{\xi_t^i\}_{t=0}^{\infty}$*, a competitive equilibrium is a list of allocations* $\{c_t^H, h_t^{k,H}, h_t^{z,H}, k_t, z_t, Q_t, M_{t+1}\}_{t=0}^{\infty}$ *to households and* $\{c_t^{E,i}, h_t^{k,E}, h_t^{z,E}, E_t^i, A_{t+1}^i\}_{t=0}^{\infty} \forall i$ *to entrepreneurs, of sectoral and economy-wide aggregates* $\{c_t, l_t^k, l_t^z, \overline{L}, \overline{K}, y_t^k, y_t^z, y_t\}_{t=0}^{\infty}$ *and of prices* $\{P_t, P_t^z, P_t^k, W_t, W_t^k, W_t^{k,H}, W_t^{k,E}, W_t^z, W_t^{z,H}, W_t^{z,E}, R_t, R_t^k, R_t^z, \tilde{R}_t\}_{t=0}^{\infty}$ *such that:*

1. *given prices, the allocation solves the household problem (2.1) as well as the basic and advanced firm problems (2.8) and (2.12);*

[24] To see this, note that the agents' end-of-period wealth $M_{t+1} + A_{t+1}$ is effectively generated via firm profits whose generation requires transactions on the goods market; from this amount, the nominal resources which are absorbed by liquidity needs and later redistributed to the household sector must be deduced.

2. *entrepreneurs follow their behavioral rules and the financial intermediary breaks even;*

3. *aggregation across agents and sectors as well as among the entrepreneurs obtains, i.e. for a generic variable $v_t^{E,i}$ belonging to the allocation to entrepreneurs: $\int_i v_t^{E,i} di = v_t^E$;*

4. *the financial market as well as the markets for final goods, intermediate goods and factor inputs clear.*

Note that the competitive equilibrium is not efficient due to the entrepreneurial moral hazard problem that leads to the termination of ex-post efficient projects and the externality of knowledge on the future productivity of investment projects.

B.4 The responsiveness of corporate liquidity to changes in the financial rate ($\mathcal{H}1$)

In the following, we demonstrate that the general equilibrium effect of the financial rate ($\tilde{R}_t$) on the corporate provision of liquidity $\hat{\xi}_t^*$ is negative as summarized in $\mathcal{H}1$. Therefore, we assume a specific functional form for the distribution of liquidity shocks: $G(\xi) = \xi^{\frac{1}{\phi}}$, $\phi > 0$. Hence, in accordance with Aghion et al. (2005), we assume that the distribution of liquidity shocks is monotonically increasing in ξ.

Moreover, the relative demand for both intermediates given by (2.6) leads to the following equilibrium condition: $\frac{y_t^z}{y_t^k} = \frac{1-\zeta}{\zeta}\left(\frac{P_t^z}{P_t^k}\right)^{-\rho}$. If we substitute for the price ratio by $\frac{P_t^z}{P_t^k} = \frac{A}{V}\frac{1}{\tilde{R}_t \int_0^{\hat{\xi}_t^*} G(\xi)d\xi}$ from (2.21), we get:

$$G(\hat{\xi}_t^*) = \frac{1-\zeta}{\zeta}\left(\frac{A}{V}\right)^{1-\rho}\left(\tilde{R}_t \int_0^{\hat{\xi}_t^*} G(\xi)d\xi\right)^{\rho} \qquad \text{(B.18)}$$

Taking the total derivative of (B.18) and noting that the functional form for the distribution of liquidity shocks implies that $\frac{dG(\hat{\xi}_t^*)}{d\hat{\xi}_t^*}\frac{\hat{\xi}_t^*}{G(\hat{\xi}_t^*)} = \frac{1}{\phi}$ and $\frac{d\int_0^{\hat{\xi}_t^*} G(\xi)d\xi}{d\hat{\xi}_t^*}\frac{\hat{\xi}_t^*}{\int_0^{\hat{\xi}_t^*} G(\xi)d\xi} = \frac{1+\phi}{\phi}$, we obtain:

$$\frac{d\hat{\xi}_t^*}{d\tilde{R}_t} = \frac{\tilde{R}_t}{\hat{\xi}_t^*} \frac{\rho\phi}{1-\rho(1+\phi)} < 0 \tag{B.19}$$

Thus, given that the functional form for the distribution of liquidity shocks is monotonically increasing in ξ, the general equilibrium provision of corporate liquidity is decreasing in the nominal financial rate $\tilde{R}$ as stated in $\mathcal{H}1$.

B.5 Construction of the TFP measure

We construct the series of aggregate TFP-growth, as a residual from the human capital augmented Solow-model.[25] We follow the basic specification in Caselli (2005) who computes TFP levels across countries for the year 1996. That is, we employ the production function: $y_t = A_t k_t^{\alpha} h_t^{1-\alpha}$, where A is the level of TFP, y the real GDP per worker in international dollars, k the physical capital stock per worker and h the human capital stock per worker. The first measures stem from the Penn World Tables (PWT) and the latter from Barro and Lee (2001), respectively. The capital stock (K) is computed with the perpetual inventory method, whereby the depreciation rate (δ) is set to 6% and the initial capital stock is computed as $K_0 = \frac{I_0}{g+\delta}$. g is the average geometric growth rate for the investment series between the first year with available data and 1970.[26] The stock of human capital is derived according to Hall and Jones (1999): $h = \exp\phi(s)$, where s is the average years of schooling in the population over 25 year old and the function $\phi(s)$ is piecewise linear with slope 0.13 for $s \leq 4$, 0.10 for $4 < s \leq 8$ and 0.07 for $8 < s$. We incorporate a share of private capital per worker of 1/3 ($\alpha = 1/3$). Caselli (2005) provides a comprehensive discussion of various robustness tests to this procedure in a development accounting framework. He shows that the explanatory power of the TFP-series (2/3) to explain variations in

[25] The inclusion of various control variables reduces the effective size of the panel to a minimum of 68 countries in some estimations.

[26] The investment series starts for 54 countries in 1950, for 17 in 1955 and for the remaining 17 in 1960.

GDP is robust to the inclusion of different measures for the quality of human capital or different estimation procedures for k.[27] Therefore, we follow his basic specification. We compute the TFP series for 88 countries from 1970-1980. Our TFP-series complies with Caselli (2005) for 1996. We drop the TFP-measure for the first ten observations and start the series in 1980 in order to minimize the influence of the initial capital stock on our results. The rankings of the TFP-measures across countries and years yield plausible results.[28]

[27]We note that this explanatory power decreases significantly if α exceeds 0.5, which, however, does not comply with existing empirical estimates.

[28]The five highest (log-) TFP level exhibit Ireland in 2000-1997, respectively, and Italy in 1999. The 50 lowest TFP-levels are measured in Zaire, Malawi, Romania, Zambia, Rwanda, Lesotho and China for different time periods, respectively. The complete ranking is available from the authors on request.

C Appendix

C.1 Empirical verification of Assumption 1

We aim to analyze whether the standardized joint distribution of log capital and log labor, i.e., $G_{\tilde{k}l}$, changes sufficiently slowly over time, so that it can be regarded as approximately equal for two 2003 and 2004. In order to answer this question, we apply a nonparametric kernel-based test of closeness between two distribution functions as proposed by Li (1996). Under the null hypothesis that two distributions are equal the test statistic T, which relies on the integrated squared difference between $G_{2003,\tilde{k}l}$ and $G_{2004,\tilde{k}l}$, has a standard normal distribution. However, the asymptotic distribution of T under the null hypothesis has a slow rate of convergence to the the standard normal distribution. In order to account for this finite sample bias, we perform the bootstrap procedure to approximate the distribution of T. We repeat the following procedure $B = 500$ times: Out of the pooled sample $\{(k^1_{2003}, l^1_{2003}), \ldots, (k^{n_{2003}}_{2003}, l^{n_{2003}}_{2003}); (k^1_{2004}, l^1_{2004}), \ldots, (k^{n_{2004}}_{2004}, l^{n_{2004}}_{2004})\}$ two samples $\{(k^{*1}, l^{*1}), \ldots, (k^{*n_{2003}}, l^{*n_{2003}})$ and $\{(k^{*1}, l^{*1}), \ldots, (k^{*n_{2004}}, l^{*n_{2004}})$ are randomly drawn with replacement. Then, based on the new samples the test statistic T^*_b is computed. The empirical distribution of T under the null hypothesis is then estimated from the sample $\{T^*_1, \ldots, T^*_B\}$. The consistency of the bootstrap in this context is proven by Li et al. (2007). Moreover, bandwidth parameters used for testing were obtained through the Sheather and Jones (1991) method.

Assumption 1 is well supported by the Amadeus data. The test results for 20 countries are given in Table 6. They indicate that changes in $G_{\tilde{k}l}$ from 2003 to 2004 can be indeed regarded as statistically insignificant for 17 out of 20 countries in our sample. We reject equality of $G_{2003,\tilde{k}l}$ and $G_{2004,\tilde{k}l}$ only for Finland, Italy, and Romania.

Table C.6: Empirical verification of Assumption 1

country	test stat.	emp. p-value	as. p-value
Austria	-1.741	0.950	0.959
Belgium	-0.454	0.591	0.675
Bosnia & H.	-2.069	0.976	0.981
Bulgaria	0.047	0.456	0.481
Czech R.	-1.659	0.922	0.951
Denmark	0.259	0.310	0.398
Estonia	-1.231	0.856	0.891
Finland	3.973*	0.001	0.000
France	-0.193	0.502	0.577
Germany	1.343	0.057	0.090
Great Britain	1.512	0.077	0.065
Italy	12.522*	0.000	0.000
Netherlands	-1.966	0.951	0.975
Norway	-0.565	0.696	0.714
Poland	-1.970	0.975	0.976
Portugal	-1.889	0.970	0.971
Romania	3.161*	0.013	0.001
Slovakia	-0.892	0.733	0.814
Spain	-1.067	0.823	0.857
Sweden	1.562	0.072	0.059

Apply Li (1996) test for equality of distributions. Asterisks denote that changes in the (coordinate-wise) standardized joint distribution of log capital and log labor from 2003 to 2004 were statistically significant at the 5% level.

C.2 Empirical verification of Assumption 2

Recall that we denote by $k_{t,\tau}$ the τ-quantile of the distribution $G_{t,k}$ and by $l_{t,\eta}$ the η-quantile of the distribution $G_{t,l}$. We analyze whether for all $0 < \tau < 1$ and $0 < \eta < 1$ the conditional distribution of attributes given $k = k_\tau$ and $l = l_\eta$, i.e., $G_{A|k_\tau,l_\eta}$ changed significantly from 2003 to 2004.

In our analysis A_t^j contains company age, industry and regional dummies, independence indicators and a dummy for being publicly quoted. Since among these variables solely the age of a company age is a continuous variable, while verifying Hypothesis 2, we concentrate on the evolution of the conditional distribution of age, i.e., $G_{age|k_\tau l_\eta}$. We study the evolution this distribution for $(\tau, \eta) \in \{(0.1, 0.1), (0.25, 0.25), (0.5, 0.5), (0.75, 0.75), (0.9, 0.9)\}$.[29] In order to assess the significance of changes in $G_{age|k_\tau l_\eta}$ from 2003 to 2004 we perform the nonparametric Kolmogorov-Smirnov test, the results of which are given in Table 7. We conclude that changes over time in $G_{age|k_\tau l_\eta}$ at most quantile positions (τ, η) are statistically significant in only four countries: the Czech Republic, Italy, Romania, and Spain. Moreover, for Bosnia and Herzegovina, France, Germany, Norway, Portugal, and Slovakia changes in $G_{age|k_\tau l_\eta}$ are significant at only one quantile position. Finally, $G_{age|k_\tau l_\eta}$ did not change significantly at any quantile position in the remaining ten countries.

[29] In fact, when analyzing the evolution of $G_{t,age|k_\tau l_\eta}$ we focus on the distribution of firm age for firms with $k_t^j \in [k_{t,\tau-0.025}, k_{t,\tau+0.025}]$ and $l_t^j \in [l_{t,\eta-0.025}, l_{t,\eta+0.025}]$.

Table C.7: Test of equality of $G_{2003,age|k_\tau l_\eta}$ and $G_{2004,age|k_\tau l_\eta}$

country	$\tau = \eta = 0.1$	$\tau = \eta = 0.25$	$\tau = \eta = 0.5$	$\tau = \eta = 0.75$	$\tau = \eta = 0.9$
Austria	0.243	0.107	0.616	0.561	0.862
Belgium	0.794	0.703	0.772	0.416	0.978
Bosnia & H.	0.059	0.058	0.827	0.473	0.003*
Bulgaria	0.548	0.980	0.730	0.884	0.382
Czech R.	0.011*	0.956	0.244	0.028*	0.001*
Denmark	0.952	0.999	0.114	0.808	0.723
Estonia	0.149	0.087	0.595	0.781	0.439
Finland	0.597	0.487	0.124	0.422	0.600
France	0.708	0.825	0.740	0.029*	0.996
Germany	0.532	0.032*	0.497	0.977	0.853
Great Britain	0.266	0.546	0.215	0.753	0.235
Italy	0.000*	0.001*	0.000*	0.672	0.474
Netherlands	0.876	0.913	0.720	0.879	0.888
Norway	0.116	0.436	0.373	0.064	0.000*
Poland	0.213	0.083	0.334	0.496	0.998
Portugal	0.499	0.029*	0.121	0.768	0.995
Romania	0.000*	0.001*	0.001*	0.000*	0.000*
Slovakia	0.957	0.021*	0.649	0.974	0.305
Spain	0.000*	0.000*	0.020*	0.000*	0.053
Sweden	0.167	0.679	0.115	0.238	0.464

Apply Kolmogorov-Smirnov test of equality of $G_{2003,age|k_\tau l_\eta}$ and $G_{2004,age|k_\tau l_\eta}$ for different quantile positions τ and η. Asterisks correspond to p-values smaller than 0.05 and indicate that changes in the distribution were statistically significant at the 5% level.

C.3 Derivation of the aggregate relation in terms of $\log \bar{K}$ and $\log \bar{L}$

Let $x_t^j = (k_t^j, l_t^j)'$ denote the observable firm-specific explanatory variables with the corresponding mean vector $\bar{x}_t$. Further, $\Sigma_t = \begin{pmatrix} (\sigma_t^k)^2 & \sigma_t^{kl} \\ \sigma_t^{kl} & (\sigma_t^l)^2 \end{pmatrix}$ denotes the covariance matrix of x_t^j across J_t. According to Hildenbrand and Kneip (2005) the growth rate g_t of the aggregate response variable is given by:

$$g_t = \beta'_{t-1}(\bar{x}_t - \bar{x}_{t-1}) + tr[\Delta_{t-1}(\Sigma_t^{1/2}\Sigma_{t-1}^{-1/2} - \mathbb{I})] + \text{ other effects,} \tag{C.1}$$

where $\mathbb{I}$ is the identity matrix, $\beta_{t-1} = (\beta_{t-1}^k, \beta_{t-1}^l)'$ is a vector and $\Delta_{t-1} = \begin{pmatrix} \delta_{t-1}^k & \delta_{t-1}^{kl} \\ \delta_{t-1}^{kl} & \delta_{t-1}^l \end{pmatrix}$ is a matrix of coefficients. Under coordinate-wise standardization (in Assumption 1) Σ_t is replaced by $\tilde{\Sigma}_t = \begin{pmatrix} (\sigma_t^k)^2 & 0 \\ 0 & (\sigma_t^l)^2 \end{pmatrix}$ and the first two rhs terms in (C.1) simplify to:

$$\beta_{t-1}^k(\bar{k}_t - \bar{k}_{t-1}) + \beta_{t-1}^l(\bar{l}_t - \bar{l}_{t-1}) + \delta_{t-1}^k(\frac{\sigma_t^k - \sigma_{t-1}^k}{\sigma_{t-1}^k}) + \delta_{t-1}^l(\frac{\sigma_t^l - \sigma_{t-1}^l}{\sigma_{t-1}^l}), \tag{C.2}$$

where

$$\delta_{t-1}^k = \frac{1}{\bar{Y}_{t-1}} \int (k - \bar{k}_{t-1}) \partial_k \bar{f}_{t-1}(k, l, A)\, dG_{t-1,klA}$$

and

$$\delta_{t-1}^l = \frac{1}{\bar{Y}_{t-1}} \int (l - \bar{l}_{t-1}) \partial_l \bar{f}_{t-1}(k, l, A)\, dG_{t-1,klA}.$$

For the sake of comparability with conventional growth models, we are interested in a relationship like (C.1) but in terms of changes in aggregate levels $\bar{K}$ and $\bar{L}$ rather than in terms of aggregate *log* levels $\bar{k}$ and $\bar{l}$. More specifically, we want to arrive at a relationship for the growth rate containing:

$$\beta_{t-1}^k(\log \bar{K}_t - \log \bar{K}_{t-1}) + \beta_{t-1}^l(\log \bar{L}_t - \log \bar{L}_{t-1})$$

We start[30] with the definition of $\log \bar{K}_t$:

[30]The derivation for $\log \bar{L}_t$ can be carried out analogously.

$$\log \bar{K}_t = \log \Big[\int K dG_{t,K} \Big] = \log \Big[\int \exp(k) dG_{t,k} \Big] \tag{C.3}$$

For two periods t and $t-1$ Assumption 1 (Structural stability of G_{kl}) implies:

$$G_{t-1,k}\Big(\frac{\sigma_t^k}{\sigma_{t-1}^k}(k - \bar{k}_{t-1}) + \bar{k}_t \Big) = G_{t,k}(k)$$

Hence, we can rewrite (C.3) by:

$$\begin{aligned} \log \bar{K}_t &= \log \Big[\int \exp\Big(\frac{\sigma_t^k}{\sigma_{t-1}^k}(k - \bar{k}_{t-1}) + \bar{k}_t \Big) dG_{t-1,k} \Big] \\ &= \bar{k}_t + \log \Big[\int \exp\Big(\frac{\sigma_t^k}{\sigma_{t-1}^k}(k - \bar{k}_{t-1}) \Big) dG_{t-1,l} \Big] \end{aligned}$$

Now, we define a function q from $\mathbb{R}_+$ to $\mathbb{R}$ such that:

$$q(\sigma^k) := \log \Big[\int \exp\Big(\frac{\sigma^k}{\sigma_{t-1}^k}(k - \bar{k}_{t-1}) \Big) dG_{t-1,k} \Big]$$

By the definition of q we have $q(\sigma_t^k) = \log \bar{K}_t - \bar{k}_t$ and simple algebra yields $q(\sigma_{t-1}^k) = \log \bar{K}_{t-1} - \bar{k}_{t-1}$. From these properties of q it follows that:

$$\bar{k}_t - \bar{k}_{t-1} = \log \bar{K}_t - \log \bar{K}_{t-1} - [q(\sigma_t^k) - q(\sigma_{t-1}^k)]$$

Further, by the first order Taylor approximation of $q(\sigma^k)$ at σ_{t-1}^k we obtain:

$$\begin{aligned} q(\sigma_t^k) &\approx q(\sigma_{t-1}^k) + \partial_{\sigma^k} q(\sigma^k)\big|_{\sigma^k = \sigma_{t-1}^k} \cdot (\sigma_t^k - \sigma_{t-1}^k) \\ &= q(\sigma_{t-1}^k) + \frac{1}{\sigma_{t-1}^k \bar{K}_{t-1}} \int (k - \bar{k}_{t-1}) \exp(k) dG_{t-1,k} \cdot (\sigma_t^k - \sigma_{t-1}^k) \end{aligned}$$

Consequently,

$$\beta_{t-1}^k(\bar{k}_t - \bar{k}_{t-1}) = \beta_{t-1}^k(\log \bar{K}_t - \log \bar{K}_{t-1}) - \frac{\beta_{t-1}^k}{\bar{K}_{t-1}} \int (k - \bar{k}_{t-1}) \exp(k) dG_{t-1,k} \cdot \Big(\frac{\sigma_t^k - \sigma_{t-1}^k}{\sigma_{t-1}^k} \Big).$$

Doing analogous derivations for $\log \bar{L}_t$, we obtain:

$$\begin{aligned} g_t &= \beta_{t-1}^k(\log \bar{K}_t - \log \bar{K}_{t-1}) + \beta_{t-1}^l(\log \bar{L}_t - \log \bar{L}_{t-1}) \\ &+ \gamma_{t-1}^k \Big(\frac{\sigma_t^k - \sigma_{t-1}^k}{\sigma_{t-1}^k} \Big) + \gamma_{t-1}^l \Big(\frac{\sigma_t^l - \sigma_{t-1}^l}{\sigma_{t-1}^l} \Big) + \text{ other effects,} \end{aligned}$$

where

$$\gamma^k_{t-1} = \delta^k_{t-1} - \frac{\beta^k_{t-1}}{\bar{K}_{t-1}} \int (k - \bar{k}_{t-1}) \exp(k) dG_{t-1,k}$$

and

$$\gamma^l_{t-1} = \delta^l_{t-1} - \frac{\beta^l_{t-1}}{\bar{L}_{t-1}} \int (l - \bar{l}_{t-1}) \exp(l) dG_{t-1,l}.$$

Bibliography

Abramovitz, M. (1956), 'Resource and output trends in the united states since 1870', *American Economic Review* **46**, 5–23.

Acemoglu, D. and F. Zilibotti (1997), 'Was prometheus unbound by chance? risk, diversification, and growth', *Journal of Political Economy* **105**, 709–751.

Acemoglu, D. and F. Zilibotti (2001), 'Productivity differences', *Quarterly Journal of Economics* (116), 563–606.

Acemoglu, D., S. Johnson and J. Robinson (2002), 'Reversal of fortune: Geography and institutions in the making of the modern world income distribution', *Quarterly Journal of Economics* (107), 1231–94.

Aghion and Howitt (1992), 'A model of growth through creative destruction', *Econometrica* **2**, 323–351.

Aghion, P., G.-M. Angeletos, A. Banerjee and K. Manova (2005), 'Volatility and growth: Financial development and the cyclical composition of investment', *Working Paper* .

Aghion, P. and R. Griffith (2005), *Competition and Growth*, MIT Press, Cambridge, MA.

Aizenman, J. and N. Marion (1993), 'Policy uncertainty, persistence and growth', *Review of International Economics* **1**, 145–163.

Angeletos, A. (2006), 'Uninsured idiosyncratic investment risk and aggregate saving', *Working Paper* .

Barro, R. (1990), 'Government spending in a simple model of endogenous growth', *Journal of Political Economy* (98), 103–117.

Barro, R. and J. Lee (1996), 'International measures of schooling years and schooling quality', *American Economic Review* (86), 218–23.

Barro, R. and X. Sala-i-Martin (1997), 'Technology diffusion, convergence, and growth', *Journal of Economic Growth* (2), 1–27.

Barro and Sala-i-Martin (1995), *Economic Growth*, McGraw-Hill, New York.

Basu, S. and D. Weil (1998), 'Appropriate technology and growth', *Quarterly Journal of Economics* (113), 1025–1054.

Beck, T and R. Levine (1999), 'A new database on financial development and structure', *World Bank Policy Research Working Paper 2146* .

Belaid, H. (2004), 'Telecommunication, infrastructure and economic development', *Working Paper* .

Blundell, R. and S. Bond (1998), 'Initial conditions and moment restrictions in dynamic panel data models', *Journal of Econometrics* **87**, 115–43.

Blundell, R. and S. Bond (2000), 'Gmm estimation with persistent panel data: an application to production functions', *Econometric Reviews* **19**, 321–340.

Bougheas, S., P. Demetriades and T. Mamuneas (2000), 'Infrastructure, specialization, and economic growth', *Canadian Journal of Economics* **33**(2), 506–522.

Bruno, M. and W. Easterly (1998), 'Inflation crises and long-run growth', *Journal of Monetary Economics* **41**, 3–26.

Calderon, C. and L. Serven (2005), The effects of infrastructure development on growth and income distribution. World Bank Working Paper, WPS3400.

Canning, D. (1999), 'The contribution of infrastructure to aggregate output', *World Bank Working Paper* .

Caselli, F (2005), 'Accounting for cross-country income differences', *Handbook of Economic Growth* (edition 1, volume 1, chapter 10, Elsevier), 679–741.

Caselli, F. and J. Coleman (2005), 'The world technology frontier', *American Economic Review* (1).

Cukierman, A., P. Kalaitzidakis L. Summers and S. Webb (1993), 'Central bank independence, growth, investment, and real rates', *Carnegie-Rochester Conference Series on Public Policy* **39**, 95–140.

De Gregorio, J. (1992), 'The effects of inflation on economic growth', *European Economic Review* **36**, 417–424.

De Gregorio, J. (1993), 'Inflation, taxation and long-run growth', *Journal of Monetary Economics* **31**, 271–298.

Easterly, W. (2005), 'National policies and economic growth: A reappraisal', *Handbook of Economic Growth, P. Aghion and S. Durlauf eds.* **1**.

Eaton, J. and S. Kortum (2002), 'Technology, geography, and trade', *Econometrica* **70**, 1741–1779.

Fan, I. and I. Gijbels (1996), *Local Polynomial Modeling and Its Applications*, Chapman and Hall, London.

Felipe, J. and F. Fisher (2003), 'Aggregation in production functions: What applied economists should know', *Metroeconomica* **54**, 208–262.

Fernald, J. (1999), 'Roads to prosperity - assessing the link between public capital and productivity', *American Economic Review* **89**(3), 619–638.

Fernald, J. and S. Ramnath (2004), 'The acceleration in u.s. total factor productivity after 1995 - the role of information technology', *Economic Perspectives, Federal Reserve Bank of Chicago* .

Fischer, S. (1993), 'The role of macroeconomic factors in growth', *Journal of Monetary Economics* **32**, 485–512.

Fisher, F. (1993), *Aggregation. Aggregate Production Functions and Related Topics*, MIT Press, Cambridge, MA.

Ghosh, S. and I. Mourmouras (2002), 'On public investment, long-run growth, and the real exchange rate', *Oxford Economic Papers* (54), 72–90.

Gorman, W. (1953), 'Community preference fields', *Econometrica* **21**, 63–80.

Gramlich, E. (1994), 'Infrastructure investment: A review essay', *Journal of Economic Literature* (32), 1176–1196.

Grossman, G and E. Helpman (1991), 'Quality ladders in the theory of growth', *Review of Economic Studies* **58**, 43–61.

Hall, R. and C. Jones (1999), 'Why do some countries produce so much more output than others?', *Quarterly Journal of Economics* (114), 83–116.

Härdle, W. and J. D. Hart (1992), 'Bootstrap test for a positive definiteness of income effect matrices', *Econometric Theory* **8**, 276–290.

Hellwig, M. and A. Irmen (2001), 'Endogenous technical change in a competitive economy', *Journal of Economic Theory* (101), 1–39.

Hildenbrand, W. and A. Kneip (2005), 'Aggregate behavior and microdata', *Games and Economic Behavior* **50**, 3–27.

Holmstrom, B. and J. Tirole (1998), 'Private and public supply of liquidity', *Journal of Political Economy* **106**, 1–40.

Holtz-Eakin, D. and A. Schwartz (1994), 'Infrastructure in a structural model of economic growth', *NBER Working PaperNo. 4824* .

Hopenhayn, H. (1992), 'Entry, exit, and firm dynamics in long run equilibria', *Econometrica* **60**, 1127–1150.

Howitt, P. (2000), 'Endogenous growth and cross-country income differences', *American Economic Review* (90), 829–46.

Hulten, C., E. Bennathan and S. Srinivasan (2003), Infrastructure, externalities, and economic development - a study of indian manufacturing industry. World Bank working paper.

Jorgenson, D. (2005), 'Accounting for growth in the information age', *Handbook of Economic Growth, P. Aghion and S. Durlauf eds.* **1**.

Jovanovic, B. and P. Rousseau (2005), 'General purpose technologies', *Handbook of Economic Growth, P. Aghion and S. Durlauf eds.* (1).

Keller, W. (2004), 'International technology diffusion', *Journal of Economic Literature* .

King, R., C. Plosser and S. Rebelo (1998), 'Production, growth, and business cycles: Ii. new directions', *Journal of Monetary Economics* **21**, 309–341.

Kosempel, S. (2004), 'Finite lifetimes and government spending in an endogenous growth model', *Journal of Economics and Business* (56), 197–210.

Levine, R., N. Loyaza and T. Beck (2000), 'Financial intermediation and growth: Causality and causes', *Journal of Monetary Economics* (46), 31–77.

Levinsohn, J. and A. Petrin (2003), 'Estimating production functions using inputs to control for unobservables', *Review of Economic Studies* **70**, 317–341.

Li, Q. (1996), 'Nonparametric testing of closeness between two unknown distribution functions', *Econometric Reviews* **15**, 261–274.

Li, Q., E. Maasoumi and J. Racine (2007), 'A nonparametric test for equality of distributions with mixed categorical and continuous data', *Working Paper* .

Lucas, R. (1990), 'Liquidity and interest rates', *Journal of Economic Theory* **50**, 237–264.

Malinvaud, E. (1993), 'A framework for aggregation theory', *Ricerche Economiche* **47**, 107–135.

Mallows, C. (1973), 'Some comments on c_p', *Technometrics* **15**, 661–675.

Melitz, M. (2003), 'The impact of trade on intra-industry reallocations and aggregate productivity', *Econometrica* **71**, 1695–1725.

Moulton, B. (1990), 'An illustration of a pitfall in estimating the effects of aggregate variables on micro units', *The Review of Economics and Statistics* **72**, 334–338.

Nataf, A. (1948), 'Sur la possibilité de construction de certains macromodèles', *Econometrica* **16**, 232–244.

Nicoletti, G. and S. Scarpetta (2003), 'Regulation, productivity and growth: Oecd evidence', *Economic Policy* **18**, 9–72.

Olley, G. and A. Pakes (1996), 'The dynamics of productivity in the telecomunications equipment industry', *Econometrica* **64**, 1263–1279.

Opler, T., L. Pinkowitz, R. Stulz and R. Williamson (1999), 'The determinants and implications of corporate cash holdings', *Journal of Economic Theory* **52**, 3–46.

Parente, S. and E. Prescott (1999), 'Monopoly rights: A barrier to riches', *American Economic Review* (89), 1216–1233.

Pareto, V. (1896), 'The dynamics of productivity in the telecomunications equipment industry', *Cours d'économie politique* **1-2**.

Prescott, E. (1998), 'Needed: A theory of total factor productivity', *International Economic Review* (39), 525–51.

Ramey, G. and V. Ramey (1995), 'Cross-country evidence on the link between volatility and growth', *American Economic Review* **85**, 1138–1151.

Roberts, M. and J. Tybout (1997), 'Producer productivity and productivity growth in developing countries', *World Bank Research Observer* **12**, 1–18.

Rodrik, D. (2005), 'Growth strategies', *Handbook of Economic Growth, P. Aghion and S. Durlauf eds.* **1**.

Roeller, L. and L. Waverman (2001), 'Telecommunications infrastructure and economic development - a simultaneous approach', *American Economic Review* **91**(4), 909–923.

Romer, P. (1990), 'Increasing returns and long-run growth', *Journal of Political Economy* (5), 71–102.

Science magazine (2005), '125 questions: What don't we know?', *Science magazine* (http://www.sciencemag.org/sciext/125th/).

Sheather, S.J. and M.C. Jones (1991), 'A reliable data-based bandwidth selection method for kernel density estimation', *Journal of the Royal Statistics Association, Series B* **53**, 683–690.

Summers, L. (2003), *Godkin Lectures*, Cambridge, MA: John F. Kennedy School of Government, Harvard University.

Turnovsky, S. (1997), 'Productive government expenditure in a stochastically growing economy', *Macroeconomic Dynamics* (3), 615–639.

Turnovsky, S. (2000), 'Fiscal policy, elastic labor supply, and endogenous growth', *Journal of Monetary Economics* (45), 185–210.

Young, A. (1993), 'Substitutions and complementarity in endogenous innovation', *Quarterly Journal of Economics* (108), 775–807.