Three Essays on the Economics of Technological Change and Technology Adoption

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Summary

This dissertation is a collection of three independent research papers about technological change and technology adoption. In these papers, I develop specific models to analyze how the process of technological change in the economy is affected by different factors. The first two chapters consider endogenous growth models to investigate the determinants of investment in research and development. The third chapter focuses on technology adoption by firms to study how new technologies enter the market.

The first chapter, *Path Dependence and Induced Innovation*, presents a model that demonstrates the process of path dependence and technological lock-in, and proposes a mechanism of induced innovation which can stimulate new research. Path dependence refers to the fact that the process of technological development depends on decisions and outcomes in the past. In the model, this is captured by imperfect spillovers of secondary development between technologies, which lead to the establishment of a dominant technology. This makes the development of new innovations unattractive until research ceases in the long run. Nevertheless, such a technological lock-in does not necessarily persist forever. In the model, new innovations can be directed to favor a particular input factor. Thereby, changes in the relative supply of primary factors allow a new technology to gain an additional advantage over the predominant technology and thus act as a stimulus for research to overcome the lock-in. A simulation using changes in crude oil prices in the US indicates the quantitative relevance of the model's implications.

The model is able to explain long wave patterns of economic development with periods of rapid growth alternating with slow growth phases. These cycles are triggered by changes in the resource endowment, which is in line with stylized facts from long wave theory. The model adds to the literature on path dependence as it allows the economy to become locked-in with a dominant technology but also offers a mechanism to initiate new research. The paper is linked to the literature on directed technological change, putting a focus on the stimulating effect of factor supply changes. Thereby, it also contributes to the literature on environmental protection and technological change as it shows that governmental regulation like Pigouvian taxes or pollution permits can induce the development of "green" technologies.

In the second chapter, *Imitation Induced Innovation in General Equilibrium*, I investigate the interaction of imitation and innovative activity in a general equilibrium model. It is a common belief that intellectual property rights protection provides the basis for investment in research. However, recent theoretical and empirical work has challenged this view, showing that a higher degree of competition and a positive imitation probability can benefit innovative activity and

productivity growth. In this model, quality leaders are threatened by imitators and protect themselves by undertaking secondary development to maintain their competitive advantage. This increases the growth rate. Nevertheless, lower intellectual property rights protection reduces the incentives to enter the research sector, which lowers innovation by outsiders. Simulations of the model show that the resulting effect on the growth rate is ambiguous. A higher imitation probability can increase or decrease the innovation rate, depending mainly on the productivity of secondary development. For a certain parameter range, the effect of imitation on the growth rate displays an inverted U-shape, so that imitation first increases technological progress but reduces it when the probability of imitation becomes too high. These results are in line with other models of growth and imitation that use a different mechanism.

The model features a rich market structure as sectors can be in competitive, monopolistic, or limited monopolistic state. A higher imitation probability lowers the measure of monopolistic sectors in favor of sectors with limited monopoly and competition. This reduces monopolistic distortions in the economy and thus raises output and the wage rate. With this, static welfare is typically increased; this is even true for many parameter values where imitation always negatively affects the growth rate.

The third chapter, *Technology Adoption and Demographic Change*, develops a quantitative model of technology adoption to study the effect of labor force aging on the technology distribution of an economy and on aggregate productivity growth. One consequence of demographic change is that the share of elderly persons in the labor force will increase steeply in the industrialized countries during the first half of the 21st century. Empirical studies indicate that a higher share of elderly workers has a substantial negative effect on aggregate productivity and growth. To investigate this relationship, I develop a model in which firms decide about the adoption of new technologies and about optimal employment. The workers in this economy age stochastically, which changes the workforce composition within the firms steadily over time. This forces firms to adapt their strategies dynamically. It turns out that firms with a higher share of elderly workers update their technology less often and prefer older technologies than firms with a younger workforce. This is because they fear that the investment in the training of elderly workers cannot be recuperated before those exit the labor market.

I calibrate the model for the German economy and simulate the projected changes of the labor force age composition from 2003 to 2025. Between 2010–2025, when labor force aging is strongest, demographic change lowers annual productivity growth by about 0.11 percentage points on average. When the expected increase in the average retirement age is also taken into account, this number increases to 0.17 percentage points. I compare these numbers to the results of empirical studies and find that the simulation results are in a plausible range.

Zusammenfassung

Die vorliegende Doktorarbeit basiert auf drei unabhängigen Forschungspapieren zum Thema technologischer Fortschritt und Adoption neuer Technologien. In diesen Papieren entwickle ich spezifische Modelle, welche die Auswirkungen verschiedener Faktoren auf den technologischen Wandel darstellen. Die ersten beiden Kapitel studieren die bestimmenden Faktoren für die Investition in Forschung und Entwicklung im Rahmen der endogenen Wachstumstheorie. Das dritte Kapitel richtet seinen Fokus auf die Technologieentscheidung von Unternehmen und untersucht, wie neue Technologien in den Markt eintreten.

Das erste Kapitel, *Path Dependence and Induced Innovation*, präsentiert ein Modell, welches den Prozess der Pfadabhängigkeit und die Entstehung von technologischen Lock-ins beschreibt, und einen Mechanismus für induzierte Innovationen vorstellt, durch welchen neue Forschung angeregt wird. Pfadabhängigkeit beschreibt die Tatsache, dass der Prozess technologischen Wandels von Entscheidungen und Ergebnissen abhängt, welche in der Vergangenheit liegen. Im Modell wird dies durch die Nichtübertragbarkeit von Folgeinnovationen zwischen verschiedenen Technologien abgebildet, was zur Entstehung einer dominierenden Technologie führt. Dies verringert die Attraktivität neuer Innovationen und führt somit auf lange Sicht zu einem vollständigen Rückgang der Forschung. Allerdings muss diese Art von technologischem Lock-in nicht für immer bestehen bleiben. Im Modell können neue Innovationen dergestalt sein, dass sie bestimmte Produktionsfaktoren besonders gut ausnutzen. Dadurch ermöglicht eine Änderung des relativen Angebots von Produktionsfaktoren einer neuen Innovation einen zusätzlichen Vorteil gegenüber der dominierenden Technologie und wirkt somit stimulierend auf die Forschung, um aus dem Lock-in herauszukommen. Die quantitative Relevanz der Modellimplikationen wird durch eine Simulation auf Basis der Änderungen von Rohölpreisen in den USA verdeutlicht.

Das Modell ist in der Lage, den langfristigen, wellenartigen Verlauf der ökonomischen Entwicklung zu erklären, wobei sich Perioden mit starkem Wachstum mit Phasen schwachen Wachstums abwechseln. Diese Zyklen werden durch Änderungen in der Ressourcenausstattung der Volkswirtschaft hervorgerufen, was im Einklang mit den grundlegenden Erkenntnissen der Theorie langfristiger ökonomischer Entwicklungszyklen steht. Das Modell ergänzt die Literatur zum Thema Pfadabhängigkeit, da es sowohl die Festsetzung einer Volkswirtschaft in einem technologischem Lock-in beschreibt, als auch eine Möglichkeit aufzeigt, wie neue Forschung angeregt werden kann. Das Papier ist verwandt mit der Literatur bezüglich zielgerichteten technologischen Wandels, wobei der Fokus auf dem Anreizeffekt einer Änderung des Faktorangebots liegt. Damit trägt es auch zur Literatur zum Thema Umweltschutz und technologischer Wandel bei, da es zeigt,

dass staatliche Regulierungsmaßnahmen wie zum Beispiel Pigou-Steuern und Emissionszertifikate die Entwicklung "grüner" Technologien auslösen können.

Im zweiten Kapitel, *Imitation Induced Innovation in General Equilibrium*, untersuche ich das Zusammenspiel von Imitation und Forschung in einem allgemeinen Gleichgewichtsmodell. Der Schutz von geistigem Eigentum wird im Allgemeinen als Grundlage für die Investition in Forschung gesehen. Diese Ansicht wird allerdings von aktuellen theoretischen und empirischen Studien in Frage gestellt, die zeigen, dass ein höherer Grad an Wettbewerb und eine positive Imitationswahrscheinlichkeit sich positiv auf Forschungsaktivitäten und Produktivitätswachstum auswirken können. Im hier vorgestellten Modell werden die Qualitätsführer durch Imitation bedroht und schützen sich durch fortgesetzte Produktentwicklung, um ihren Vorsprung gegenüber dem Imitator zu halten. Dies erhöht die Wachstumsrate der Wirtschaft. Nichtsdestotrotz reduziert ein geringerer Schutz von geistigem Eigentum die Anreize in den Forschungssektor einzutreten, was zu einem Rückgang von Innovationen durch Außenstehende führt. Simulationen des Modells zeigen, dass der resultierende Effekt auf die Wachstumsrate nicht eindeutig ist. Eine höhere Wahrscheinlichkeit für Imitationen kann die Innovationsrate steigern oder reduzieren. Dies ist hauptsächlich von der Produktivität der weitergehenden Produktentwicklung durch die Qualitätsführer abhängig. Für bestimmte Parameterbereiche weist die Auswirkung von Imitation auf die Wachstumsrate eine umgedrehte U-Form auf, so dass Imitation zunächst den technologischen Wandel verstärkt, ihn aber verringert, wenn die Wahrscheinlichkeit für Imitationen zu stark steigt. Diese Ergebnisse passen zu den Ergebnissen anderer Modelle zum Thema Wachstum und Imitation, welche einen anderen Mechanismus benutzen.

Das Modell verfügt über eine detaillierte Marktstruktur, in der sich die Sektoren sowohl in einem Wettbewerbs- oder Monopolzustand als auch in einem eingeschränkten Monopolzustand befinden können. Eine höhere Imitationswahrscheinlichkeit reduziert die Anzahl der monopolistischen Sektoren zu Gunsten der Sektoren mit Wettbewerb oder eingeschränktem Monopol. Dies reduziert die Verzerrungen durch Monopole in der Wirtschaft, wodurch die Produktionsmenge und der Lohn steigen. Dadurch steigt die statische Wohlfahrt; dies ist auch für viele Parameterkonstellationen der Fall, bei denen sich Imitation ausschließlich negativ auf die Wachstumsrate auswirkt.

Das dritte Kapitel, *Technology Adoption and Demographic Change*, entwickelt ein quantitatives Modell zur Beschreibung der Technologieentscheidung von Unternehmen, um den Effekt einer alternden Arbeitnehmerschaft auf die Technologieverteilung und das Wachstum der Produktivität der Volkswirtschaft zu analysieren. Eine der Konsequenzen des demographischen Wandels ist der starke Anstieg der Anzahl älterer Arbeitnehmer in den Industrienationen während der ersten Hälfte des 21. Jahrhunderts. Empirische Studien zeigen, dass ein größerer Anteil älterer Arbeitnehmer sich deutlich negativ auf die allgemeine Produktivität und das Wachstum auswirkt. Um diesen Zusammenhang zu untersuchen, entwickle ich ein Modell, in dem Firmen über die Adoption neuer Technologien und ihre optimale Belegschaft entscheiden. Die Arbeitnehmer altern stochastisch in diesem Modell, so dass sich die Zusammensetzung der Belegschaft innerhalb der Unternehmen ständig verändert. Dies zwingt die Unternehmen dazu ihre Strategie dynamisch anzupassen. Es stellt sich heraus, dass Firmen mit einem größeren Anteil älterer Arbeitnehmer im Vergleich zu Unternehmen mit jüngerer Belegschaft seltener neue Technologien übernehmen und ältere Technologien bevorzugen. Dies geschieht, da die Firmen befürchten, dass sich die Investitionen für die entsprechende Weiterbildung bei älteren Arbeitnehmern nicht auszahlen, bevor diese den Arbeitsmarkt verlassen.

Ich kalibriere das Modell für die deutsche Volkswirtschaft und simuliere die erwarteten Veränderungen der Altersstruktur der Arbeitnehmerschaft über den Zeitraum von 2003 bis 2025. Innerhalb der Zeit von 2010 bis 2025, während der die Alterungsrate der Erwerbspersonen am stärksten ist, führt der demographische Wandel zu einem durchschnittlichen Rückgang des jährlichen Produktivitätswachstums von etwa 0,11 Prozentpunkten. Wenn der erwartete Anstieg des Renteneintrittsalters in die Betrachtung eingeschlossen wird, erhöht sich diese Zahl auf 0,17 Prozentpunkte. Ein Vergleich dieser Zahlen mit den Ergebnissen empirischer Studien zeigt, dass die Simulationsergebnisse plausibel sind.

Chapter 1

Path Dependence and Induced Innovation

1.1 Introduction

In this chapter, I develop a model of path dependence, where the establishment of a dominant technology leads to a technological lock-in, and propose a mechanism of induced innovation, by which changes in the relative factor supply stimulate new research and allow to replace the dominant technology.

Path dependence denotes the fact that the trajectory of technological development depends on previous decisions and outcomes. The worldwide dominance of the light-water nuclear reactor despite the fact that it is considered inferior to other reactor types, is an example for this phenomenon. The success of the light-water reactor originates from the strong research founded by the US navy, who needed a small reactor as energy source for its submarines. This gave this reactor type a headstart over competing designs, so that it also became the dominant technology for stationary nuclear power plants (Cowan, 1990). Another prominent example is the QWERTY keyboard, which became an industry standard upon introduction with the first typewriters and could not be replaced by better keyboard layouts because typists had been trained for it already (David, 1985).

Path dependence can result from a number of origins. In his seminal article, Arthur (1989) points out the existence of specific human capital, that cannot be used for the competing technologies, network effects and technical interrelatedness, as well as increasing returns that hinder new technologies from overcoming the existing technology. Farrell and Saloner (1985, 1986) add the existence of standards and a large installed base as factors supporting the establishment of a dominant technology. Also headstart advantages and setup costs may prohibit the development of new technologies that may have a higher potential but are less productive in the short run.

Nevertheless, such a technological lock-in does not have to persist forever. Changes in the environment may provide enough incentives to overcome the dominant technology and to develop alternatives. This notion has been proposed already by Hicks (1932), who postulated that

"A change in relative prices of factors of production is itself a spur to invention, and to invention of a particular kind - directed towards economizing the use of a factor which has become relatively expensive."

The second part of this statement has found enormous attention by the literature on directed technical change during the last years, for example in Acemoglu (1998, 2002, 2007), Kiley (1999), and Jones (2005).[1] Although this paper is related to that literature, the focus here lies on the first part of Hicks' statement. Can changes in the relative supply of factors provide an incentive to research and lead to new innovations that replace the predominant technology?

A real world example for this idea is the automobile industry. During the course of the twentieth century, the development of electrical cars has ceased and gasoline cars have become the only widespread technology. However, in recent years the development of electrical, hydrogen or hybrid vehicles has gained new momentum. With fossil fuels becoming scarce and expensive in the near future and ongoing climate change debates, alternatives to gasoline have become attractive again. At the end of the 1990s, the world's biggest car manufacturer Toyota introduced the Prius, a hybrid car that combines gasoline and electrical engines, which became a huge success. Now in 2015, all major car manufacturers work on concepts for alternative drive systems or have already brought the first models to the market. So, the prospective change of the availability of natural resources has triggered new research, which will lead eventually to the replacement of gasoline cars.

The model developed in this paper captures both the origins of path dependence that lead to technological lock-in as well as the induced innovation, that can lift the economy out of the trap again. The endogenous growth model is based on two sources of productivity growth: fundamental research and secondary development that builds on fundamental innovations. Secondary development is linked to a particular fundamental technology and cannot be transferred to the next fundamental innovation. With this, the expected productivity gain of a new fundamental innovation decreases as the stock of secondary knowledge for the current fundamental technology grows. This makes fundamental research less attractive and thus lowers the probability for a new innovation. In the long run, this leads to a technological lock-in and fundamental research ceases.

However, fundamental research does not only improve the productivity in general but can also be directed to increase the relative marginal productivity of a particular input factor. With this, fundamental researchers can react to changes in the relative factor supply and tailor a new innovation optimally for the new resource endowment. Hence, if the relative factor supply in the economy changes over time, the new fundamental innovation gains an advantage over the predominant technology, which makes fundamental research attractive again, so that the technological lock-in can be overcome.

[1] While Hicks focused on the effect of price changes, the modern literature on directed technical change typically assumes exogenous changes in the (inelastic) relative supply of factors with relative prices being determined endogenously in equilibrium. This paper follows this line as this allows to compare the results with the current literature. The common denominator with Hicks' statement lies in the idea that a certain factor becomes relatively abundant or scarce.

With this result, the model is able to explain long wave patterns of economic development, where periods of strong growth alternate with slow growth phases. Changes in the relative supply of production factors induce new fundamental innovations, leading to a high-growth phase, which slowly fades out until the next fundamental innovation is triggered by a change in the resource endowment. The model can also explain technological backlashes, where factor price changes can lead to the development of new technologies, which are replaced again by the previous technology shortly after, when the price regime switches back to the old level. Examples for this pattern can be found during the energy crises of the 1970s when research into alternative energy sources and engines soared but was quickly dropped again during the oil glut of the 1980s.

To illustrate the quantitative significance of the model's implications, I simulate the effect of the relative changes in the crude oil price compared to renewable energy sources in the US from 1870 onward. The simulation results indicate that fundamental research and hence productivity growth is triggered by changes in the oil price. Due to the ongoing price changes, fundamental research is stimulated again and again and does not die out over time. By contrast, in the cross-check simulation without price changes, fundamental research and productivity growth cease over time and the economy becomes trapped in a technological lock-in. This indicates that the model's implications are quantitatively relevant.

This paper adds to the literature on path dependence and technological lock-in, where agents decide on adopting new technologies, while specific human capital or secondary development may stop them from doing so (Arthur, 1989; Brezis et al., 1993; Chari and Hopenhayn, 1991; Parente, 1994; Jovanovic and Nyarko, 1996). This paper is most closely related to Redding (2002), who proposes a model of endogenous growth, in which path dependence can lead to a technological lock-in. This model continues that work and adds a mechanism by which induced innovation can lift the economy out of the lock-in. This allows for growth and fundamental research in the long run, whereas in Redding's model, there was no possibility to continue research.

The paper is linked to the literature on directed or biased technological progress which has its origin in the ideas of Hicks (1932) and was formally characterized initially in the works of Fellner (1961), Kennedy (1964), Samuelson (1965), Ahmad (1966), Drandakis and Phelps (1966), and Binswanger (1974).[2] Since the seminal article by Acemoglu (2002), who proposed a micro-founded endogenous growth model in which changes in the supply of primary factors lead to directed technological change, this literature has attained new momentum (Acemoglu, 1998, 2007; Kiley, 1999; Jones, 2005; Wing, 2006). Recent empirical studies have found supportive evidence for directed technological progress. Newell et al. (1999) show that the energy price hikes due to the oil crises induced the development of more energy-efficient air-conditioners; Popp (2002) finds that higher energy prices have significantly increased the relative amount of energy-saving innovations in the U.S.; a similar result is obtained by Lanzi and Sue Wing (2011) for a panel of OECD countries; and Aghion et al. (2012a) demonstrate that increased fuel prices raised the number of clean innovations in the U.S. automobile industry.

[2] See also Acemoglu (2003) for an overview of the early literature.

In this paper, the focus is not so much on the mechanism that determines the direction of technological change but more on the innovation stimulus that is triggered by a change in the relative supply of primary factors. Nevertheless, the model's implications concerning the bias of technological progress for relative factor supply changes are in line with the literature. With the focus on induced innovation, this paper also contributes to the growing literature on environmental protection and technological change (Goulder and Schneider, 1999; Unruh, 2002; Acemoglu et al., 2012a,b; Gans, 2012). In difference to those models, here, changes in the relative supply of primary factors, which may come in the form of Pigouvian taxes on fossil fuels or pollution permits, can induce a "green" innovation which displaces the dominant "dirty" technology and thus increase the total innovation rate.

Finally, this paper adds to the literature on long-run patterns of economic development and growth cycles (Kondratieff, 1984; Schumpeter, 1939; Mensch, 1979; Marchetti and Nakicenovic, 1979; Graham and Senge, 1980; Volland, 1987; Grübler and Nakicenovic, 1991). The model proposes an analytical explanation based on the decisions of rational agents how new cycles are triggered by changes in the supply of production factors, which is a stylized fact in long wave analysis.

The paper is organized as follows: the next section introduces the model; Section 1.3 derives the economy's equilibrium and the paper's main results; Section 1.4 analyzes the bias of technological change that is induced by a change in factor supply and compares it to the results of the existing literature; in Section 1.5, the effect of oil-price changes for the US economy is simulated; and Section 1.6 concludes and discusses opportunities for future research.

1.2 The Model

General Setup

The model is set in discrete time on an infinite horizon. The economy is populated with overlapping generations of uniform agents of mass one who live for two periods. Each agent is endowed with one unit of labor per period. In addition, there is an exogenously given perfectly inelastic supply of primary inputs Q and Z in every period. These primary inputs are supplied competitively at market prices p^Q, p^Z and are not owned by the agents.[3] Generations are indexed by $t \in [1, \infty)$ and lifetime periods by 1 and 2 such that p^Q_{2t} refers to the price of input Q in the second life period of generation t for example.

The economy comprises four sectors: Fundamental research and secondary development, which take place during the first period of an agent's life, and intermediate and final goods production during period 2. Each final good producer produces an individual final good indexed by i. These final goods are imperfect substitutes for consumption. Intermediate goods are produced from primary inputs Q, Z and used for final goods production. Each fundamental innovation creates a new type of intermediate good. The different types of intermediate goods that are available are indexed by k.

[3]These assumptions are not necessary for the results but simplify the analysis of the equilibrium.

Fundamental research is modeled as directed technological progress with uncertain success that generates a sequence of blueprints for intermediate goods production technologies with increasing productivity. Secondary development takes place under certainty and takes the form of continuous productivity improvements in final goods production. Secondary development is specific to a particular type of intermediate good, similar to Brezis et al. (1993), Jovanovic and Nyarko (1996), and Redding (2002). This implies that for each new fundamental innovation, which produces a new type of intermediate good, the stock of secondary knowledge has to be accumulated again.

The total productivity of the economy in terms of transforming raw inputs into final goods is determined by the joint productivity of intermediate and final goods production and depends on the type of intermediate good that is used and the stock of secondary knowledge that has been developed for this type of intermediate good. This is illustrated in Figure 1.1.

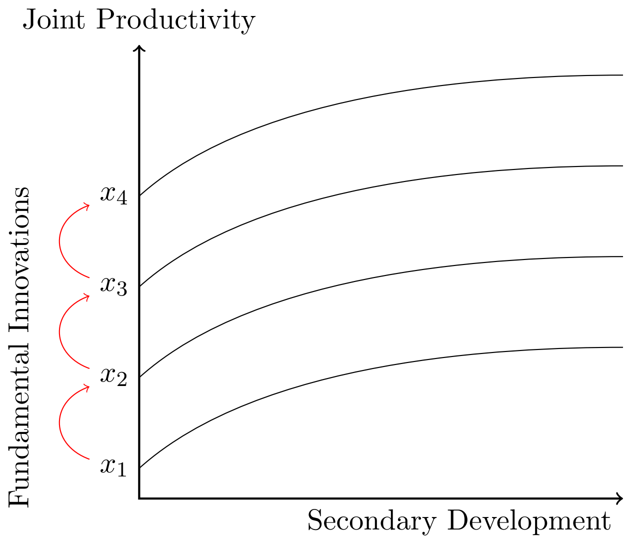

Figure 1.1: Joint productivity of fundamental technology and secondary development

Timing of Decisions

At the beginning of period 1, newborn agents inherit the blueprints for intermediate goods production technologies from previous generations and the body of secondary knowledge that has been accumulated up to this time.[4] The agents then decide whether to become fundamental researchers or secondary developers. In the remainder of period 1, fundamental researchers aim to discover a new technology for intermediate goods production while secondary developers augment the body of secondary knowledge for a chosen type of existing intermediate good. During this process, the latter also acquire the skills needed to become final good producers in period 2. Consequently, the initial decision to continue along fundamental research or secondary development marks a decision on lifetime labor supply.

[4]The inherited technologies and secondary development constitute the endogenous state variables of the economy.

At the end of period 1, all research uncertainty is revealed. If a success in fundamental research has been made, the successful researcher becomes the monopoly supplier of the new type of intermediate good in period 2. If no new fundamental innovation has been made, an already existing type of intermediate good is produced competitively. Secondary developers become final good producers under monopolistic competition; unsuccessful fundamental researchers have no profession in the second period.

Production and Consumption

Intermediate goods production uses primary inputs Q and Z in a CES production function with constant returns to scale,

$$x_{2t,k} = A_k \left[\psi_k^{\frac{1}{\epsilon}} Q_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_k)^{\frac{1}{\epsilon}} Z_{2t}^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} . \tag{1.1}$$

The productivity of intermediate goods production A_k and the share parameter ψ_k are linked to the type of intermediate good x_k. They are determined in the process of fundamental research which is specified below. The market price of intermediate goods is denoted p_k^x.

Final good producers use a linear CRS production function and the intermediate good as input,

$$y_{2t,i} = S_{2t,k}\, x_{2t,k}(i), \tag{1.2}$$

where $S_{2t,k}$ denotes the stock of secondary knowledge for intermediate good x_k that has been accumulated. It is implicitly assumed, that all final goods producers possess the same amount of secondary knowledge. Given that the agents inherit the body of secondary knowledge at the beginning of period 1, this assumption states that all secondary developers are equally productive in augmenting the stock of secondary knowledge. This assumption can be relaxed to give $y_{2t,i} = S_{2t,k}(i) x_{2t,k}(i)$, however, this does not change the results and only complicates the model.

All production activities take place in period 2, hence income is only generated in the second life period of each generation. There are no credit markets, so consumption takes place only in period 2. Agents are indexed by j; they are risk neutral and do not suffer disutility from supplying labor. They have Dixit-Stieglitz type preferences on the basket of final goods, so the lifetime utility of an individual agent is given by

$$u_{t,j} = \left(\int_0^{L_t} c_{2t,i}(j)^{\rho} \, \mathrm{d}i \right)^{\frac{1}{\rho}} , \tag{1.3}$$

where $c_{2t,i}(j)$ denotes the agent's consumption of final good $y_{2t,i}$ at price $p_{2t,i}^y$ and L_t denotes the measure of final good producers in generation t, which gives the range of different final goods.[5] Since final goods are imperfect substitutes, $0 < \rho < 1$.

[5] L_t does not carry an index for the lifetime period since the decision for labor supply is a lifetime decision and L_t refers to the mass of secondary developers in generation t in the first lifetime period and to final good producers in the second period.

Fundamental Research

Fundamental researchers try to discover a better production technology for intermediate goods. Let x_m denote the latest type of intermediate good that is available at the start of the first period of generation t. Every researcher creates an innovation that results in a new type of intermediate good x_{m+1} with probability p. The successful innovator obtains a patent for the innovation that is valid for one period (that is until the end of the innovator's life). Let R_t be the mass of researchers of generation t. Since R_t consists of infinitely many elements, the resulting aggregate innovation probability is approximated by a Poisson distribution (Feller, 1950). Hence the aggregate probability that a new innovation is made is given by

$$\Omega(R_t) = 1 - \mathrm{e}^{-pR_t}. \tag{1.4}$$

If more than one innovation is created, the patent is attributed to one of the innovators by lottery. The individual probability of obtaining the patent for a new technology is given by

$$P(R_t) = \frac{1 - \mathrm{e}^{-pR_t}}{R_t}. \tag{1.5}$$

The aggregate probability to discover a new fundamental technology increases in R_t whereas the individual probability to obtain a patent decreases in R_t.

Fundamental research can be directed so that not only general productivity is increased but also the relative marginal product of one particular input factor. This means that researchers can adjust the intermediate goods production technology if the relative supply of primary factors Q, Z changes, in order to use these resources optimally.

The effect of a new fundamental innovation is composed of two parts. First, the general productivity of intermediate goods production evolves with productivity factor A according to

$$A_{m+1} = \gamma A_m = \gamma^{m+1} A_0 \quad \text{with } \gamma > 1, \tag{1.6}$$

where A_0 is normalized to 1. Second, fundamental innovators adjust the direction of technological progress by choosing the optimal share parameter ψ_{m+1} for the intermediate goods production function, which changes the relative marginal productivity of the input factors.

Secondary Development

The stock of secondary knowledge for a specific intermediate good is increased by secondary developers during the first lifetime period of every generation. Secondary development is regarded as a product of the following three processes: the accumulation of specific human capital needed to use the respective fundamental technology efficiently, engineering refinements that make the fundamental technology more productive, and the creation of supplementary technologies and networks that are needed to release the productive potential of the underlying fundamental technology. These achievements are specific for every underlying fundamental technology. So when a new fundamental technology is discovered, secondary development starts from the beginning again. These assumptions capture the essence of the origins of path dependence as described in the introduction.[6]

Secondary development features diminishing marginal returns so that the marginal productivity improvements decline with ongoing secondary development. When a new technology in form of a fundamental innovation is introduced, final good producers have to accommodate themselves with this technology and learn to use it efficiently. At the beginning, this will lead to great productivity improvements but further gains in efficiency are harder to achieve. Also a new technology is most often not perfect at the start-up but rather comes as a beta-version. So in the early days, there are a lot of possibilities for improvements (Rosenberg, 1994). After the first important rework has been undertaken, future improvements will be of lesser importance until finally the productive potential of the underlying technology is completely released.[7]

Secondary developers decide for which type of intermediate good they undertake secondary development and spend the first period augmenting the stock of secondary knowledge for this technology. The stock of secondary knowledge for the chosen technology x_k evolves during the agents' first lifetime period according to

$$S_{2t,k} = \mu S_{1t,k}^{\phi} \quad \text{with: } \mu > 1,\ 0 < \phi < 1, \tag{1.7}$$

where $S_{1t,k}$ denotes the stock of secondary development for technology k that has been inherited from the previous generation.

Notice, that due to diminishing returns of secondary development, the economy can exhibit growth in the long run only by fundamental innovations. This is similar to the assumptions in Jovanovic and Nyarko (1996).

1.3 Equilibrium

Given the time structure of decisions, the model is solved by backward induction for the decisions of an arbitrary generation t and given number of fundamental technologies available with corresponding body of secondary development. First, I derive the equilibrium in final and intermediate goods markets in period 2 for a given number of fundamental researchers and secondary developers. Two states of the world have to be considered in this analysis: successful and unsuccessful fundamental research in period 1. After that, the equilibrium allocation of fundamental research and secondary development in period 1 as well as the choice of a fundamental technology for secondary development and the direction of fundamental research is obtained.

[6] The assumption of zero spillovers of secondary development can be relaxed to allow for imperfect spillovers between fundamental technologies, so that a part of the accumulated stock of secondary development can be used with a new fundamental technology, similar to Redding (2002). This does not change the fundamental results of the model.

[7] See also the discussion in Doraszelski (2004) about different specifications for secondary development.

Period 2

The equilibrium in the final goods market is independent of success in fundamental research in period 1. Agents optimize their consumption portfolio subject to their preferences given in (1.3) and their individual budget constraint

$$\int_0^{L_t} p^y_{2t,i}\; c_{2t,i}(j)\;\mathrm{d}i \leq E_{2t}(j), \tag{1.8}$$

where $E_{2t}(j)$ denotes the agent's income in period 2, depending on his lifetime labor decision and research success.

This yields individual demand for each type of final good

$$c_{2t,i}(j) = \left(\frac{p^y_{2t,i}}{P_{2t}}\right)^{-\frac{1}{1-\rho}} \frac{E_{2t}(j)}{P_{2t}}, \tag{1.9}$$

with price index

$$P_{2t} = \left[\int_0^{L_t} {p^y_{2t,i}}^{-\frac{\rho}{1-\rho}}\;\mathrm{d}i\right]^{-\frac{1-\rho}{\rho}}. \tag{1.10}$$

Final goods producers maximize their profit, subject to demand for final goods derived above.

As in Dixit and Stiglitz (1977), the optimal competitive-monopoly price is a constant mark-up over marginal cost $MC^y_{2t,i}$

$$p^y_{2t,i} = \frac{1}{\rho} MC^y_{2t,i}.^{8} \tag{1.11}$$

To derive the equilibrium results for intermediate goods production, the two possible cases for the period 1 outcome, successful and unsuccessful fundamental research, are considered separately.

Unsuccessful Fundamental Research in Period 1

If no fundamental innovation was made in period 1, all types of existing intermediate goods are free of patent protection and can be produced by competitive enterprises. Intermediate goods producers choose the type of intermediate good that delivers the highest joint productivity in combination with the body of secondary knowledge in period 2 to maximize their output. This involves a potential trade-off between productivity in intermediate goods production and productivity in final goods production, which depends on the stock of secondary knowledge that has been accumulated for each type of intermediate good. Let x_n denote the chosen intermediate

[8] Since preferences are homothetic, the distribution of income among agents does not influence equilibrium mark-ups of final good producers (Foellmi and Zweimueller, 2003).

good. The type n is defined by

$$S_{2t,n}A_n\left[\psi_n^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_n)^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}=\sup_{k\leq m}\left\{S_{2t,k}A_k\left[\psi_k^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_k)^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}\right\}, \tag{1.12}$$

where $\bar{Q}_{2t},\ \bar{Z}_{2t}$ denote the exogenous supply of factors $Q,\ Z$ during this period.

Since intermediate goods production is competitive, the price $p^x_{2t,n}$ equals marginal production costs and intermediate goods producers make zero profits. Intermediate good x_n is the only type of intermediate good that is produced and it is taken as the economy's numeraire, so

$$p^x_{2t,n}=1. \tag{1.13}$$

Since this type of intermediate good is used by all final good producers, marginal costs are the same for all types of final goods, hence

$$p^y_{2t,i}=p^y_{2t}=\frac{1}{\rho S_{2t,n}}. \tag{1.14}$$

Total demand for Q_t and Z_t equals the supply $\bar{Q}_t$, $\bar{Z}_t$, hence total intermediate goods production is given by

$$X_{2t,n}=A_n\left[\psi_n^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_n)^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}. \tag{1.15}$$

Primary factors are paid their marginal value product

$$p^Q_{2t}=\frac{\partial A_n\left[\psi_n^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_n)^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\partial\bar{Q}_{2t}},\quad p^Z_{2t}=\frac{\partial A_n\left[\psi_n^{\frac{1}{\epsilon}}\bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+(1-\psi_n)^{\frac{1}{\epsilon}}\bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\partial\bar{Z}_{2t}}, \tag{1.16}$$

and the individual profit of final good producers is given by

$$\pi^y_{2t,n}=\frac{1-\rho}{\rho}\frac{X_{2t,n}}{L_t} \tag{1.17}$$

Successful Fundamental Research in Period 1
If fundamental research was successful in period 1, the innovator obtains a patent for the new intermediate good x_{m+1} and becomes the monopoly supplier of this intermediate good in period 2. The monopolist maximizes his profit given the demand for intermediate goods and takes the

prices for primary inputs Q and Z as given[9]

$$\max_{p^x_{2t,m+1}} \{p^x_{2t,m+1} x_{2t,m+1} - p^Z_{2t} Z_{2t} - p^Q_{2t} Q_{2t}\}, \tag{1.18}$$

$$\text{s.t. } x_{2t,m+1} = A_{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}} Q_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} Z_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}},$$

$$\frac{p^x_{2tm+1}}{S_{2t,m+1}} \leq \frac{1}{S_{2t,n}},$$

$$S_{2t,m+1} = 1.$$

Notice, that no secondary development has been undertaken yet for the new technology, therefore $S_{2t,m+1} = 1$. The resulting monopoly price is given by

$$p^x_{2t,m+1} = \frac{1}{S_{2t,n}}. \tag{1.19}$$

This price secures the monopolist the whole market for intermediate goods because the marginal cost for final good producers are equal to the best available alternative x_n. Increasing the price would lead to zero profits because final good producers are not willing to pay a higher price and independent intermediate goods producers, who offer intermediate goods of type x_n would fill the gap. The price for the new intermediate good is lower than for intermediate goods of previous generations. The new intermediate good is equally productive as its predecessors but final goods producers have not had the time yet to build up secondary knowledge for the new type of intermediate good. Therefore, the new intermediate good is less attractive to them and only marketable at a lower price. However, the production of the new intermediate good needs less resources, so the monopolist is able to make a profit.

Since the marginal cost for final good producers is equal to that in the case of unsuccessful research in period 1, the price for a final good p^y_{2t} remains the same and is independent of research success.

Equilibrium intermediate goods output is given by

$$X_{2t,m+1} = A_{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}} \bar{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \bar{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1.20}$$

and the profit for the successful fundamental researcher is given by

$$\pi^X_{2t,m+1} = \frac{1}{S_{2t,n}} X_{2t,m+1} - p^Z_{2t}\bar{Z}_{2t} - p^Q_{2t}\bar{Q}_{2t}. \tag{1.21}$$

[9]Even though the monopolist is the only buyer of primary factors in equilibrium, he is in competition with independent producers of intermediate goods of the next best quality n. Therefore he can not act as a monopsonistic buyer and takes factor prices as given.

Using the fact that $p^Z_{2t}\bar{Z}_{2t} + p^Q_{2t}\bar{Q}_{2t} = X_{2t,n}$, the monopolist's profit can be written as

$$\pi^X_{2t,m+1} = \frac{X_{2t,m+1} - S_{2t,n}X_{2t,n}}{S_{2t,n}}. \tag{1.22}$$

This equation makes it clear that the overall productivity based on the new type of intermediate good, even without any secondary development in the final goods sector, must be higher than the combined productivity of the competing intermediate goods production technology together with the respective stock of secondary knowledge. Otherwise fundamental researchers would not make positive profits, which implies that nobody would have wanted to become a fundamental researcher in the first period.

The final good producers' individual profit is given by

$$\pi^Y_{2t,m+1} = \frac{1-\rho}{\rho}\frac{X_{2t,m+1}}{S_{2t,n}L_t}. \tag{1.23}$$

Period 1

At the beginning of period 1, agents decide whether to become a fundamental researcher or to go into secondary development and become a final good producer in the second period. Fundamental researchers then have to decide, in which direction to focus their research, while secondary developers have to choose the type of existing intermediate good for which the stock of secondary knowledge will be increased. These decisions depend on the agents' expectations in the first period about the endowment with primary input factors in period 2. The expected supply of primary factors is denoted by $\tilde{Q}_{2t} \equiv \mathbb{E}_{1t}\left(\bar{Q}_{2t}\right)$ and similar for $\tilde{Z}_{2t}$.

The optimal choice for the type of intermediate good for secondary development is very similar to the choice of the best production technology in period 2. Secondary developers choose the intermediate good, for which the final goods output in the next period is maximized, given the expected factor supply in period 2 and the contribution to the secondary stock of knowledge by the developers themselves during the first period. The chosen technology $\tilde{n}$ is defined by

$$\mu S^{\phi}_{1t,\tilde{n}}A_{\tilde{n}}\left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} = \sup_{k\le m}\left\{\mu S^{\phi}_{1t,k}A_k\left[\psi_k^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_k)^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}\right\}. \tag{1.24}$$

If the relative supply of input factors is expected to remain constant, the chosen technology for secondary development $\tilde{n}$ is the same technology that is currently used by the previous generation for production in their second lifetime period. Furthermore, if the relative factor supply actually remains constant, than technology $\tilde{n}$ is identical to technology n, which is chosen for production in period 2.[10]

[10]This could of course also be true if the actual relative factor supply in the second period is different but technology $\tilde{n}$ is still the best available technology. However, this is not necessarily the case.

Fundamental researchers decide on the optimal share parameter ψ_{m+1} that determines the relative productivity of the primary factors Q, Z with the new intermediate goods production technology, taking the expected supply of these factors in the next period into account. Equation (1.22) shows that the prospective monopolist's profit increases in the amount of intermediate goods that can be produced with the given amount of $\bar{Q}_{2t}$ and $\bar{Z}_{2t}$. Therefore, fundamental researchers choose $\psi^*_{m+1}(\tilde{Q}_{2t}, \tilde{Z}_{2t})$ to maximize expected output from intermediate goods production:

$$\psi^*_{m+1}(\tilde{Q}_{2t}, \tilde{Z}_{2t}) = \arg\max\ \gamma A_m \left[\psi_{m+1}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}. \qquad (1.25)$$

Proposition 1.1. *For $\epsilon \neq 1$, a unique interior solution for the optimal value of ψ_{m+1} exists, that maximizes intermediate goods production subject to the economy's expected relative factor supply. The optimal ψ_{m+1} is unique for every expected relative supply of primary factors $\frac{\bar{Z}_{2t}}{\bar{Q}_{2t}}$.*

Proof. For the proof, derive the first order condition for maximization of equation (1.25). This gives

$$\psi_{m+1} = \frac{\tilde{Q}_{2t}}{\tilde{Q}_{2t} + \tilde{Z}_{2t}},$$

which proves both parts of the proposition. □

Corollary 1.1. *If the expected relative supply of primary input factors remains constant after a fundamental innovation, fundamental researchers of the following generations do not change the share parameter ψ in their research.*

Corollary 1.1 states that once the intermediate goods production technology has adjusted to a certain relative supply of input factors, technological progress becomes factor neutral. Only if the relative supply of input factors changes (or is expected to change), fundamental research becomes biased and changes the relative marginal productivity of input factors.

The final step to close the model is to determine the equilibrium levels of employment in fundamental research and secondary development. An individual fundamental researcher makes an innovation and receives a patent with probability $P(R_t)$. This allows him to extract profits as the monopolistic intermediate goods producer in the second period. An unsuccessful researcher gains zero profits. The expected lifetime income of a fundamental researcher is thus given by

$$V_t^R =$$

$$P(R_t)\ \frac{\gamma^{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}} - \mu S^{\phi}_{1t,\tilde{n}} \gamma^{\tilde{n}} \left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}} \tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}} \tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\mu S^{\phi}_{1t,\tilde{n}}}. \qquad (1.26)$$

Final goods producers are able to extract competitive-monopoly profits irrespective of success in fundamental research in period 1. However, successful fundamental research increases the profits of final goods producers. So the expected lifetime profit for secondary developers is given by

$$V_t^S = \Omega\left(R_t\right)\frac{1-\rho}{\rho}\frac{\gamma^{m+1}\left[\psi_{m+1}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+\left(1-\psi_{m+1}\right)^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{\mu S_{1t,\tilde{n}}^{\phi}\left(1-R_t\right)}$$
$$+\left(1-\Omega\left(R_t\right)\right)\frac{1-\rho}{\rho}\frac{\gamma^{\tilde{n}}\left[\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+\left(1-\psi_{\tilde{n}}\right)^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}}{1-R_t}, \quad (1.27)$$

where the fact is used that $L_t = 1 - R_t$. It can be seen that if the mass of fundamental researchers nears one, the profit of secondary developers becomes infinite, hence there will be always a positive amount of secondary developers in equilibrium. With this, the arbitrage equation that determines the amount of fundamental and secondary researchers is given by

$$V_t^R \leq V_t^S, \quad (1.28)$$

which can be rearranged to yield

$$1 \geq \frac{\gamma^{m+1-\tilde{n}}}{\mu S_{1t,\tilde{n}}^{\phi}}\left[\frac{\psi_{m+1}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+\left(1-\psi_{m+1}\right)^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}{\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}}+\left(1-\psi_{\tilde{n}}\right)^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}\right]^{\frac{\epsilon}{\epsilon-1}}\frac{\rho-(1-\rho)\frac{R_t}{1-R_t}}{\rho+(1-\rho)\frac{1-\Omega(R_t)}{\Omega(R_t)}\frac{R_t}{1-R_t}}. \quad (1.29)$$

Proposition 1.2. *If the arbitrage equation is binding, a unique positive equilibrium level of fundamental researchers R_t exists.*

Proof. The nominator of the RHS of (1.29) strictly decreases in R_t, whereas the denominator increases in R_t. While the first part can be directly seen, showing the monotonous behavior of the denominator demands more work. The derivative of the nominator with respect to R_t is given by

$$\frac{\partial\left(\rho+(1-\rho)\frac{e^{-pR_t}}{1-e^{-pR_t}}\frac{R_t}{1-R_t}\right)}{\partial R_t} = (1-\rho)\frac{e^{-pR_t}\left(1-e^{-pR_t}-pR_t(1-R_t)\right)}{\left(1-e^{-pR_t}\right)^2\left(1-R_t\right)^2}. \quad (1.30)$$

Equation (1.30) is non-negative iff:

$$1-e^{-pR_t}-pR_t(1-R_t) \geq 0. \quad (1.31)$$

The left side of above expression is strictly convex and the global minimum of the function is at $R_t = 0$. Plugging this result back into (1.31) validates the fact that the nominator of the arbitrage equation increases in R_t. Hence the RHS of the arbitrage equation is strictly decreasing in the number of fundamental researchers, whereas the LHS is constant, so a unique equilibrium exists if the arbitrage condition is fulfilled. □

If the arbitrage equation is not binding, the expected lifetime income of fundamental research is always lower than that of secondary development and there is no fundamental research in equilibrium.

Proposition 1.3. *Equilibrium employment in fundamental research is monotonically decreasing in the stock of accumulated secondary knowledge* $S_{1t,\tilde{n}}$ *for the best existing type of intermediate good* $x_{\tilde{n}}$. *Further, a critical value for the stock of accumulated secondary knowledge* $S^*_{1t,\tilde{n}} > 1$ *exists at which equilibrium employment in fundamental research becomes zero and technological lock-in occurs.*

Proof. The RHS of the arbitrage equation is decreasing in $S_{1t,\tilde{n}}$ and decreasing in R_t, so the number of fundamental researchers decreases as $S_{1t,\tilde{n}}$ increases. The second part follows directly. □

Proposition 2 captures the essence of the problem of path dependence. The more secondary investment has been put into an existing technology, the more difficult it becomes for a new technology to outperform its predecessor. This makes searching for new technologies less attractive, since the profit that can be earned decreases. The negative effect of the existing stock of secondary development on the equilibrium level of fundamental research is depicted in Figure 1.2.

In this model, two competing forces that determine the profitability of a fundamental innovation exist. On the one hand, each new type of intermediate good yields a productivity gain in intermediate goods production. On the other hand, there is a loss of productivity in final goods production, that comes from loosing the stock of secondary knowledge when production switches to the new type of intermediate good. As long as the first effect is stronger, a new type of intermediate good yields an overall improvement in productivity, from which profits for the successful fundamental innovator can be extracted. However, the larger the stock of secondary knowledge that benefits the existing rival intermediate good grows, the lower the productivity gain from using a new intermediate good becomes. Consequently, the potential monopoly profit for fundamental researchers decreases. Therefore, fewer agents are willing to undertake fundamental research while a greater number prefers to work as secondary developers. This process aggravates until no agent finds it attractive any more to engage in fundamental research.

This results in a technological lock-in in which no fundamental research is conducted and no new types of intermediate goods are produced. With the assumptions on the evolution of the productivity of intermediate goods production by fundamental research (1.6) and the improvements of final goods production by secondary development (1.7), it becomes clear that unlimited growth is only possible through fundamental innovations. Secondary development gradually releases the underlying productive potential of the associated intermediate good. Once this potential is completely exhausted, there is no further room for improvement. Therefore, the economy cannot grow endlessly through secondary improvements alone. Once the economy has been trapped in a technological lock-in, economic growth will quickly cease.

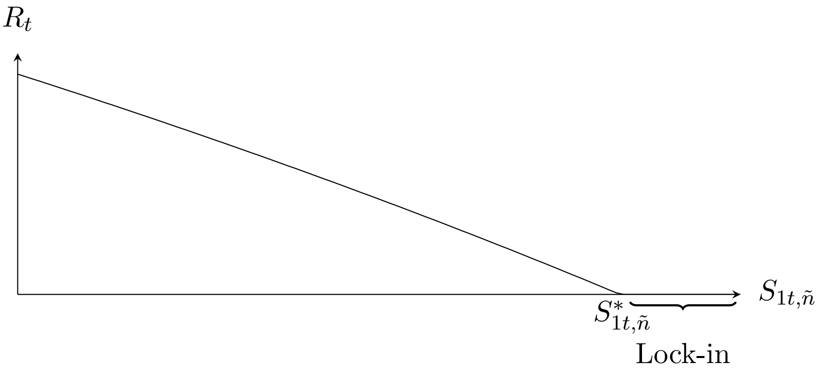

Figure 1.2: Equilibrium number of fundamental researchers with respect to accumulated secondary development

The process of becoming trapped in an equilibrium with no fundamental research is self-reinforcing. Every period without success in fundamental research, the stock of secondary knowledge for the competing intermediate good increases. This makes fundamental research less attractive for workers of the next generation, resulting in a smaller number of fundamental researchers. Consequently, the probability to make a new fundamental innovation in the next period is lowered. So with every period without fundamental research success, the probability to end up in a no-growth equilibrium increases. Fewer and fewer workers find it attractive to become fundamental researchers until fundamental research ceases completely.

Proposition 1.4. *Let $\epsilon \neq 1$, then a change in the expected relative supply of primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$ compared to the situation when the production technology for the competing type of intermediate good $x_{\tilde{n}}$ was developed, increases the equilibrium number of workers in fundamental research.*

Proof. By Proposition 1.1, for every expected relative supply with primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$, a unique optimal ψ^* exists. Therefore, if the expected relative resource endowment has changed since the competing type of intermediate good $x_{\tilde{n}}$ was developed, fundamental researchers will change the share parameter so that $\psi_{m+1} \neq \psi_{\tilde{n}}$. Furthermore, since ψ_{m+1} is chosen to be the optimal ψ^* for the expected relative endowment $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$, it is true that

$$\left[\frac{\psi_{m+1}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{m+1})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}{\psi_{\tilde{n}}^{\frac{1}{\epsilon}}\tilde{Q}_{2t}^{\frac{\epsilon-1}{\epsilon}} + (1-\psi_{\tilde{n}})^{\frac{1}{\epsilon}}\tilde{Z}_{2t}^{\frac{\epsilon-1}{\epsilon}}}\right]^{\frac{\epsilon}{\epsilon-1}} > 1.$$

This implies that the right hand side of the arbitrage equation (1.29) increases when the expected relative supply of primary factors in the economy changes. Since the right hand side of the arbitrage equation decreases in the number of fundamental researchers, a change in the relative endowment with primary factors results in a higher number of fundamental researchers. □

Corollary 1.2. *If the change in the expected relative supply of primary factors is large enough, fundamental research R_t is positive.*

Proposition 4 captures the original idea of induced innovation. Just as in Hicks (1932), it states that a change in the availability of factors of production stimulates innovation. The intuition behind Proposition 1.4 is as follows. A new fundamental innovation has to compete against previous types of intermediate goods which have already benefited from secondary development, however, it has the advantage that it can be adapted to a change in relative factor supply. Hence, if the relative supply of primary factors changes, the productivity gain of the new fundamental innovation becomes larger. The opportunity to adjust the direction of technological change makes the new fundamental innovation more profitable and thus provides an incentive for workers to go into fundamental research. This effect becomes stronger, the stronger the change in the relative factor supply is.

If the economy has been trapped in a technological lock-in, a change in the relative supply of primary factors can make fundamental research attractive again, which is captured by Corollary 1.2. With the possibility to adapt the new fundamental technology to the change in relative factor supply, the new innovation now outperforms the legacy technology which was created for a different resource regime. The probability to escape a lock-in increases, the stronger the change in the relative supply of primary factors is. Notice, that a great change in the relative endowment does not have to come within one period but the relative supply may change in little steps. As long as the incentive effect is not strong enough, fundamental research does not start. However, once the difference between the actual relative factor supply and the endowment for which the competing technology had been developed has become large enough, fundamental research becomes attractive again and starts anew.

If the relative factor supply has enough variation over time, the model is able to generate technological progress and economic growth in the long run. During periods with little variation in the supply of primary factors, employment in fundamental research may go down until fundamental research stops and technological progress eventually ceases. However, if at some point in time substantial shifts in the relative factor supply occur, or if over time small changes accumulate to larger ones, the economy is lifted out of the lock-in and fundamental research starts again. The result is permanent growth that fluctuates between periods with more fundamental research and periods with little or no fundamental research.

The positive effect of a change in the relative supply of primary factors on fundamental research is illustrated in Figure 1.3. Similar to Figure 1.2, it shows the amount of fundamental research as a function of the stock of secondary development that has been accumulated for the competing technology. The solid line depicts the basic scenario with no changes in the relative factor supply where fundamental research ceases for a high level of secondary development. The dashed line in contrast displays the amount of fundamental research when the relative factor supply has changed by 25%.[11] It can be seen that the amount of fundamental research increases for all levels of secondary development. With this, secondary development has to be higher before fundamental research ceases. The dash-dotted line shows the results for a change in the relative factor supply by 50%. It turns out, that the increase in fundamental research is much higher

[11] The direction of the change does not play a role.

now, so the positive effect of induced innovation grows progressively as the relative factor supply changes.

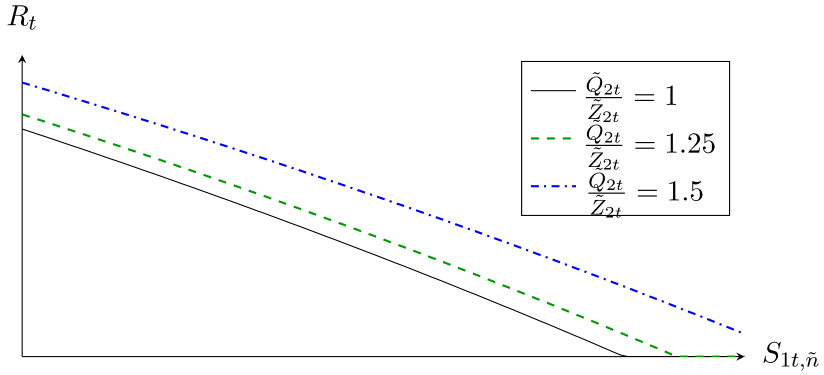

Figure 1.3: Effect of changes in relative factor supply on fundamental research

An important implication of the model is that governmental regulations, that affect the availability of primary factors, can act as a stimulus to innovative activity and induce new innovations. This becomes especially relevant in the context of environmental protection. A growing literature discusses the possibilities and limitations of bringing the economy on a clean growth track that avoids the growth of greenhouse gas emissions and the depletion of natural resources (Goulder and Schneider, 1999; Unruh, 2002; Acemoglu et al., 2012a,b; Gans, 2012). This model predicts, that regulations reducing the availability of the factor which is harmful to the environment, for example a limitation of pollution permits or Pigouvian taxes on fossil fuels, induce the development of technologies that use the now scarce factor less.

Unlike other models such as Acemoglu et al. (2012a,b), the process of switching to a new technology with a different input factor utilization does not take place gradually but rather comes as one fundamental new innovation like the change from gasoline cars to electrical vehicles or from fossil-fuel based electricity generation to solar energy. However, this implies also that the push from governmental regulation (or natural changes in the relative supply) must be strong enough to overcome the technological lock-in. Hence small regulations may have no effect as they are not sufficient to induce a replacement of the dominant technology. This could lead to the wrong conclusion that this kind of policy is not able to put the economy on a clean growth track, however, the truth is that the policy has to be intensified to increase the changes in the relative factor supply and induce the switch to a clean technology.

The model is also able to provide an explanation for the long wave patterns of economic development, also known as Kondratiev waves, during which periods with rapid growth are followed by periods with little or no growth. In this model, a new fundamental innovation produces drastic technological progress followed by a high-growth phase with strong secondary development, which yields the upswing phase of the cycle. Then in the downswing phase, secondary improvements slowly fade out until the next fundamental innovation arrives. Many authors point out that the turning points of these movements are marked by strong changes in the price of commodities; especially the scarcity or price peak of the current dominant energy source marks the begin of a new cycle (Graham and Senge, 1980; Marchetti and Nakicenovic, 1979; Volland, 1987; Grübler and Nakicenovic, 1991). In the model presented here, these price changes lead to increased fundamental research, which can trigger a new fundamental innovation and thus start a new growth cycle. So the model is able to replicate this stylized fact.

An example for the start of such a long economic cycle is the process in the eighteenth century leading to the Industrial Revolution in England. As Acemoglu (2002) points out, the great increase in skill-replacing technologies which took place in England at that time, coincided with the sudden increase in the supply of unskilled workers due to migration and other effects. Acemoglu concludes, that this increase was the source for the bias of technological progress towards unskilled workers at this time. This paper follows this conclusion,[12] but goes one step further by arguing that the sudden increase in the availability of unskilled labor was also the very source of the rapid technological progress itself. The shift in the supply of unskilled workers provided the necessary incentive to introduce new technologies of cheap mass production that made use of these unskilled workers, compared to the previously dominating artisan production that required specialized craftsmen.

An interesting feature of the model is, that it can explain technological backlashes where a new technology is developed but is given up after a short time and replaced again by the previous technology. This happens if a change in the supply of input factors is only a temporary shock. During the shock, new technologies are developed which are designed for the changed factor supply. Once the supply returns to the old state, legacy technologies that were designed for that factor supply become suddenly more profitable again than the newer interim technology. The big shocks to worldwide oil supplies during the oil crises in the 1970s provide an example for this switch-back effect. During that time, research in alternative energies and on economizing energy increased tremendously. In 1973, Europe's greatest research center for solar energy was founded in Almeria in Spain. Around the same time, a number of solar power plants were built in California and other parts of the US. However, as the oil price returned to a normal level after 1980, research in this direction was quickly given up and the few research solar power stations remained the only ones. So the newly developed technologies remained unused for mass commercial energy production. That is true until the late 1990s, when increasing energy prices and the public debate about climate change triggered research in this direction again.

In the extreme case, a new technology is developed with a certain (expected) factor endowment in mind in the first period. However, if the relative factor supply returns to old levels in the second period, the new technology might not be used at all, even though it appeared to be profitable during the first period. The history of hybrid automobiles brings this to the point. The first gasoline-electric hybrid automobile was invented already in 1901 by Ferdinand Porsche, but, although technologically outstanding, could not gain a relevant market share and hybrid automobiles were not further developed. Then during the oil crises in the 1970s, US manufacturer Briggs & Stratton developed a hybrid car that arrived at the market in 1980. However, since energy prices had declined again already, the concept remained unsuccessful. So even though the

[12]See also the next section on the direction of technical progress in the model compared to the results in Acemoglu (2002, 2007).

new technology seemed to be profitable during development, its time was over before it could reach the market. Only at the end of the 20th century, when the dangers of global warming became of world wide political concern and the need to cut down the use of fossil fuels in the future became apparent, the slow but steady triumph of hybrid automobiles began with the Toyota Prius, which was presented in 1997.

1.4 Direction of Technological Change

Even though the direction of technological change is not the primary interest of this paper, it is interesting to compare the results in this paper with those of the base model for directed technological change in Acemoglu (2002, 2007). Acemoglu defines technical change as being biased towards a certain input if it increases the relative marginal product of that particular factor compared to other inputs. For the production technology used in this paper, technological progress that is relatively biased towards input Q can be expressed as

$$\frac{\frac{\partial x(A,Q,Z)/\partial Q}{\partial x(A,Q,Z)/\partial Z}}{\partial A} > 0. \tag{1.32}$$

Acemoglu (2002) finds that an increase in the supply of one input always leads to technical change that is biased towards this input.

In this model, the direction of technical change is determined by fundamental researchers, that choose the share coefficient ψ of the intermediate goods production function according to economy's expected relative supply of primary factors $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$. As the solution to the maximization problem in (1.25), the optimal ψ^* is given by

$$\psi^* = \frac{\tilde{Q}_{2t}}{\tilde{Q}_{2t} + \tilde{Z}_{2t}}, \tag{1.33}$$

hence ψ^* rises if the expected relative endowment $\frac{\tilde{Q}_{2t}}{\tilde{Z}_{2t}}$ increases and vice versa.

The relative marginal product of Q compared to Z in intermediate goods production is given by

$$\frac{\partial x(Q,Z)/\partial Q}{\partial x(Q,Z)/\partial Z} = \left(\frac{\psi}{1-\psi}\right)^{\frac{1}{\epsilon}} \cdot \left(\frac{Q}{Z}\right)^{\frac{1}{\epsilon}}, \tag{1.34}$$

hence it increases in ψ. Both results, together with the fact that a change in ψ always comes together with an increase in A, imply that technical progress is always biased towards the input that has become relatively more abundant, which is in line with Acemoglu (2002, 2007).

Notice however, that this finding is only true with respect to technological progress that results from fundamental innovations. In this paper, technological progress in the short run can result from fundamental innovations as well as from secondary development. A change in the relative factor supply will only result in directed technical progress, if a fundamental innovation is made. If, on the other hand, fundamental researchers are unsuccessful and technological progress results only from secondary development, only factor neutral technical change will be observed.

1.5 Simulation

To illustrate the quantitative significance of the model's implications, I simulate the model and study the effect of the relative changes in fossil fuel prices compared to renewable energy sources in the US from 1870 until today. Figures 1.4 and 1.5 display the development of fossil fuels (excluding nuclear energy) and renewable energy for primary energy consumption and the first purchase price for crude oil over time in the US.[13] It can be seen that the share of fossil fuels and renewables has remained fairly constant over the past 60 years with a slight shift towards renewables between the second half of the 1970s until the beginning of the 1980s and from 2005 onward. Similarly, the price for crude oil has been relatively stable with the exception of the time between 1910–1920, the two energy crises in the 1970s during which the real price increased dramatically, and a gradual increase from 2000 onward.

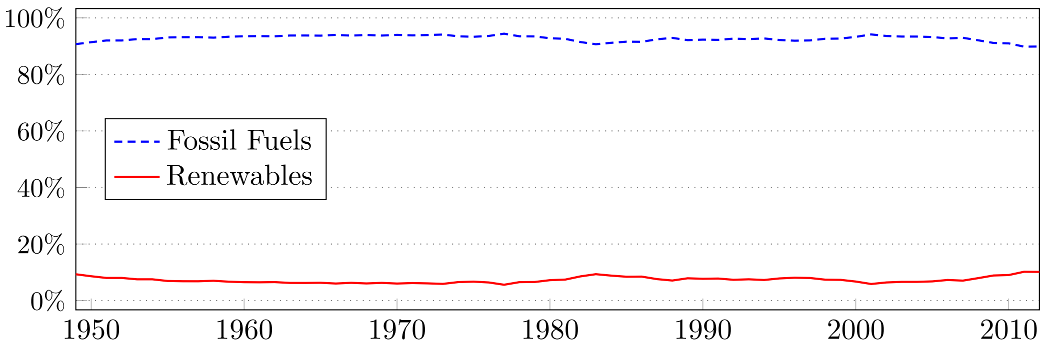

Figure 1.4: US primary energy consumption by source (Source: EIA)

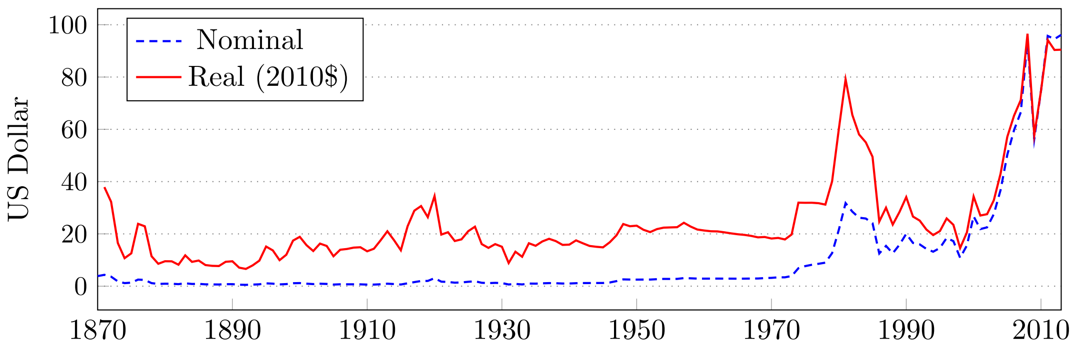

Figure 1.5: US crude oil first purchase price (Dollar per barrel) (Source: EIA)

For the simulation, the period length is set to 10 years and the model's parameters are set to match the long term development of the US economy characterized in the spectral analysis by Korotayev and Tsirel (2010), which covers the time from 1871–2007. The authors estimate an average long-term cycle length of 50 years and an annual growth rate of 2.8%. Accordingly, the productivity increase of a fundamental innovation is set to $\gamma = 3$.[14] The monopolist's share of the productivity gain of a new innovation ρ and the individual probability to be successful

[13] The price for crude oil is used as a proxy for fossil fuel prices in the simulation.

[14] This value is also used in Acemoglu and Cao (2010) for a fundamental innovation, based on the findings in Scherer (1986) and Freeman and Soete (1997).

in fundamental research p have a very similar effect in the calibration, therefore one of them has to be held constant while the other is adjusted to yield the estimated growth rate. I set $p = 0.5$ and $\rho = 0.81$. The average annual growth rate during the upswing phase is estimated between 3.35–3.66 whereas for the downswing phase it is between 1.68–1.95. To match these values, I set the parameters for secondary development to $\mu = 1.30$ and $\phi = 0.75$. The elasticity of substitution between inputs is taken from Lanzi and Sue Wing (2011), who estimate a value of $\epsilon = 1.46$ for fossils fuels and renewables in the US energy sector. For the expectations about the future factor supply, I assume that the agents expect the supply to remain at its current level, so $\mathbb{E}_{1t}\left(\bar{Q}_{2t}\right) = \bar{Q}_{1t}$ and equally so for $\bar{Z}$.[15]

The simulation covers the period for which information on crude oil prices are available, that is from 1870 onward. Five additional periods are simulated upfront and then cut off to avoid the influence of initial conditions; especially the fact that there is zero secondary development at the beginning of the simulation and hence the amount of fundamental research is at the maximum. For the presented results, the development of the economy has been simulated 1,000 times and the mean of the outcomes is reported. To eliminate the influence of extreme outcomes, the lowest and highest 10% of outcomes in terms of productivity at the end of the simulation period are dropped. I do the complete simulation in two versions: one without changes in the supply of crude oil, which serves as a benchmark, and one where the price changes given in Figure 1.5 are taken into account. To be in line with the model, these price changes have been translated into changes in the (inelastic) supply of crude oil while the supply of renewables has been held constant.

Figure 1.6 displays the development of the simulated economy without crude oil price changes taken into consideration.[16] The upper part shows the share of fundamental researchers and the lower part gives the annual rate of productivity growth. It turns out, that the share of fundamental researchers falls over time until it becomes zero at the end of the simulation period. Accordingly, productivity growth diminishes constantly over time with only minor fluctuations.

By contrast, Figure 1.7 depicts the simulation results when the changes in the crude oil price are included in the simulation.[17] It turns out that in this case, fundamental research and productivity growth do not decline over time and that they follow the changes in the supply of crude oil given in Figure 1.5. After some initial fluctuations, the crude oil price remains fairly constant until 1910. Accordingly, the share of fundamental researchers and productivity growth declines in the simulation. From 1910 onward, the crude oil price starts to increase substantially and more than doubles around 1920 compared to average value of the previous period. In the simulation, these price changes nearly double the share of fundamental researchers

[15] Since energy price hikes have typically arrived in the form of unforeseeable shocks during the 20. century, this assumption seems to be justified. Only lately, from the middle of the 1990s onward, a gradual increase of energy price can be noted, which should induce agents to adapt their expectations accordingly. Nevertheless, for the objective of this simulation, to illustrate the model's implications in terms of renewed fundamental research, the correct assumption for the agents' expectations about future energy prices has no great relevance. Even if the agents had perfect foresight, the reaction in terms of increased fundamental research would be similar, only the timing would vary.

[16] To provide smooth curves, annual numbers are interpolated from the 10-year-period raw data.

[17] To take the length of a simulation period into account, 10-year rolling averages of crude oil prices have been used.

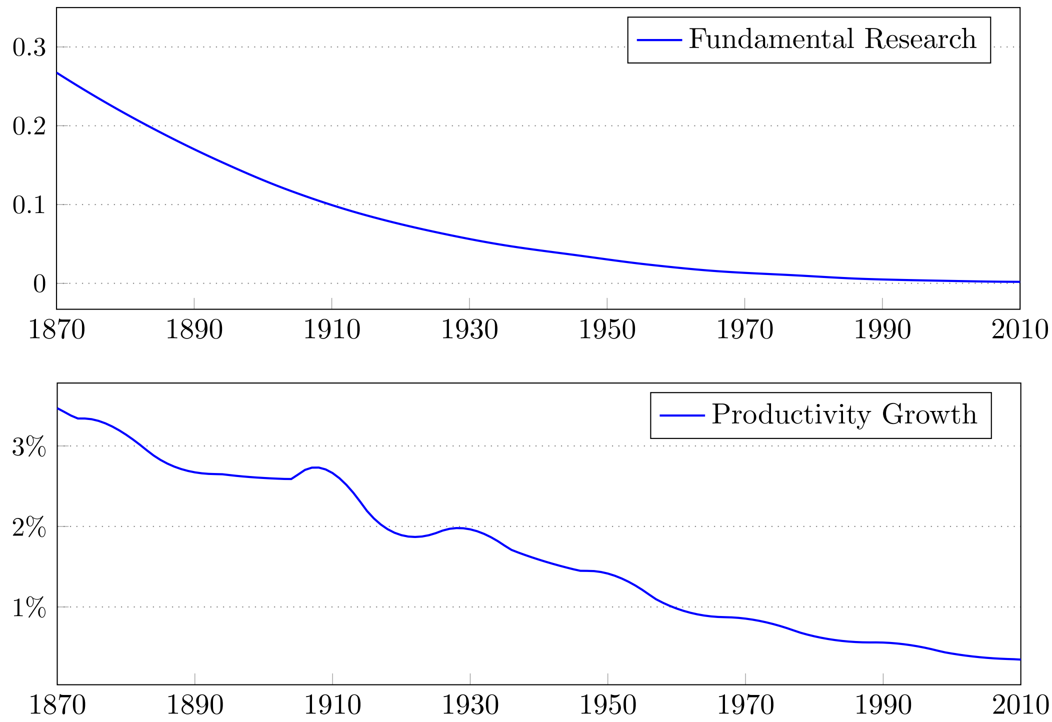

Figure 1.6: Simulation without price changes

in 1920 compared to 1910 which leads to increased productivity growth. After the peak, the crude oil price becomes fairly stable again. The next price hike takes place around 1950 which is mirrored in the simulation by a reinforcement of fundamental research and a higher productivity growth rate. This is followed by the double oil crisis during the 1970s, which again is reflected in the simulation by a higher share of fundamental research; the same is true for the price increase from 2000 onward.

The simulations show that real world factor price changes have a strong influence on the incentives for fundamental research. While fundamental research eventually ceases over time and path dependence lets the simulated economy become trapped in a technological lock-in in the case with no price changes, the version that took the changes in crude oil prices into account could avoid this fate. Although fundamental research declined during the phases with stable prices, the substantial changes in the oil price that occurred several times during the simulation period stimulated fundamental research and led to new fundamental innovations, so that neither research nor productivity growth ceased in the long run. These results indicate that the model's implications are quantitatively important and significantly influence real world economic development.

1.6 Conclusions

Path dependence denotes the fact that the trajectory of technological development is shaped by previous decisions and outcomes which can lead to the dominance of certain technologies in

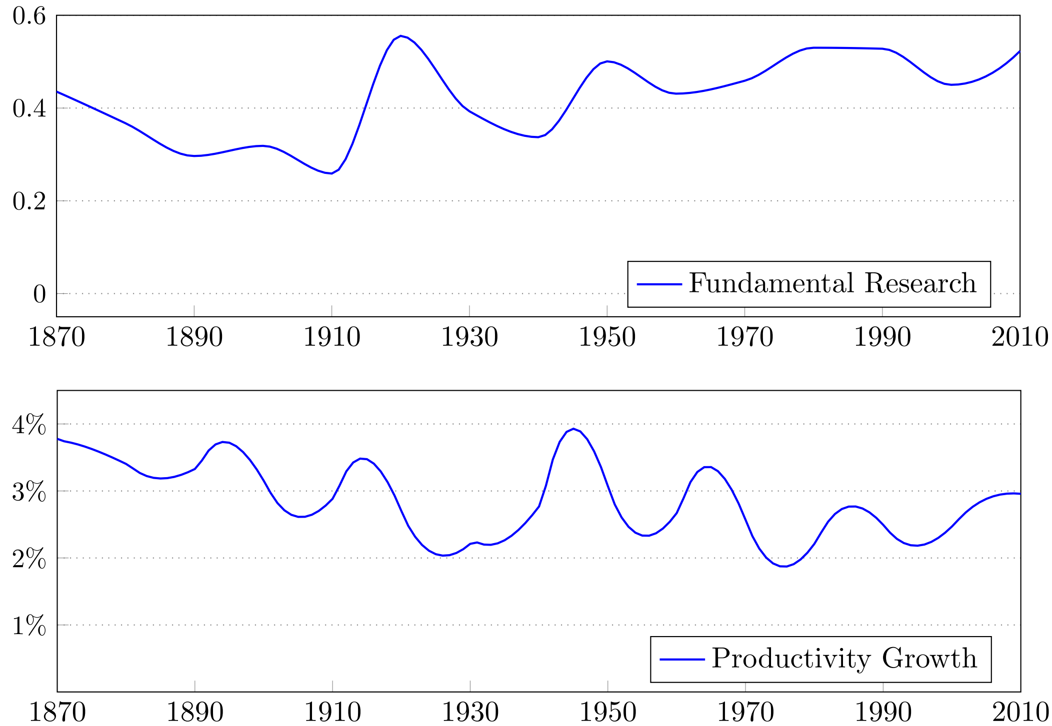

Figure 1.7: Simulation with changes in crude oil price

spite of the availability of better alternatives. However, this dominance is sometimes overcome when changes in the environment induce new innovations and make alternative technologies more attractive.

In this paper, I develop a model that captures the origins of path dependence and also introduces a mechanism of induced innovation which allows to escape from technological lock-in. Due to imperfect spillovers of secondary development, new technologies can be inferior in comparison to dominant existing technologies and the economy becomes trapped in a technological lock-in. However, since fundamental innovations can be directed to favor a particular input factor, changes in the relative supply of primary factors increase the productivity gain of a new technology and induce research to overcome the lock-in.

The model is able to explain the long waves of economic development, where supply changes trigger a new growth cycle. A simulation of the model using the changes of crude oil prices indicates, that the model's implications are quantitatively relevant. With its main finding, that changes in the supply of primary factors can induce innovative activity and stimulate technological progress, the paper also provides a new rationale for policies that aim to increase social welfare and reduce environmental damage by the use of Pigouvian taxes or pollution permits.

For future work, the model could be extended in a number of ways. First, the assumption of zero spillovers of secondary development between fundamental technologies could be relaxed to allow partial spillovers as in Redding (2002). Obviously, some of the human capital and efficiency improvements can be also used for other technologies as well. For the keyboard layout example, it is documented that QWERTY-trained typists need less time to adapt to the Dvorak layout than untrained people. Also the development of alternative-drive vehicles benefits from many of the improvements of gasoline cars over the last century. Second, the adjustment to a new relative supply regime, which is done within one fundamental innovation, could be limited in such a way that it takes a number of fundamental innovations until the economy has completely adapted to the new environment. This would move the model closer to the typical models of directed technological change, where these adjustments take place gradually. Third, the model could be easily extended to use a larger number of primary factors. With a nested intermediate goods production function, different elasticities of substitution can be taken into account. A change in the supply of any of these factors could than induce new research. Such an extension could be especially helpful for empirical work.

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Chapter 2

Imitation and Innovation in General Equilibrium

2.1 Introduction

In this chapter, I analyze the effect of imitation on the rate of technological progress in an endogenous growth model with active incumbents. For a long time, intellectual property rights (IPR) protection has been regarded as the principal condition to foster technological progress. Already Schumpeter (1942) pointed out that the protection of the innovator's monopoly against imitation is a necessary condition for innovative activity. Also, endogenous growth theory typically predicts that imitation lowers the economy's growth rate as the investment in research is reduced due to lowered expected monopoly profits (Romer, 1990; Grossman and Helpman, 1991a; Aghion and Howitt, 1992; Davis and Şener, 2012).

The work of Boldrin and Levine (2008), who argue against the necessity of IPR protection, has challenged this view recently. Also empirical research has shown that increased competition within industries or the entry of foreign competitors can lead to more innovative activity, measured by R&D expenses and patents, and to higher productivity growth (Geroski, 1990; Blundell et al., 1999; Nickell, 1996; Bloom et al., 2011; Correa and Ornaghi, 2011; Buccirossi et al., 2009).

In this paper, I develop a model in which the threat of competition by an imitator induces the incumbent quality leader to increase his innovative activity. This escape-competition-innovation increases the economy's growth rate. Nevertheless, the probability of being challenged by an imitator reduces the expected profit of an innovator since his advantage over the imitator is only strong enough to charge a limited monopoly price. This lowers the incentives to enter the research sector and consequently reduces the rate of technological progress. The aim of this paper is to examine which of the two effects dominates and which parameters control the trade-off between both effects.

The basic structure of the model is similar to Acemoglu and Cao (2010) where radical innovations are made by outsiders and incremental quality improvements are undertaken by incumbents.

This model adds the possibility that an incumbent is challenged by an imitator and evaluates the incumbent's reaction towards this threat. In the model, the decision to enter the research sector and how much secondary development to conduct as a monopolist are determined endogenously, depending on the threat of imitation and replacement. The model also features a rich market structure with intermediate goods sectors that switch between states of monopoly, limited monopoly, or competition. This allows to evaluate the effect of IPR protection on market distortions and to discuss welfare changes.

The results show that a higher probability of imitation can indeed increase the growth rate of the economy. However, in general, the effect is ambiguous and depends primarily on the productivity of secondary development. If increasing secondary development is relatively cheap, the positive effect of imitation induced innovation by the monopolist prevails and lower IPR protection increases the growth rate. Conversely, if increasing secondary development is expensive, the incumbent cannot gain the necessary advantage over the imitator and the growth rate is reduced. For a certain parameter range, the relationship between imitation and growth becomes inversely U-shaped, so that lowering IPR protection first increases the growth rate and then reduces it.

The model also indicates a strong positive effect of imitation on current welfare, which is caused by the influence on the economy's market structure. A higher probability of imitation increases the share of competitive industries and also the share of industries with limited monopoly relative to full monopoly industries. This reduction of monopoly distortions increases output, the wage rate, and utility in the economy. This is even true for some of the cases where imitation unambiguously lowers the innovation rate. A surprising result is that a higher probability of imitation increases the value of an innovation. This comes from the fact that the reduced number of outside innovators leads to a lower probability of displacement which compensates for the increased probability of imitation.

This paper adds to the literature on the interplay of imitation and innovation, which has been studied by a number of authors since the emergence of endogenous growth theory. Segerstrom (1991) develops a quality-ladder model with a continuum of industries where innovation and imitation races take turns within each sector. When imitated, the innovator and the imitator collude and share the monopoly profit. Along the balanced growth path (BGP), the share of sectors in either state is constant. A subsidy to imitative activity has an ambiguous effect on the growth rate, that is facilitating imitation may increase or decrease the growth rate of the economy. A North-South model of innovation and imitation by Grossman and Helpman (1991b) produces similar results. The difference between the two models is that in the latter, imitators in the South have a lower production cost and thus are able to take over the whole market from the innovator.

The model by Mukoyama (2003) uses a similar mechanism. However, in contrast to the models above, imitation leads to Bertrand competition between the innovator and the imitator which eliminates the markup in these industries. Upon imitation, an innovation race between the original innovator and the imitator starts. This provides the incentive for imitation because leap-frogging is excluded and imitation is a precondition for innovation. The fact that imitation leads to competition allows to study the welfare effects of monopolistic distortions. A subsidy to imitation has an ambiguous effect on the growth rate and increases static welfare as the share of industries in competition increases. These results are very similar to those obtained in this model. Also Horii and Iwaisako (2007) derive comparable results. However, they use a different mechanism that is based on the idea that innovation is easier in competitive sectors.

What all these models have in common is that they do not allow the innovator to react towards the threat of imitation and to protect himself. Therefore, the positive effect of imitation on the growth rate never comes from increased R&D intensity but from the increased share of competitive sectors in which innovative activity takes place. In the model by Davis and Şener (2012), the innovator is able to undertake costly rent-protection activities to repel imitation and innovation. It turns out that rent-protection activities can increase the growth rate and welfare when IPR protection is low.[1] However, the effect of imitation on the economy is always negative as it does not lead to increased innovative activity.

Another way for the incumbent quality leader to defend himself against imitation and competition is to undertake own research to escape the outside pressure. This mechanism is introduced and used in a series of papers (Aghion et al., 1997, 2001, 2011, 2012b; Czarnitzki et al., 2014) in which either two firms are in an innovation race against each other or an industry leader fights against potential entrants. They show that a higher rate of imitation can increase the innovation rate as the quality leader tries to stay ahead of competition. Since a higher rate of imitation also lowers expected monopoly profits, the relationship between ease of imitation and the growth rate has typically an inverted U-shape, similar to the results in Mukoyama (2003) and in this paper. However, in these models, the competitive structure within industries is exogenously given. So they lack the decision to enter into research in any industry and constitute only partial models of growth. This paper fills this gap by endogenizing the decision to enter the research sector and allowing an industry leader to innovate further to escape potential imitation.

The organization of the paper is as follows. The next section introduces the model and derives prices and output as well as the optimal amount of secondary development by the incumbent. Section 2.3 solves for the stationary distribution of industries and the number of researchers along the balanced growth path and derives the equilibrium condition for entry into the research sector. In section 2.4, I discuss the potential effects of a change in IPR protection and present numerical simulations to show the possible outcomes. Section 2.5 concludes and gives an outlook for future work.

2.2 The Model

General Setup

The economy comprises three sectors: final goods production, a continuum of industries indexed by $\nu \in [0, 1]$ that produce intermediate goods, and a research sector that develops new designs for the intermediate goods industries. The economy is populated by overlapping generations

[1] This is in contrast to Dinopoulos and Syropoulos (2006) who show that without the threat of imitation, rent-protection activities that prolong the expected monopoly duration of an innovator always lower the growth rate and welfare.

of uniform agents of mass H who live for three periods. Newborn workers decide to work in final goods production or to enter the research sector. Research is stochastic and may either produce a new innovation that can be patented or an imitation of the latest patented technology of an intermediate goods sector. The research sector produces innovations and imitations for all intermediate goods sectors with equal probability. Research success is revealed at the end of the period. If a researcher creates an innovation for one of the intermediate goods sectors, he takes the monopoly position in this sector and produces intermediate goods with the new technology in his second life period. The monopolist is also able to conduct secondary research to further improve his technology. The unsuccessful researchers who did not obtain a patent for a new technology become workers in their remaining life.

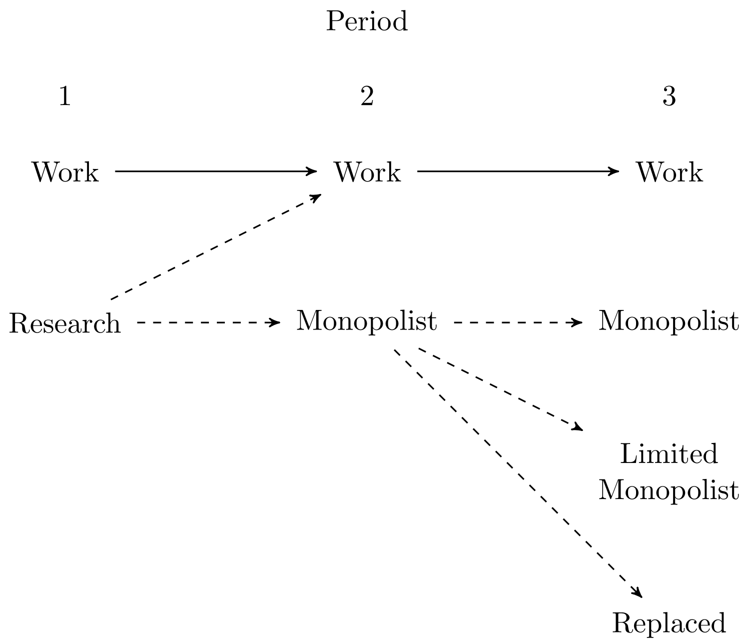

Figure 2.1: Lifecycle of individuals

At the end of that period, the research outcome of the subsequent cohort is revealed. For the actual monopolist of an intermediate goods sector, this yields three possible scenarios for the third period. First, if the research of the subsequent cohort produced neither an innovation nor an imitation for his sector, the monopolist remains the full-fledged monopolist in the last period of his life. Due to the secondary research he has undertaken in the second period, his profit is higher than in the previous period. Second, if the subsequent cohort has been partially successful and created an imitation of the monopolist's technology, the monopolist faces competition in his last period. However, since his technology has already undergone further improvement during the second period which is not included in the imitation, the current monopolist still has a technological advantage that allows him to make a positive profit in the last period. Nevertheless, he is now forced to lower the price due to the competition of the imitator and becomes a limited monopolist. The imitator himself does not take an active role in intermediate goods production since he cannot compete against the incumbent monopolist and only poses the threat point. So he becomes a worker in his subsequent life. Third, if the research of the next cohort created a new innovation for this intermediate goods sector, the actual monopolist is replaced. The positions, in which individuals can find themselves during their lifetime are depicted in Figure 2.1.

If the monopolist is not replaced by a new monopolist before he exits the economy, his patent expires and the technology becomes public knowledge. That means that independent firms produce intermediate goods of the latest technology in this sector. With regard to the market structure, intermediate goods sectors can be in four different states: competition (CO), monopolistic with a monopolist in his second lifetime period (M2), monopolistic with a monopolist in this third period (M3), and in a limited monopoly in which the monopolist is challenged by an imitator (LM). The possible transitions from state to state are depicted in Figure 2.2.[2] The difference between the states M2 and M3 is that no secondary research takes place in M3 since the monopolist will not invest in his last period, and also that M3 is followed by CO if no new innovation is made in this period.

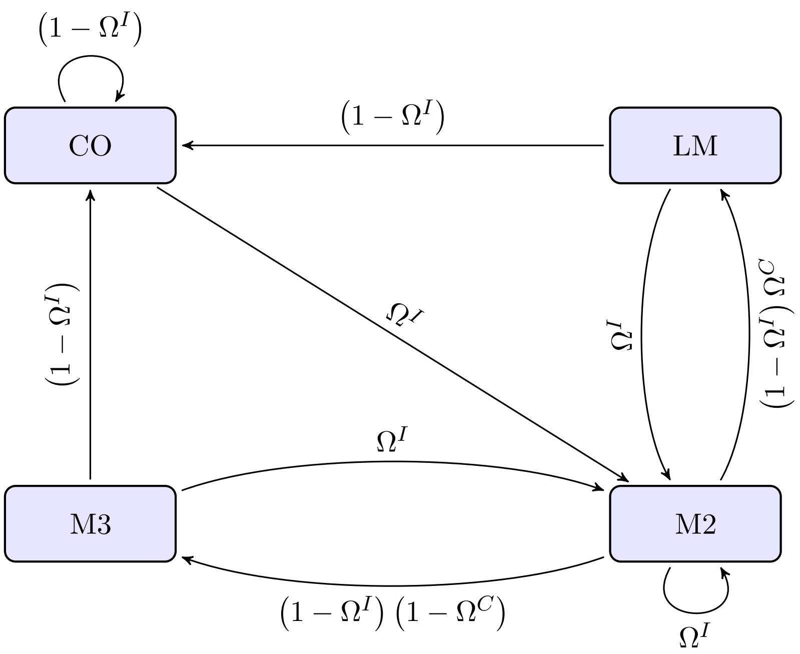

Figure 2.2: States of the intermediate goods sectors

Consumer Preferences

Individual agents are endowed with one unit of labor per period which they can use for working in final goods production, conducting research, or operating a business as a monopolist in an intermediate goods sector. There is no disutility from supplying labor and workers are risk neutral with no discounting.[3] Utility is therefore a linear function of consumption during the three life periods,

$$U_t = c_t + c_{t+1} + c_{t+2}. \tag{2.1}$$

[2] Ω^I, Ω^C denote the probability of an innovation or an imitation in an intermediate goods sector respectively. They are endogenously determined in the equations below.

[3] The omission of a discount factor serves to simplify the model but does not affect the results qualitatively.

Final Goods Production

The final good is produced under perfect competition from intermediate goods and labor, following the production function

$$y_t = \frac{1}{1-\beta}\left[\int_0^1 q_{\nu,t}^{\beta} x_{\nu,t}^{1-\beta} \mathrm{d}\nu\right] L_t^{\beta}, \tag{2.2}$$

where x_ν denotes the amount of intermediate goods of type ν with their respective quality q_ν and L_t denotes the measure of agents employed in final goods production. Throughout, the price of the final good in each period is normalized to 1.

Research

Primary Research

Agents engaged in the research sector try to discover new designs for intermediate goods that increase the productivity of the existing intermediate good by the factor λ.[4]

Throughout the paper I assume that $\lambda \geq (1-\beta)^{-\frac{1-\beta}{\beta}}$. This assumption assures that a new monopolist always completely replaces the previous monopolist and is able to charge the full monopoly price.

Every worker in the research sector has the individual probability $\tilde{p}$ of discovering a technology for a random intermediate goods sector. However, once the technology is developed, there is a probability $\tilde{i}$ that it does not constitute a technology improvement for this sector but rather an imitation of the latest patent . The probability for discovering a genuine new technology is thus given by

$$p = \tilde{p} \cdot (1 - \tilde{i}). \tag{2.3}$$

For the case of an imitation, with probability Φ, the imitation is not treated as a patent infringement and thus can compete against the existing technology on the market. So the inverse of Φ can be regarded as a measure of intellectual property rights protection in the economy. The individual probability to create a marketable imitation of the latest patented technology of an intermediate goods sector is given by

$$i = \tilde{p} \cdot \tilde{i} \cdot \Phi. \tag{2.4}$$

For the remainder of the paper, I will only use the reduced forms of the individual innovation and imitation probabilities p and i.

Let R_t be the total mass of researchers in period t. Since R_t consists of infinitely many elements, the resulting aggregate innovation probability is approximated by a Poisson distribution (Feller, 1950). Technologies are discovered for all intermediate goods sectors with equal probability, so

[4] Notice, that the quality jump takes place at the end of the period. This implies that in the case of an $M2$-$M2$ transition, where a second-period monopolist has undertaken secondary development and is then replaced by a new innovator, the quality of the intermediate good increases by secondary development and by fundamental development. So for $M2$-$M2$ transitions, the quality evolves by $q_{\nu,t+1} = \lambda S_{\nu,t} q_{\nu,t}$. This assumption is in line with Acemoglu and Cao (2010).

the aggregate probability that at least one true innovation is made in any intermediate goods sector is given by

$$\Omega^I(R_t) = 1 - \mathrm{e}^{-pR_t}. \tag{2.5}$$

If more than one innovation is created for a particular intermediate goods sector, the patent is attributed to one of the innovators by lottery. The individual probability of obtaining the patent for a new technology for any intermediate goods sector is given by

$$P(R_t) = \frac{1 - \mathrm{e}^{-pR_t}}{R_t}. \tag{2.6}$$

The aggregate probability that at least one marketable imitation is made for any intermediate goods sector is equivalently given by

$$\Omega^C(R_t) = 1 - \mathrm{e}^{-iR_t}. \tag{2.7}$$

The individual probability of obtaining a patent $P(R_t)$ is decreasing in R_t whereas the aggregate probabilities of innovation and imitation in a sector $\Omega^I(R_t), \Omega^C(R_t)$ are increasing in R_t. Also, the individual and aggregate probabilities of innovation or imitation are increasing in p and i respectively. In the remainder of the paper, the shorter notations Ω_t^I and Ω_t^C will be used for the aggregate probabilities.

Secondary Research

In addition to primary research that creates new designs for intermediate goods replacing the previous generation, the quality of an intermediate good can be improved by the current incumbent of an intermediate goods sector. This secondary development is modeled as technology improvement under certainty that takes one period of time. Since secondary development is costly and time-consuming, the incumbent of an intermediate goods sector will undertake secondary development only during his second life period to reap the benefits of it in his third period. The change of quality is given by

$$q_{\nu,t+1} = S_{\nu,t} \cdot q_{\nu,t}, \tag{2.8}$$

$$s.t.\ S_{\nu,t} = \alpha \left(\frac{s_{\nu,t}}{q_{\nu,t}} \right)^{\sigma} + 1, \tag{2.9}$$

where $s_{\nu,t}$ denotes the cost of secondary development (measured in terms of the final good) and $\alpha \in \mathbb{R}^+$ and $\sigma \in (0,1)$ are parameters that control the magnitude and curvature of the cost function. Throughout the paper, I assume that the parameters α, σ are such that the optimal amount of secondary development chosen by the monopolist $\hat{S}_{\nu,t}$ is bounded by

$$\hat{S}_{\nu,t} < (1-\beta)^{-\frac{1-\beta}{\beta}}. \tag{2.10}$$

This assumption ensures that in the case of imitation, the monopolist is limited in his price setting by the imitator and cannot charge the unconstrained monopoly price.

Intermediate Goods Production

Intermediate goods are produced at constant marginal cost ψ which is normalized to $\psi = 1 - \beta$ without any loss of generality. Demand for intermediate goods is given by

$$x_{\nu,t} = q_{\nu,t} p_{\nu,t}^{-\frac{1}{\beta}} L_t. \tag{2.11}$$

The price of intermediate goods depends on the actual market structure in the particular intermediate goods sector:

Monopoly

If the technology leader of an intermediate goods sector is an unchallenged monopolist $(M2, M3)$, the price of the intermediate good and the quantity demanded are given by

$$p^M = \frac{\psi}{1-\beta} = 1, \tag{2.12}$$

$$x_{\nu,t}^M = q_{\nu,t} L_t. \tag{2.13}$$

Limited Monopoly

If the monopolist is challenged by an imitator in his third life period, the technological advantage of the monopolist is reduced to the amount of secondary development that he undertook in the previous period, $S_{(t-1)}$. In this case, the monopolist can only charge the limited monopoly price, which makes final good producers just indifferent between buying from the monopolist or the imitator. The resulting price and quantity demanded are given by

$$p_{\nu,t}^{LM} = \psi \cdot S_{\nu,(t-1)}^{\frac{\beta}{1-\beta}} = (1-\beta) \cdot S_{\nu,(t-1)}^{\frac{\beta}{1-\beta}} \leq 1, \tag{2.14}$$

$$x_{\nu,t}^{LM} = (1-\beta)^{-\frac{1}{\beta}} q_{\nu,t} S_{\nu,(t-1)}^{-\frac{1}{1-\beta}} L_t, \tag{2.15}$$

where the amount of secondary development $S_{\nu,(t-1)}$ is already included in $q_{\nu,t}$.

Competition

If the monopolist of an intermediate goods sector exits the economy, his patent expires and the technology becomes publicly available. As long as no researcher creates a new innovation for this sector, the intermediate good of the latest technology is produced competitively by independent firms. The resulting price and quantity demanded are given by

$$p_{\nu,t}^{CO} = \psi = (1-\beta), \tag{2.16}$$

$$x_{\nu,t}^{CO} = (1-\beta)^{-\frac{1}{\beta}} q_{\nu,t} L_t. \tag{2.17}$$

Profit of an Innovator

After a researcher has obtained a patent for a new design, he becomes the monopolist of the particular intermediate goods sector in his second life period. His profit for this period is given by

$$\pi^{M2}_{\nu,t}(q_{\nu,t}) = \beta q_{\nu,t} L_t - s_{\nu,t}. \tag{2.18}$$

With regard to his third life period, there are three possibilities. With probability $\left(1-\Omega^I_t\right)\left(1-\Omega^C_t\right)$ neither an innovation nor an imitation is made for this sector, so he remains the unchallenged monopolist in his third period. With probability $\left(1-\Omega^I_t\right)\Omega^C_t$ he is not replaced by a new innovator but challenged by an imitator. In this case, he will be a limited monopolist in his third period. Finally, with probability Ω^I_t a new innovation is made for this sector and the current monopolist is replaced. The two possible outcomes for a positive profit in the third period depend on the amount of secondary development that the monopolist undertakes in his second life period $S_{\nu,t}$. They are given by

$$\pi^{M3}_{\nu,t+1}(q_{\nu,t}, S_{\nu,t}) = \beta S_{\nu,t} q_{\nu,t} L_{t+1}, \tag{2.19}$$

$$\pi^{LM}_{\nu,t+1}(q_{\nu,t}, S_{\nu,t}) = (1-\beta)^{-\frac{1-\beta}{\beta}} \left[1 - S_{\nu,t}^{-\frac{\beta}{1-\beta}}\right] q_{\nu,t} L_{t+1}. \tag{2.20}$$

The monopolist's profit is smaller in the limited monopoly case than with an unchallenged monopoly. Furthermore, the profit increases in both cases with the amount of secondary development undertaken in the previous period. However, the marginal effect of secondary development is stronger in the limited monopoly case than under a pure monopoly.

The expected total profit over the two periods $\Pi_{\nu,t}$ of an innovator who obtains the monopoly with new technology level $q_{\nu,t}$ is given by

$$\begin{aligned} \mathbb{E}_t\left(\Pi_{\nu,t}\right) = \beta q_{\nu,t} L_t - s_{\nu,t} + \left(1-\Omega^I_t\right)\left(1-\Omega^C_t\right) \beta S_{\nu,t} q_{\nu,t} L_{t+1} \\ + \left(1-\Omega^I_t\right)\Omega^C_t (1-\beta)^{-\frac{1-\beta}{\beta}} \left[1 - S_{\nu,t}^{-\frac{\beta}{1-\beta}}\right] q_{\nu,t} L_{t+1}. \end{aligned} \tag{2.21}$$

Optimal Secondary Development
In his second life period, the monopolist chooses the amount of secondary development which maximizes his expected profit

$$\hat{S}_{\nu,t} = \underset{S_{\nu,t}}{\arg\max}\ \mathbb{E}_t\left(\Pi_{\nu,t}\right), \tag{2.22}$$

$$s.t. \quad s_{\nu,t} = \left(\frac{S_{\nu,t}-1}{\alpha}\right)^{\frac{1}{\sigma}} q_{\nu,t}. \tag{2.23}$$

Notice that the monopolist does not take into account the possible effect of $S_{\nu,t}$ on the aggregate economy, that is on the number of active researchers and on future wages. Optimal secondary development is then implicitly defined by

$$\left(1-\Omega_t^I\right)\left[1+\Omega_t^C\left((1-\beta)^{-\frac{1}{\beta}}\hat{S}_{\nu,t}^{-\frac{1}{1-\beta}}-1\right)\right]\beta L_{t+1}=\frac{\left(\hat{S}_{\nu,t}-1\right)^{\frac{1-\sigma}{\sigma}}}{\sigma\alpha^{\frac{1}{\sigma}}}. \tag{2.24}$$

Proposition 2.1. *A unique optimal value of secondary development $\hat{S}_{\nu,t}\geq 1$ exists, which is independent of the technology level of the monopolist, so $\hat{S}_{\nu,t}=\hat{S}_t$*

Proof. The LHS of equation(2.24) is strictly decreasing in $\hat{S}_t$ and bounded between $\left(1-\Omega_t^I\right)\left[1+\Omega_t^C\left((1-\beta)^{-\frac{1}{\beta}}-1\right)\right]\beta L_{t+1}$ for $\hat{S}_t=1$ and $\left(1-\Omega_t^I\right)\left[1-\Omega_t^C\right]\beta L_{t+1}$ for $\hat{S}_t\to\infty$. The RHS of the equation is strictly increasing in $\hat{S}_t$ and is zero for $\hat{S}_t\to 1$ and goes to infinity for $\hat{S}_t\to\infty$. This establishes the existence of a unique intersection. The independence of the monopolist's level of technology $q_{\nu,t}$ can be inferred directly from equation (2.24). □

Proposition 2.2. *An increase of the aggregate imitation probability Ω_t^C ceteris paribus increases secondary development $\hat{S}_t$ while an increase of the aggregate innovation probability Ω_t^I lowers secondary development $\hat{S}_t$. Furthermore, an increase of the aggregate imitation probability Ω_t^C or an increase of the aggregate innovation probability Ω_t^I reduces the expected monopoly profit of an innovator $\mathbb{E}_t\left(\Pi_{\nu,t}\right)$.*

Proof. To prove the first part, writing equation (2.24) as implicit function of aggregate innovation and imitation probability and secondary development $F\left(\Omega_t^I,\Omega_t^C,\hat{S}_t\left(\Omega_t^I,\Omega_t^C\right)\right)=0$ allows for implicit differentiation to obtain

$$\frac{d\hat{S}_t}{d\Omega_t^C}=-\frac{\frac{\partial F(\cdot)}{\partial\Omega_t^C}}{\frac{\partial F(\cdot)}{\partial\hat{S}_t}}=-\frac{\left(1-\Omega_t^I\right)\left((1-\beta)^{-\frac{1}{\beta}}\hat{S}_t^{-\frac{1}{1-\beta}}-1\right)\beta L_{t+1}}{-\frac{1}{1-\beta}\left(1-\Omega_t^I\right)\Omega_t^C(1-\beta)^{-\frac{1}{\beta}}\hat{S}_t^{\frac{-2+\beta}{1-\beta}}\beta L_{t+1}-\frac{1-\sigma}{\sigma}\frac{\left(\hat{S}_t-1\right)^{\frac{1-2\sigma}{\sigma}}}{\sigma\alpha^{\frac{1}{\sigma}}}}>0,$$

$$\frac{d\hat{S}_t}{d\Omega_t^I}=-\frac{\frac{\partial F(\cdot)}{\partial\Omega_t^I}}{\frac{\partial F(\cdot)}{\partial\hat{S}_t}}=-\frac{-\Omega_t^I\left[1+\Omega_t^C\left((1-\beta)^{-\frac{1}{\beta}}\hat{S}_t^{-\frac{1}{1-\beta}}-1\right)\right]\beta L_{t+1}}{-\frac{1}{1-\beta}\left(1-\Omega_t^I\right)\Omega_t^C(1-\beta)^{-\frac{1}{\beta}}\hat{S}_t^{\frac{-2+\beta}{1-\beta}}\beta L_{t+1}-\frac{1-\sigma}{\sigma}\frac{\left(\hat{S}_t-1\right)^{\frac{1-2\sigma}{\sigma}}}{\sigma\alpha^{\frac{1}{\sigma}}}}<0.$$

For the second part, differentiating the expected profit $\mathbb{E}_t\left(\Pi_{\nu,t}\right)$ with respect to the aggregate imitation probability Ω_t^C or the aggregate innovation probability Ω_t^I respectively directly yields the result.

$$\frac{\partial\mathbb{E}_t\left(\Pi_{\nu,t}\right)}{\partial\Omega_t^C}=-\left(1-\Omega_t^I\right)q_{\nu,t}L_t\left[\beta\hat{S}_t-(1-\beta)^{-\frac{1-\beta}{\beta}}\left(1-\hat{S}_t^{-\frac{\beta}{1-\beta}}\right)\right]<0, \tag{2.25}$$

$$\frac{\partial\mathbb{E}_t\left(\Pi_{\nu,t}\right)}{\partial\Omega_t^I}=-\left(\left(1-\Omega_t^C\right)\beta S_{\nu,t}+\Omega_t^C(1-\beta)^{-\frac{1-\beta}{\beta}}\left[1-S_{\nu,t}^{-\frac{\beta}{1-\beta}}\right]\right)q_{\nu,t}L_{t+1}<0. \tag{2.26}$$

□

An increase in the imitation probability raises secondary development because the marginal profit of secondary development is greater in the limited monopoly situation than for an unchallenged monopoly. Without secondary development, the monopolist cannot make any profit when being imitated. Increasing secondary development reduces the negative effect of imitation as the monopolist expands his quality advantage over the imitator which allows him to raise the limited monopoly price. Therefore, secondary development can be regarded as "escape innovation", similar to the results in Aghion et al. (2011, 2012b). An exogenous increase of the innovation probability of outsiders has the opposite effect on secondary development. This is due to the fact, that the monopolist cannot compete against an innovator that replaces him but only fight against competition of an imitator. If an innovation takes place in the sector, the monopolist is completely replaced in his third period and all investment in secondary development is lost from his point of view.

The second part of Proposition 2.2 indicates that even though the monopolist can react towards a higher probability of imitation by increasing secondary development, the expected monopoly profit ultimately declines. This implies, that entering the research sector becomes less attractive, when the probability of imitation increases.

Final goods sector
The amount of goods demanded from each intermediate goods sector depends on the quality of the particular good and on the price. The latter depends on the current market structure of the particular intermediate goods sector. In order to derive the final goods output, the intermediate goods sectors are grouped together according to their current state. Let N_t^{CO} be the set of intermediate goods sectors with competitive market structure at time t and μ_t^{CO} the Lebesgue measure of this set. $N_t^{M2}, N_t^{M3}, N_t^{LM}$ with $\mu_t^{M2}, \mu_t^{M3}, \mu_t^{LM}$ are defined equivalently, so that

$$N_t^{CO} \cup N_t^{M2} \cup N_t^{M3} \cup N_t^{LM} = [0,1],$$

and

$$\mu_t^{CO} + \mu_t^{M2} + \mu_t^{M3} + \mu_t^{LM} = 1.$$

With this, final goods production can be rewritten as

$$y_t = \left[\int_{N_t^{CO}} q_{\nu,t}^{\beta} \left[(1-\beta)^{-\frac{1}{\beta}} q_{\nu,t} L_t \right]^{1-\beta} \mathrm{d}\nu + \int_{N_t^{M2}} q_{\nu,t}^{\beta} \left[q_{\nu,t} L_t \right]^{1-\beta} \mathrm{d}\nu \right.$$
$$\left. + \int_{N_t^{M3}} q_{\nu,t}^{\beta} \left[q_{\nu,t} L_t \right]^{1-\beta} \mathrm{d}\nu + \int_{N_t^{LM}} q_{\nu,t}^{\beta} \left[(1-\beta)^{-\frac{1}{\beta}} q_{\nu,t} \hat{S}_t^{-\frac{1}{1-\beta}} L_t \right]^{1-\beta} \mathrm{d}\nu \right] \frac{1}{1-\beta} L_t^{\beta}, \quad (2.27)$$

which simplifies to

$$y_t = \frac{(1-\beta)^{-\frac{1-\beta}{\beta}} \int_{N_t^{CO}} q_{\nu,t} \mathrm{d}\nu + \int_{N_t^{M2}} q_{\nu,t} \mathrm{d}\nu + \int_{N_t^{M3}} q_{\nu,t} \mathrm{d}\nu + (1-\beta)^{-\frac{1-\beta}{\beta}} \hat{S}_t^{-1} \int_{N_t^{LM}} q_{\nu,t} \mathrm{d}\nu}{1-\beta} L_t. \quad (2.28)$$

The average quality of intermediate goods in the CO-type sectors at time t is given by

$$Q_t^{CO} = \frac{\int_{N_t^{CO}} q_{\nu,t} \mathrm{d}\nu}{\mu_t^{CO}},$$

and $Q_t^{M2}, Q_t^{M3}, Q_t^{LM}$ are defined equivalently. This allows to write final goods output in terms of the average quality of each type of intermediate goods sectors.

$$y_t = \frac{(1-\beta)^{-\frac{1-\beta}{\beta}} \mu_t^{CO} Q_t^{CO} + \mu_t^{M2} Q_t^{M2} + \mu_t^{M3} Q_t^{M3} + (1-\beta)^{-\frac{1-\beta}{\beta}} \hat{S}_t^{-1} \mu_t^{LM} Q_t^{LM}}{1-\beta} L_t. \quad (2.29)$$

2.3 Balanced Growth Path

Definition of BGP Equilibrium

On the balanced growth path, the number of total researchers R, the optimal amount of secondary development $\hat{S}$, and the measures of the four types of intermediate goods sectors $\mu^{CO}, \mu^{M2}, \mu^{M3}, \mu^{LM}$ are constant over time. The average quality of each type of intermediate good sectors $Q^{CO}, Q^{M2}, Q^{M3}, Q^{LM}$, output y, the wage for workers in the final goods sector w, and the expected profit of researchers $\mathbb{E}(\Pi)$ grow at a constant growth rate g.

Stationary Distribution of Intermediate Goods Sectors

The transition of the intermediate goods sectors between states as pictured in Figure 2.2 is a Markov chain. On the balanced growth path, where innovation and imitation probabilities are constant, the Markov chain is time-homogeneous and the stationary distribution can be derived.

Along the BGP, the transition matrix for every intermediate goods sector is given by

$$\mathbb{P} = \begin{array}{c} \\ CO \\ M2 \\ M3 \\ LM \end{array} \begin{array}{c} \begin{array}{cccc} CO & M2 & M3 & LM \end{array} \\ \begin{pmatrix} (1-\Omega^I) & \Omega^I & 0 & 0 \\ 0 & \Omega^I & (1-\Omega^I)(1-\Omega^C) & (1-\Omega^I)\Omega^C \\ (1-\Omega^I) & \Omega^I & 0 & 0 \\ (1-\Omega^I) & \Omega^I & 0 & 0 \end{pmatrix} \end{array},$$

and the stationary measures of the sets of intermediate sector types are given by

$$\begin{pmatrix} \mu^{CO} \\ \mu^{M2} \\ \mu^{M3} \\ \mu^{LM} \end{pmatrix} = \begin{pmatrix} (1-\Omega^I)^2 \\ \Omega^I \\ (1-\Omega^I)(1-\Omega^C)\Omega^I \\ (1-\Omega^I)\Omega^C\Omega^I \end{pmatrix}. \quad (2.30)$$

The stationary distribution specifies the time-invariant measures of the sets of intermediate goods sectors in a certain stage. Another possible interpretation is, that it denotes the average time share that each intermediate sector spends in a certain stage.

Growth Rate and Average Qualities
The stable distribution allows to calculate the growth rate of the economy. All sectors have the same probability Ω^I for a new innovation which increases the quality by λ. Additionally, in $M2$ sectors secondary development increases the quality by $\hat{S}$. For $M2$ to $M2$ transitions, the quality increment from fundamental research λ comes on top of the quality improvement from secondary development. With this, the steady-state growth rate of the economy is given by

$$g = \left(\mu^{CO} + \mu^{M3} + \mu^{LM}\right) \cdot \Omega^I(\lambda - 1) + \mu^{M2} \cdot \left[\Omega^I(\hat{S}\lambda - 1) + \left(1 - \Omega^I\right)(\hat{S} - 1)\right]$$

$$= \Omega^I \left[\hat{S} + \lambda - 2 + \Omega^I(\lambda - 1)(\hat{S} - 1)\right]. \tag{2.31}$$

Proposition 2.3. *An increase of the aggregate innovation probability Ω^I or an increase of secondary development $\hat{S}$ ceteris paribus increases the economy's growth rate on the balanced growth path.*

Proof. Differentiating (2.31) with respect to Ω^I or with respect to $\hat{S}$ directly leads to the result

$$\frac{\partial g}{\partial \Omega^I} = (\hat{S} + \lambda - 2) + 2\Omega^I(\lambda - 1)(\hat{S} - 1) > 0, \tag{2.32}$$

$$\frac{\partial g}{\partial \hat{S}} = \Omega^I \left[1 - \Omega^I + \Omega^I \lambda\right] > 0. \tag{2.33}$$

□

Proposition 2.3 together with Proposition 2.2 capture the trade-off that motivates this paper. The growth rate rises if innovation by outsiders increases as well as when secondary development by monopolists is augmented. A higher aggregate imitation probability lowers expected monopoly profits and so reduces the amount of fundamental research, resulting in a lower Ω^I. But imitation also raises optimal secondary development by monopolists. Hence the expected result on the growth rate is ambiguous.

With the time-invariant measures of intermediate sector types, the development of the average quality level of the different intermediate sector types can be traced. For the CO-type, the average quality level evolves according to

$$Q_{t+1}^{CO} = \frac{\left(1 - \Omega^I\right)\mu^{CO} Q_t^{CO} + \left(1 - \Omega^I\right)\mu^{M3} Q_t^{M3} + \left(1 - \Omega^I\right)\mu^{LM} Q_t^{LM}}{\left(1 - \Omega^I\right)\left(\mu^{CO} + \mu^{M3} + \mu^{LM}\right)}$$

$$= \frac{\mu^{CO} Q_t^{CO} + \mu^{M3} Q_t^{M3} + \mu^{LM} Q_t^{LM}}{1 - \mu^{M2}}. \tag{2.34}$$

Doing this for all types of intermediate goods sectors and using the fact that the average quality of each type of intermediate goods sector grows with rate g on the BGP, the development of the mean quality in the four intermediate sector types can be expressed by the system of linear equations

$$\begin{pmatrix} \frac{\mu^{CO}}{1-\mu^{M2}} & 0 & \frac{\mu^{M3}}{1-\mu^{M2}} & \frac{\mu^{LM}}{1-\mu^{M2}} \\ \lambda\mu^{CO} & \lambda\hat{S}\mu^{CO} & \lambda\mu^{M3} & \lambda\mu^{LM} \\ 0 & \hat{S} & 0 & 0 \\ 0 & \hat{S} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} Q_t^{CO} \\ Q_t^{M2} \\ Q_t^{M3} \\ Q_t^{LM} \end{pmatrix} = (1+g) \begin{pmatrix} Q_t^{CO} \\ Q_t^{M2} \\ Q_t^{M3} \\ Q_t^{LM} \end{pmatrix}. \tag{2.35}$$

The solution to this system of equations yields the time-invariant average quality of each type of intermediate sector relative to the mean quality level of the economy. It is given by

$$\begin{pmatrix} Q_t^{CO} \\ Q_t^{M2} \\ Q_t^{M3} \\ Q_t^{LM} \end{pmatrix} = \begin{pmatrix} \frac{\hat{S}}{(1+g)\left(g+\Omega^I+\hat{S}(1-\Omega^I)\right)} \\ \frac{\left(g+\Omega^I\right)}{\Omega^I\left(g+\Omega^I+\hat{S}(1-\Omega^I)\right)} \\ \frac{\hat{S}\left(g+\Omega^I\right)}{(1+g)\left(g+\Omega^I+\hat{S}(1-\Omega^I)\right)\Omega^I} \\ \frac{\hat{S}\left(g+\Omega^I\right)}{(1+g)\left(g+\Omega^I+\hat{S}(1-\Omega^I)\right)\Omega^I} \end{pmatrix} \cdot Q_t, \tag{2.36}$$

where Q_t is the average quality of all intermediate goods in the economy,

$$Q_t = \int_0^1 q_{\nu,t} \mathrm{d}\nu = \mu^{CO} Q_t^{CO} + \mu^{M2} Q_t^{M2} + \mu^{M3} Q_t^{M3} + \mu^{LM} Q_t^{LM}. \tag{2.37}$$

Notice that $Q_t^{M3} = Q_t^{LM}$ which is obvious since all intermediate goods sectors that are included in either N^{M3} or N^{LM} are directly coming from N^{M2} with added secondary development during the $M2$ state and no further changes. It can be easily verified that Q_t^{CO} is smaller than any of the other average qualities. However it is indeterminate whether Q_t^{M2} is greater or lower than Q_t^{M3} or Q_t^{LM} respectively.

Final goods output and wage
Let $q^{CO} = \frac{Q^{CO}}{Q}$ and q^{M2}, q^{M3}, q^{LM} be defined similarly. Then final goods output is given by

$$y_t = \frac{(1-\beta)^{-\frac{1-\beta}{\beta}} \mu^{CO} q^{CO} + \mu^{M2} q^{M2} + \mu^{M3} q^{M3} + (1-\beta)^{-\frac{1-\beta}{\beta}} \hat{S}^{-1} \mu^{LM} q^{LM}}{1-\beta} L Q_t, \tag{2.38}$$

where the mass of workers is given by the total population net of the mass of researchers, monopolists in the intermediate goods sectors, and the monopolists from last period that have been displaced by new monopolists,

$$L = 3H - R - 2\Omega^I. \tag{2.39}$$

Having derived the economy's final goods output, the wage for workers in the final goods sector is given by

$$\begin{aligned} w_t = \frac{\partial y_t}{\partial L} &= \beta \frac{(1-\beta)^{-\frac{1-\beta}{\beta}} \mu^{CO} q^{CO} + \mu^{M2} q^{M2} + \mu^{M3} q^{M3} + (1-\beta)^{-\frac{1-\beta}{\beta}} \hat{S}^{-1} \mu^{LM} q^{LM}}{1-\beta} Q_t \\ &= Q_t \cdot \bar{w} \ , \end{aligned} \tag{2.40}$$

where $\bar{w}$ is the technology-adjusted wage.

The fact that $q^{M3} = q^{LM}$ implies that if a higher share of intermediate goods industries changes from $M2$ to LM instead of switching to $M3$, caused by a higher aggregate imitation probability Ω^I, final goods output and the wage rate increase. This effect comes from reduced monopoly distortions due to the the lower market power of the limited monopolist and yields another positive effect of imitation. On the other hand, as the wage rate increases, becoming a worker in the final goods sector becomes more attractive which implies a negative effect on the amount of primary research.

Lifetime Income of a Worker

A newborn agent who decides to work in the final goods sector earns the wage during his three life periods. The wage increases every period by the economy's growth rate g. Hence life-time income W_Q is given by

$$W_t = Q_t \sum_{\tau=0}^{2} (1+g)^{\tau} \bar{w} = Q_t \cdot \bar{W}, \tag{2.41}$$

where $\bar{W}$ denotes the worker's technology-adjusted life-time income.

The lifetime income of a worker depends on two factors: the wage rate and the growth rate of the economy. As the probability of imitation goes up, the wage increases due to the reduced market power in the economy. If the growth rate also rises, the impact on the worker's lifetime income is clearly positive. However, if the growth rate is negatively affected, the resulting effect on the worker's lifetime income is ambiguous.

Gains from an Innovation

A newborn agent who decides to enter the research sector and observes an average level of technology Q, expects the quality level of his innovation to be

$$\mathbb{E}_t(Q^V_{t+1}) = (1+g) q^{M2} Q_t.$$

The expected value of an innovation for a researcher is then given by

$$\begin{aligned}V_t =& Q_t \cdot (1+g)q^{M2}\left[\beta L - \left(\frac{\hat{S}-1}{\alpha}\right)^{\frac{1}{\sigma}}\right.\\ &\left. + \left(1-\Omega^I\right)\left(1-\Omega^C\right)\beta\hat{S}L + \left(1-\Omega^I\right)\Omega^C(1-\beta)^{-\frac{1-\beta}{\beta}}\left[1-S^{-\frac{\beta}{1-\beta}}\right]L\right]\\ =& Q_t \cdot \bar{V}, \end{aligned} \tag{2.42}$$

where $\bar{V}$ denotes the technology-adjusted value of an innovation.

Arbitrage Equation

Having derived the expected value of an innovation for a researcher and the life-time income of a worker, the arbitrage equation that determines the equilibrium number of researchers along the balanced growth path can be written as

$$\bar{W} = P(R)\cdot\bar{V} + (1-P(R))\left[\bar{W}-\bar{w}\right], \tag{2.43}$$

given that the number of researchers is positive and not all young agents enter the research sector,

$$0 < R < H. \tag{2.44}$$

If the arbitrage condition cannot be fulfilled because no newborn agent finds it attractive to enter the research sector, the economy features zero growth, constant wages, and all intermediate goods sectors are in the competitive state CO. Conversely, it could be possible that entering the research sector becomes so attractive, that the RHS of (2.43) is greater than the LHS for $R = H$ and all young agents enter the research sector. At this point, there is a kink in the decision to enter the research sector. In principle, agents could also enter the research sector in their second life period. However, they would then only have the chance of a one-period monopoly instead of a potential two-period monopoly as young researchers have. In the following, I rule out these two possibilities and focus on the interior solution where a part of newborn agents enters the research sector and the remainder works in final goods production.

The arbitrage equation is independent of the current technology level. Hence the number of researchers does not change over time, which establishes the balanced growth path property. The BGP equilibrium of the economy is determined by the solution to the system of implicit functions (2.24) and (2.43) which define the amount of researchers and optimal secondary development from which all other endogenous variable can be derived directly. Unfortunately, an analytic proof for the uniqueness of the equilibrium could not be established. Nevertheless, numerical computation of the equilibrium over a wide range of parameters suggests that uniqueness is fulfilled in practice.

The arbitrage equation can be rearranged to provide further insight how the equilibrium number of researchers is determined

$$\frac{P(R)}{1 - P(R)} \left(\bar{V} - \bar{W}\right) = \bar{w}. \tag{2.45}$$

A higher value of an innovation increases the benefits of research and hence raises the number of researchers in equilibrium. The number of researchers decreases if the life-time income of a worker $\bar{W}$, which is the alternative to research, or the opportunity cost of research, namely the wage lost during the period of research, $\bar{w}$ increase. The life-time income $\bar{W}$ is closely connected to the wage rate $\bar{w}$ but also positively affected by the growth rate, which in turn positively depends on the number of researchers.

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Welfare
As the arbitrage equation states that the expected utility of an agent that enters the research sector is equal to the life-time income of a worker in final goods production, the latter becomes a perfect measure for the expected life-time utility of any newborn agent in the model.[5] This can be regarded as a measure of welfare. However, it should be pointed out that it concerns only the welfare of the current newborn generation, not that of future generations which would profit more strongly from an increased rate of economic growth. It can be easily extended into a utilitarian welfare measure where the utility of future generations is weighted with the inverse of the growth rate.

2.4 Effects of a Change of the Imitation Probability

A change in the individual probability of (a marketable) imitation i affects the economy's equilibrium in a number of ways. First, a higher i increases the aggregate imitation probability and thus reduces the expected profit of an innovator and the number of researchers in equilibrium. In return, the aggregate innovation probability Ω^I drops while the individual success probability of a researcher rises, which dampens the negative effect on the amount of researchers. The higher aggregate imitation probability and the lower aggregate innovation probability together raise the amount of optimal secondary development $\hat{S}$ in equilibrium. The resulting effect on the growth rate is ambiguous.

The higher aggregate imitation probability also reduces monopolistic distortions by increasing the measure of industries in limited monopoly relative to that in third-period monopoly, which

[5]This holds also for the zero-growth equilibrium without research.

raises final goods output and the wage rate. The latter effect further lowers the equilibrium number of researchers as the opportunity cost of research increases. The impact on the life-time income of the worker depends on the growth rate as well and is therefore ambiguous.

Due to the complexity of equations (2.24) and (2.43), it is not possible to derive comparative static results for changes of the imitation probability. Therefore I use numerical examples to gain further insight about the effects of an increase in the individual imitation probability. In the remainder of the paper, I focus solely on a change in the individual probability of making a marketable imitation i while the individual probability of successful innovation p is held constant. This implies, that the change of i comes from a change in the parameter Φ, that is from a change in the protection of intellectual property rights.

For the simulation, the period length is set to 15 years. The mass of agents is $H = 5$ and the innovation probability is set to $p = 0.0615$ to yield an annual growth rate of 2% when the imitation probability is set to zero. I set $\beta = 2/3$ to capture the labor share of income. Following Acemoglu and Cao (2010), the quality improvement of a fundamental innovation is set to $\lambda = 3$ and the cost of secondary development is chosen to yield $S = 1.5$ at zero imitation probability.[6] For the first figure, the chosen values are $\alpha = 0.374$ and $\sigma = 0.5$. All figures are quality adjusted, that is they are divided by the average level of technology.

Figure 2.3 illustrates how the economy reacts to a change in the individual imitation probability i which increases from zero to one on the horizontal axis. Looking at the two topmost plots, it can be seen that secondary development grows constantly as the imitation probability increases whereas the number of researchers falls. The combined result on the growth rate is mixed in this example and represents an inverted U-shape, similar to the results in Aghion et al. (2001, 2002) and Mukoyama (2003). For small values of i, the positive effect of stronger secondary development is dominant, so that the growth rate increases. The highest growth rate is achieved when the aggregate imitation probability in a sector reaches 28%. As i increases further, the negative effect of having less fundamental research becomes more important and the growth rate decreases even though it remains above the value for zero-imitation probability. Overall, the effect on the growth rate is quite small in this example.

The next plots reveal how the determinants of the arbitrage equation are affected by changes in the individual imitation probability. The wage in the final goods sector increases with higher imitation probability as the measure of sectors with competition or limited monopoly increases relative to those with pure monopoly. The higher wage rate, which can be regarded as the cost of fundamental research, adds an indirect negative effect of increased imitation probability on fundamental research. A similar result can be found in Horii and Iwaisako (2007). The life-time income of a worker also grows with the imitation probability. In the area where the growth rate increases, this result is clear, since both, the wage and the growth rate positively affect the life-time income of a worker. However, even in the area where the growth rate starts to decline, the life-time income of workers rises further. The wage effect dominates because the changes in

[6] See also Freeman and Soete (1997) and Scherer (1986) for accounts of the innovation process.

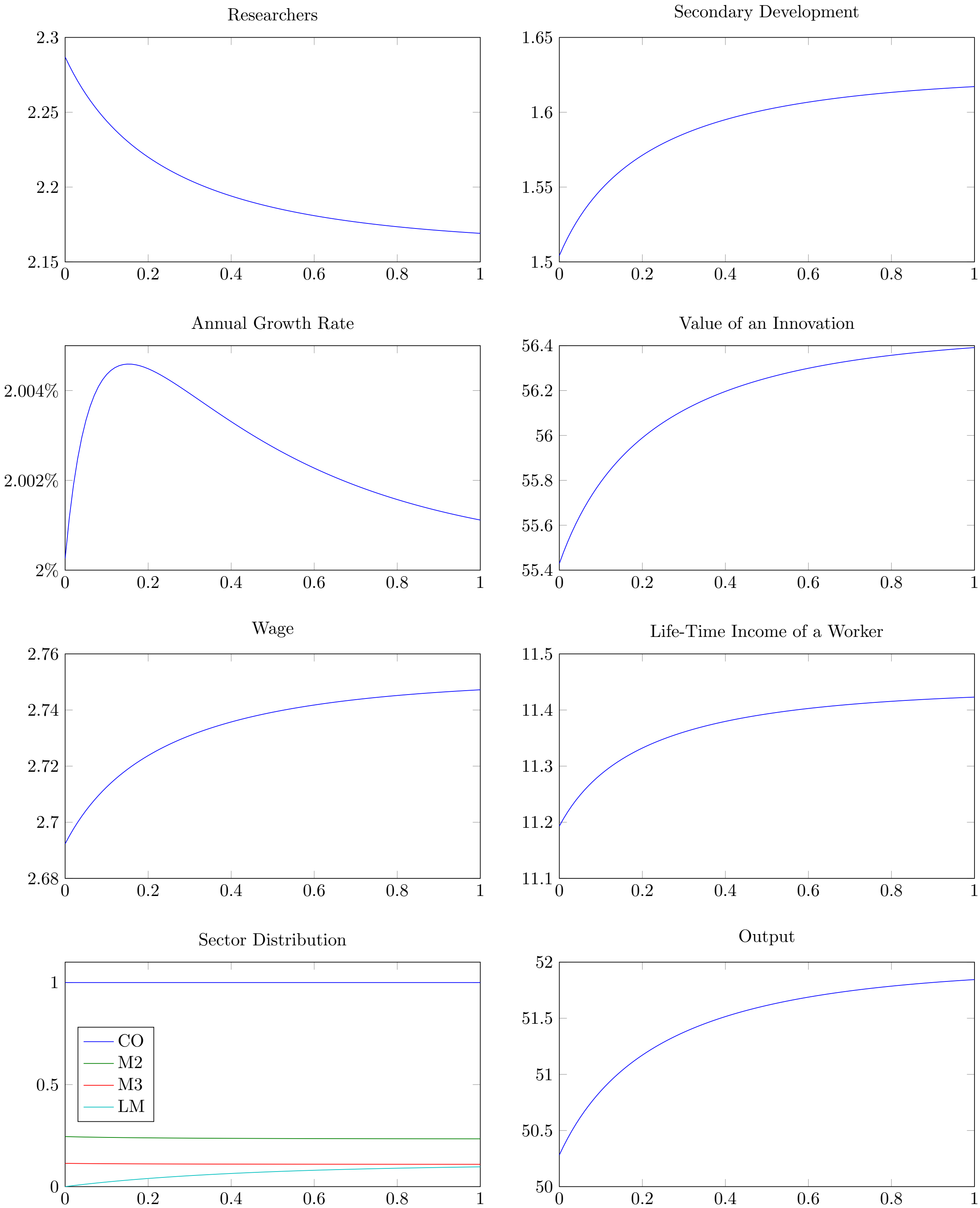

Figure 2.3: Effect of changes in the individual imitation probability
(Imitation probability i given on horizontal axis)

the growth rate are very small. This adds to the reduction of researchers, as the outside option of research increases.

Interestingly, the expected value of an innovation does not decrease but rather increases as the imitation probability rises. This comes as a surprise as the threat of imitation should lower the expected monopoly profit. However, as the number of researchers declines, the threat of being replaced by another innovator drops. Also, fewer researchers imply a higher number of production workers which increases demand for intermediate goods and hence raise the monopoly profit.

The life-time income of a worker also measures the expected utility of all newborn agents in the economy. Here it turns out, that a higher rate of imitation always increases utility, even though the growth rate starts to decline at some point. This implies, that the positive effect caused by reduced market power is stronger, than the loss due to less growth. The life-time income of final good workers rises because monopolistic distortions are reduced and thus wages increase. The expected utility of researchers goes up because the individual probability to obtain a patent increases with fewer researchers while the probability of being displaced in the third period falls. In addition, the monopoly profit increases as the number of production workers rises.

The last two plots provide some more insight about how the aggregate economy reacts to a change in the individual imitation probability. The left plot shows the equilibrium distribution of the states of intermediate goods sectors. As the imitation probability rises, the measure of sectors in limited monopoly increases at the expense of the sectors in third-period monopoly until eventually, all monopolists are imitated and $M3$ vanishes. In addition, the measure of sectors in a second-period monopoly declines whereas the measure of sectors in competition increases as the number of researchers falls. Since both effects imply a reduction of monopolistic distortions in the economy, the output increases. A second factor, that raises output, is the increase in the number of workers in final goods production.

Productivity of Secondary Development
The results derived above depend on how strong secondary development reacts towards an increase in the imitation probability. Figure 2.4 illustrates how the economy is affected by a higher imitation rate with different parameters for the cost of secondary development.

For this comparison, I use different combinations of the parameters α and σ that control the scale and curvature of the productivity of secondary development. The focus is on the effect of different values for σ, since this parameter controls the convexity of the cost of secondary development and thus strongly affects the decision how much to increase secondary development in reaction towards an increase in the imitation probability. Therefore, I compare the results for $\sigma = \{0.1, 0.25, 0.4, 0.5, 0.6\}$. To be able to compare the results, I hold the level of secondary development at zero imitation probability constant at $\hat{S} = 1.5$ and chose α accordingly. All other parameters of the model have been left constant, only the individual innovation probability has been adapted slightly to give the same growth rate at zero imitation probability for all parameter setups.[7]

[7] The adjustment of the individual innovation probability amounts to only 6% at most.

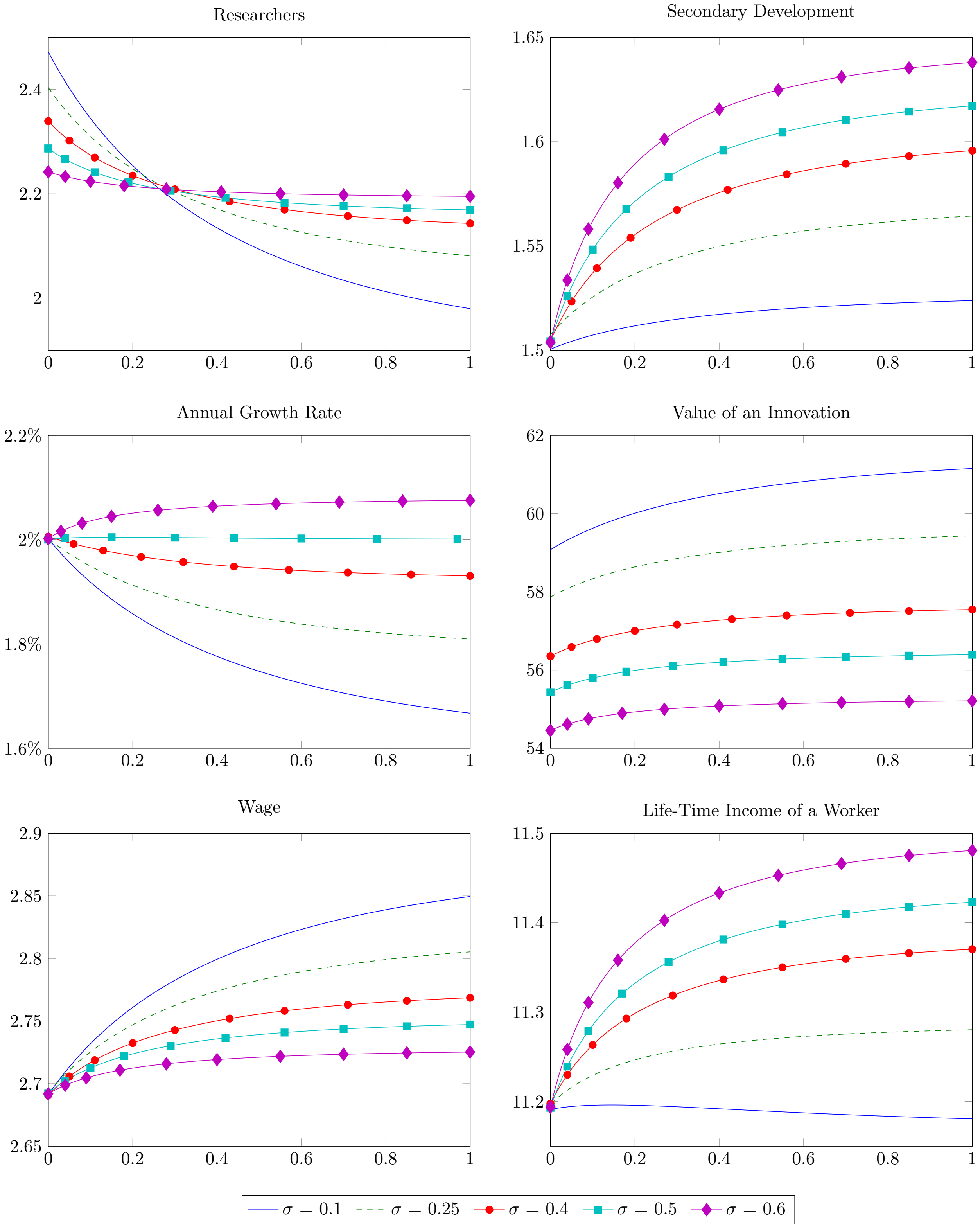

Figure 2.4: Impact of the productivity of secondary development
(Imitation probability i given on horizontal axis)

It can be seen, that the steeper the cost increase of secondary development is (lower σ), the smaller is the rise of secondary development in reaction to the increased individual imitation probability. As this reduces the innovators profit in the limited monopoly case and thus the expected value of an innovation, the number of researchers decreases stronger in the case of higher marginal costs of secondary development. Since secondary development rises to a lesser extent and the number of researchers decreases stronger, the growth rate always falls with the individual imitation probability when σ is small.

On the other hand, if the marginal cost of secondary development is low, the growth rate always increases with the probability of imitation because secondary development increases sharply to escape the competition. This is the case for $\sigma = 0.6$ and higher. The special case where an increase of the individual imitation probability first increases the growth rate and then reduces it occurs only for a small interval of σ.

The wage rate in final goods production increases with the imitation probability for all σ as the market power is reduced. The effect is stronger the higher the marginal cost of secondary development is. This comes from the fact that for a high marginal cost of secondary development, the number of researchers declines stronger, leading to a higher share of sectors in competition and also because the lower amount of secondary development leads to reduced monopoly distortions in the limited monopoly sectors as the advantage of the innovator over the imitator shrinks. The level of output behaves similarly as wages. In addition to the reduced monopoly distortions, a lower number of researchers implies a higher number of workers in the final goods sector. This effect increases output even further.

The life-time income of a worker, which also represents expected utility for all agents in the economy, typically increases with the imitation probability. This is even true for cases where the growth rate is reduced by imitation. Only for very high marginal costs of secondary development, the strong decline of the growth rate outbalances the positive effect of the reduced market power and welfare is negatively affected by imitation. This is an important result, as it shows that the probability of imitation may have opposing effects on growth and on welfare. This implies that the discussion whether imitation is harmful or not should shift from a sole focus on the growth rate towards potential welfare gains.

The most unexpected result is the fact the the value of an innovation always increases with the individual imitation probability which is contrary to the canonical result of endogenous growth theory that imitation lowers the expected monopoly profit. Interestingly, the effect is strongest for high marginal cost of secondary development, when monopolists are less able to protect themselves from imitators. However, the number of researchers declines very strongly in this case, caused by the strong increase in the wage rate. This reduces the aggregate innovation probability and thus lowers the probability of displacement by another innovator. So the expected value of an innovation increases. Furthermore, the higher number of production workers increases the demand for intermediate goods and thus the expected monopoly profit.

2.5 Conclusions

In this paper, I have developed a model to explore whether imperfect IPR protection can stimulate technological progress by inducing technology leaders to increase their research activities in order to escape the competition of imitators. An increased probability of imitation lowers research by outsiders but increases secondary development by incumbents. It turns out that the combined effect on the growth rate is ambiguous, depending primarily on the research productivity of incumbents. If secondary development by incumbents is highly productive, the increased threat of imitation increases the growth rate and vice versa. For certain parameters, the relationship between imitation probability and economic growth resembles an inverted U-shape.

The model also shows a strong market effect that increases output, the wage rate, and static welfare due to a higher degree of competition in the economy. These positive effects can be found also for cases where the effect on the growth rate is negative. The results imply that imitation should be seen more positively than it is typically the case. Policy makers who decide on the degree of property rights protection should focus not solely on the effects on the growth rate but also on potential welfare gains from reduced market power.

For future work it would be desirable to completely endogenize the imitation decision and decouple it from outsider innovation. To achieve this, imitators must have the opportunity to gain something from imitation, which is not the case in the actual model. The literature offers three ways of achieving this goal: lower production cost of the intermediate good for the imitator as it is assumed in the North-South model by Grossman and Helpman (1991b), a profit sharing approach as in Segerstrom (1991), or an increased chance to become the future innovator as in Mukoyama (2003). With regard to the model presented here, the profit sharing approach appears to be the most promising. However, the implementation is not straightforward as the number of successful imitators will be important while currently the focus is only on the fact whether at least one imitation takes place in a sector.

A further step would be to extend the model's three period OLG setup into a framework with infinitely-lived households. This would not only help the model to fit into the literature but also would allow for a better calibration to real world moments, especially to increase the role of secondary development. As argued in Acemoglu and Cao (2010), incumbent quality leaders make up for about two thirds of TFP growth. In the current structure of the model, incumbents have only one period for further improvements, so the influence of secondary development on the growth rate is rather limited. In a multiple period setup, incumbents could undertake quality improvements over a longer time while constantly being in danger of imitation. With this increased role of secondary development, the positive effect of imitation on the growth rate could be even greater.

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Chapter 3

Technology Adoption and Demographic Change

3.1 Introduction

As a consequence of demographic change, the share of elderly persons in the labor force will increase steeply in the industrialized countries during the first half of the 21st century. In the majority of OECD countries, the share of workers aged 55 and above in the labor force will increase by 50–100% between 2000–2030 (Carone, 2005; Toossi, 2006). Empirical studies indicate that an increase in the share of elderly workers has a substantial negative influence on aggregate productivity and productivity growth (Tang and MacLeod, 2006; Feyrer, 2007; Werding, 2008; Grönqvist, 2009). To investigate the underlying sources of this relationship, I model the effect of labor force aging on productivity growth at the firm level and for the aggregate economy.

I develop a quantitative model that explores firms' technology decisions with respect to the age composition of their workforce and explains the influence of the labor force age composition on aggregate productivity. The model allows to determine the impact of labor force aging on the technology distribution of the economy and aggregate productivity growth. In the dynamic general equilibrium model, firms decide to adjust their workforce and to adopt new technologies. The economy is populated with overlapping generations of workers who age stochastically. This aging process changes the workforce composition in each firm steadily over time. It turns out that firms that employ a higher share of elderly workers update their technology less frequently because they fear that investment in training their workers for a new technology cannot be recuperated as the expected remaining worklife is too short. Also, firms with a high share of older workers prefer to adopt non-state-of-the-art technologies at a lower training cost to reduce the investment in their elderly workers.

I calibrate the model for the German economy and use the firm policies to derive the equilibrium firm distribution of the economy. I then simulate the projected changes of the labor force age composition for the period 2003–2025 by varying the inflow of young workers into the economy. Between 2010–2025, when labor force aging is strongest, I find that demographic change lowers annual productivity growth by about 0.11 percentage points on average. This translates into a cumulated GDP loss of approximately 416bn Euro in constant prices of 2005 for this period.

Demographic change is accompanied by an increase in the average retirement age in Germany. During the simulation period, it is expected to increase from 60 years to about 63 years (Carone, 2005). Two opposing effects accompany this increase in the retirement age. At the micro level, the longer expected job duration of elderly workers leads to shorter technology updating intervals which moves the economy closer to the technological frontier and lowers the impact of demographic change. At the aggregate level, however, the increased retirement age raises the share of elderly workers further, in addition to demographic change. This amplifies the negative effect on productivity growth. The model allows to disentangle the contribution of demographic change and the increased retirement age. Taking the change of the average retirement age into account increases the average growth loss between 2010–2025 to 0.17 percentage points annually.

As a policy experiment, I analyze the consequences of an additional increase in the average retirement age of three years. It turns out that in this case the negative effect is further amplified. The economy moves further away from the technological frontier, which adds to the negative effect of demographic change. For the period 2010–2025, the resulting annual growth loss amounts to 0.21 percentage points. As a second experiment, I reduce the firms' cost for worker training by 10% assuming that training methods become more efficient. As expected, the economy moves closer to the technological frontier as firms update their technologies in shorter intervals and also the effect of demographic change is reduced. Between 2010–2025, the annual loss of growth now amounts to 0.09 percentage points.

The existing literature offers two alternative mechanisms to explain the negative relationship between worker aging and the adoption of modern technologies. Some authors argue that older workers are not well prepared for new technologies as economic skill obsolescence reduces the value of their knowledge over time (Rosen, 1975; de Grip and van Loo, 2002) or that they are less able to adapt to new technologies (Skirbekk, 2004; Weinberg, 2004). An alternative explanation, which I use in this model, is that the short remaining worklife duration of older workers makes the investment in training for new technologies less attractive. This idea does not depend on assumptions about the workers' abilities and applies for all types of workers in all sectors of the economy. As Figure 3.1 illustrates, workers aged 55 and above receive significantly less on-the-job training than workers aged 25–54 in the European Union. On average, the amount of training that elderly workers received accumulated to only 47% of the training for prime-age workers, whereby large discrepancies between countries exist. According to Klös (2000), only 5% of citizens aged 50-55 and only 1% of citizens above 55 received on-the-job-training in Germany in 1998.

Swanson et al. (1997) also focus on the influence of the remaining worklife duration. In a life-cycle model with exogenously moving technological frontier, individuals decide whether to adopt new technologies, to work or to enjoy leisure. The authors show that individuals stop adopting new technologies in the later stages of their lives as the investment could otherwise not be recuperated. They also suggest that this mechanism leads to lower realized technological progress when the population ages. In a similar paper by Ahituv and Zeira (2000), elderly

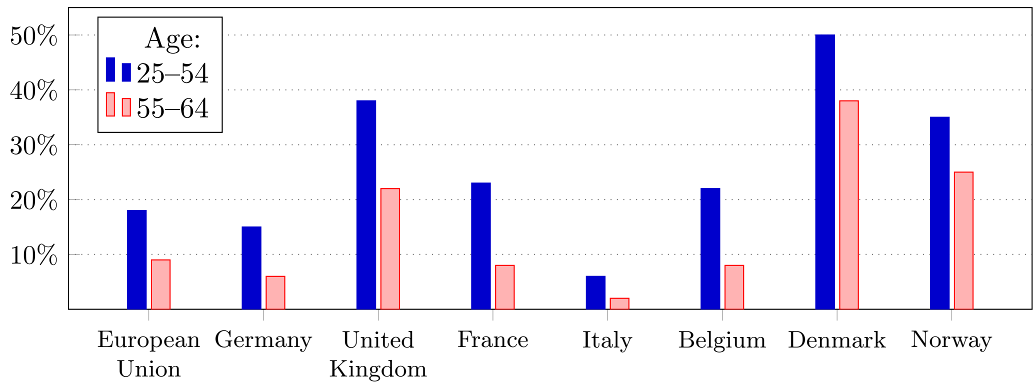

Figure 3.1: Annual incidence of training for young and old workers in the European Union (Source: Eurostat (2013))

workers decide between working with an old technology, adopting a new technology and early retirement. Langot and Moreno-Galbis (2008) analyze the technology adoption decision from the view point of a firm that employs a single worker who ages stochastically. Their focus lies on whether technological progress is beneficial for the employment prospects of older workers or not. Nevertheless, their paper shares some results with the paper presented here: old-worker firms update their technology less often than young-worker firms, a higher training cost for new technologies decreases the updating frequency whereas a higher rate of exogenous technological progress increases it.

This model contributes to this literature by adding the following: first, the perspective is shifted towards the aggregate economy with a focus on technology diffusion. Second, the quantitative model allows to analyze the effects of demographic change on the level of total factor productivity (TFP) and realized productivity growth with a calibration to the German economy. Third, the technology decision is put in the hands of multi-worker firms which can decide when to update to a new technology and which technology to choose, and also choose the number of young and old workers they employ. Since worker aging implies that firms have heterogeneous workforces, their decision problem becomes far more complex. Firms may want to train their young workers for a new technology, however, they have to take into account their elderly employees as well, for which investment might be less profitable. This can lead firms to lay off their elderly workers but also to delay the technology upgrading decision. With this, firm heterogeneity leads to much richer dynamics compared to previous models.

The model is consistent with the findings of empirical studies on technology adoption at the firm level. For French private sector firms, Aubert et al. (2006) find that innovative firms have a lower wage-bill share of older workers. Meyer (2007, 2009) shows that an older workforce in firms leads to less technology adoption in German small and medium-sized firms, and this effect increases with worker age beginning from the age of 30. Schneider (2008) uses a linked employer-employee dataset to study the innovative potential of German firms in relation to their workforce. He finds an inverted U-shaped relationship that indicates that middle-aged workers increase the innovative activities of their employers whereas elderly workers and very young workers have a negative influence. Malmberg et al. (2008) analyze the productivity of Swedish manufacturing and mining enterprises between 1985–96 and find that firms with a higher share of employees aged 50 and above are generally less productive though more productive when technology is controlled for. This implies that firms with an older workforce use on average less productive technologies.

At the aggregate level, several empirical studies have scrutinized the relationship between the share of elderly workers and aggregate productivity and the impact of demographic change on productivity growth. Tang and MacLeod (2006) find that a one-percent increase in the share of workers aged 55 and above reduces productivity growth in Canadian provinces by 0.07%. Two studies by Feyrer (2007) and Werding (2008) analyze the relationship between the age composition of the labor force and TFP for a panel of 27 OECD countries and other countries for the period 1960-2000. They find a positive effect on productivity for workers aged 40–49 but negative effects for workers aged 50 and above. Grönqvist (2009) uses industry-level for Finland between 1971–2005 and finds that an increase of the share of workers aged 55 and above by 1% lowers annual labor productivity growth by about 0.22 percentage points. A comparison of the simulation results with these estimates indicates that the model results are in a plausible range.

The remainder of the paper is organized as follows: the next section presents the model and section 3.3 derives the stationary equilibrium. In section 3.4, I show how the model is calibrated for the German economy and section 3.5 illustrates the results for the stationary equilibrium and discusses the effect of the model's parameters. Section 3.6 provides the results for the simulation of the projected demographic change followed by robustness tests for the simulation results. Section 3.8 concludes and discusses possible extensions of the model.

3.2 The Model

The model analyzes firm dynamics in a competitive economy in a similar framework as Hopenhayn and Rogerson (1993), where firms expand or contract, make technology choices and enter or exit the market. In their decisions, firms take into account workforce aging with overlapping generations of workers.

Workers and Firms

The economy is populated by a continuum of firms and workers. New workers enter every period as young workers, turn into old workers and finally exit the labor market, determined by a stochastic aging process. All variables referring to young workers will be denoted by subindex y whereas o is used to indicate old workers. The exogenous probability of becoming old for a young worker is given by λ_y and the exogenous probability of retirement for an old worker is λ_o. Consequently, workers are young for $1/\lambda_y$ periods on average whereas the expected worklife duration of an old worker is $1/\lambda_o$ periods. Employed workers separate from firms with exogenous probabilities q_y and q_o or when exiting the labor market. Apart from the expected remaining time in the labor market and the exogenous separation probabilities, old and young workers are equal in all aspects. In particular, this means that there are no experience effects or learning on the job and also no loss of human capital or falling individual productivity with age. This assumption is made to isolate the impact of the expected remaining worklife on training and its effect on technology adoption.[1]

The evolution of the economy's workforce is given by:

$$P_{y,t+1} = (1-\lambda_y)\cdot P_{y,t} + P^N_{y,t}, \quad (3.1)$$

$$P_{o,t+1} = \lambda_y \cdot P_{y,t} + (1-\lambda_o)\cdot P_{o,t}, \quad (3.2)$$

where $P_{y,t}$ and $P_{o,t}$ denote the mass of young and old workers in the economy respectively and $P^N_{y,t}$ denotes the inflow of new young workers in a period.

Workers have a zero reservation wage and are employed by firms for which labor is the only variable input. Each single firm employs a mass of young and old workers who are hired in competitive markets at wage rates $w_{y,t}$ and $w_{o,t}$ and hiring cost[2] $c_{N,t}$ per worker. All firms produce an identical good which is taken as the economy's numeraire and discount profits at a common, exogenous discount rate r. Firms can enter the market at a positive entry cost $c_{E,t}$ and exit with exogenous probability δ. The free entry condition ensures zero expected profits prior to entering.

A firm's production function is given by

$$Y^i_t = A^i_t F(y^i_t + o^i_t), \quad (3.3)$$

where y^i_t and o^i_t denote the total number of young and old workers employed by the respective firm at time t and A^i_t is a productivity parameter that depends on the technology that the firm currently uses. The function $F(x)$ is increasing and convex. The latter fact ensures a large number of heterogeneous firms.

exhibits decreasing returns to scale to restrict the firm's size.

Technological Progress

The economy features exogenous technological progress and a new technology arrives in every period. New technologies increase the productivity frontier by a constant factor g so that the productivity parameter evolves according to

$$A_{t+1} = (1+g)\cdot A_t. \quad (3.4)$$

A firm has two options for adopting new technologies. It can either adopt the newest technology A_t or a technology that is B steps away from the technological frontier A_{t-B}. To adopt a

[1]The assumption that the productivity of workers remains constant over the working life is supported by recent empirical work (Börsch-Supan and Weiss, 2011; Pekkarinen and Uusitalo, 2012). Oster and Hamermesh (1998) find that publishing by economists decreases with age, however they can not discern whether this is related to a reduction of productivity or caused by other issues such as lower incentives or an increase of other duties. This latter view is supported by Rauber and Ursprung (2008), who find that the cycle pattern of economists' productivity originates from incentive effects. Besides they find very strong cohort effects at work. A similar result is found by van Ours (2009).

[2]The hiring cost increases the value of a worker who is employed in a firm. This provides firms with an incentive to keep old workers instead of exchanging them for young workers and increases firm heterogeneity in the model.

production technology, a firm has to train its workers to use it. This implies that technology is embodied in the workers of a firm. All workers within a firm need to use the same technology and a firm cannot split itself into two entities that use different technologies. If a firm hires new workers, it has to train them for the technology that is currently used in the firm.

Training cost is a fixed cost per worker and depends on the type of technology that is adopted. The training cost for the newest technology A_t is denoted by $c_{T,t}$ while adopting the older technology A_{t-B} involves the cost $\beta \cdot c_{T,t}$ where $0 < \beta < 1$. If a firm hires new workers without upgrading its technology, the training cost for new workers is $c_{T,t}$ if the firm's technology is $A_t^i \in [A_t, A_{t-(B-1)}]$ and $\beta \cdot c_{T,t}$ if $A_t^i \leq A_{t-B}$. Introducing two different technology updating choices enlarges the decision space of firms and makes the model more realistic. It also helps to fit the calibrated model as the parameter B effects the technology dispersion in the economy.

The training cost comprises all direct and indirect costs of adopting a new technology. This includes monetary training costs, lost production for the time of training, and lower production for the time that workers need until they are experienced enough with the new technology to become more productive than with the old technology (see e.g. Helpman and Rangel (1999)). When a firm decides to use a different technology, all of its workers have to be trained for it. Worker training is firm specific, hence a worker who changes his employer has to be trained anew, irrespective of the previous trainings he received. This implies that training costs are borne by the employing firm, not by the worker (Becker, 1962).

Since technology progresses every period, all cost constants and wages are expressed in efficiency units relative to the technological frontier and written without time index, i.e. the actual costs are multiplied by $p(t) = (1+g)^t$, e.g. $c_{T,t} = (1+g)^t c_T$. This ensures the existence of a steady state equilibrium on the growth path.

Timing of Events
Each period starts with production where output is determined by the firms' technology decision in the preceding period. Thereafter, the existing firms, together with new firms that enter the market, hire young and old workers or lay off part of their workforce and decide whether to upgrade to a new technology in the next period. At the end of the period, firm exit and worker aging and separation take place.

3.3 Equilibrium

In this section I focus on a stationary equilibrium along a balanced growth path.

The firm's problem
Along the balanced growth path, the problem of an active firm that employs a mass of y young workers and a mass of o old workers at given wages in efficiency units w_y, w_o[3] and uses technology $A_{(k)}$, which has a distance of k stages to the latest technology , can be expressed recursively in

[3] In a stationary equilibrium, wages in efficiency units w_y, w_o are constant over time and for each period, wages are given by $w_{y/o,t} = (1+g)^t w_{y/o}$

efficiency units as

$$
\begin{aligned}
v(y,o,k) &= (1+g)^{-k}F(y+o) - y\cdot w_y - o\cdot w_o \\
&\quad + \max_{y',o',k'}\Bigg\{ -\left(c_N + c_T(k)\right)\left(y^H + o^H\right) + \frac{1-\delta}{1+r}v(y',o',k+1)(1+g), \\
&\quad - c_T(y - y^F + o - o^F) - (c_N + c_T)\left(y^H + o^H\right) + \frac{1-\delta}{1+r}v(y',o',0)(1+g), \\
&\quad -\beta c_T(y - y^F + o - o^F) - (c_N + \beta c_T)\left(y^H + o^H\right) + \frac{1-\delta}{1+r}v(y',o',B)(1+g)\Bigg\},
\end{aligned}
\tag{3.5}
$$

$$
\text{s.t.}\quad y' = (1-\lambda_y)(1-q_y)\cdot\left[y + y^H - y^F\right] \tag{3.6}
$$

$$
o' = (1-\lambda_o)(1-q_o)\cdot\left[o + o^H - o^F\right] + \lambda_y(1-q_y)\cdot\left[y + y^H - y^F\right], \tag{3.7}
$$

$$
c_T(k) = \begin{cases} c_T & \text{for } k < B, \\ \beta c_T & \text{for } k \geq B, \end{cases}
$$

where y^H, o^H and y^F, o^F denote hired and fired young and old workers respectively.

A firm's value is given by its instantaneous profit, that is output net of wage payments, and the discounted future value of the firm which depends on the firm's optimal policy decisions. A firm decides in every period on the optimal employment of young and old workers in the next period, given its technology decision and with respect to employment adjustment in (3.6) and (3.7). With regard to technology, a firm has three options: First, it can continue with its current production technology; second, it can update to the newest technology at cost c_T per worker; and third, it can update its technology to the level B steps behind the technological frontier at cost $\beta \cdot c_T$ per worker. If a firm decides to continue with its actual technology and hires new workers, training cost per worker are c_T if the firm is less than B steps behind the technological frontier and $\beta \cdot c_T$ if the firm is further behind the frontier.

The state of a firm is completely described by the mass of young and old workers it employs and the technology it uses. The state of the economy is given by the distribution of state variables for all individual firms and is expressed as a measure over triples $\mu(y,o,k)$, which is invariant in the stationary equilibrium.[4] The optimal employment decisions for young and old workers are denoted $N_y(y,o,k)$ and $N_o(y,o,k)$ respectively[5], the optimal technology decision is denoted $X(y,o,k) \in \{0, B, k+1\}$.

Entry of new firms and wages

Entry is free; therefore entering firms expect zero profits. For entering firms, two technology choices are possible: they can either adopt the newest technology $A_{(0)}$ or the vintage technology

[4] In the numerical solution where y and o are restricted to a finite number of values, $\mu(y,o,k)$ can be represented as a three-dimensional matrix where each element gives the mass of firms in a particular state.

[5] $N_y(y,o,k)$ and $N_o(y,o,k)$ denote the mass of young and old workers respectively, that a firm which is described by (y,o,k) at the beginning of the period employs after the employment decision has been made.

$A_{(B)}$. The zero-profit conditions for the two options are given by:

$$(1+g)\frac{1-\delta}{1+r}v(y',o',0) - c_E - (c_N + c_T)\left(y^H + o^H\right) \leq 0 \quad \forall\, y^H, o^H \geq 0, \tag{3.8}$$

$$(1+g)\frac{1-\delta}{1+r}v(y',o',B) - c_E - (c_N + \beta c_T)\left(y^H + o^H\right) \leq 0 \quad \forall\, y^H, o^H \geq 0, \tag{3.9}$$

where y^H, o^H denote the masses of young and old workers that an entrant hires and y' and o' give the labor force in the next period according to (3.6) and (3.7) respectively. Since the model features exogenous firm exit, a stationary equilibrium necessarily requires positive entry of firms. Therefore at least one of the two zero-profit conditions must be binding, that is one combination y^H, o^H exists for which a zero-profit condition is binding. For a certain range of the model's parameters, especially β and B, it is possible that two types of entrants exist, where one type chooses the newest technology $A_{(0)}$ and one type chooses the vintage technology $A_{(B)}$. Otherwise it can turn out that only one technology choice is attractive for entering firms, so that only one entrant type exists and either all entering firms adopt the newest technology $A_{(0)}$ or all entrants adopt the vintage technology $A_{(B)}$. Together with simultaneous labor market clearing for both types of workers, equations (3.8) and (3.9) determine the wage rates w_y, w_o. The fact that the entrants' technologies move with the technological frontier ensures that wages grow with the rate of technological progress and are constant in efficiency units.

Entering firms are completely described by their employment decision and the chosen technology. The distribution of entrants is therefore expressed as a measure over triples which is denoted as $\mu^N\left(y^H, o^H, k\right)$. With this, enough information has been collected to trace the evolution of the economy. At the beginning of period t, let the incumbents be summarized by the measure μ. Incumbents make optimal employment decisions, given by the policy functions $N_y(y,o,k)$ and $N_o(y,o,k)$, and decide on technology upgrading $X(y,o,k)$. At the same time, new firms summarized by the measure μ^N enter the economy and hire the remaining workers that are not employed by incumbent firms. After workers have separated from firms with probabilities q_y and q_o and aged according to aging probabilities λ_y and λ_o and firms have exited with probability δ, the aggregate state of the economy for period $(t+1)$ is given by the measure μ'. The transition from μ to μ' is written as $\mu' = T(\mu, \mu^N, w_y, w_o)$. The wage rates for young and old workers appear in the operator T as they determine the decision rules of incumbent and entering firms.

Labor markets

In a stationary equilibrium with constant population size, the inflow of young workers must equal the outflow of old workers in every period, so $P_y^N = \lambda_o \cdot P_o$. The mass of the total workforce is normalized to one, so the supply of old and young workers in the labor market is given by:

$$L_y^s = P_y = \frac{\lambda_o}{\lambda_y + \lambda_o}, \tag{3.10}$$

$$L_o^s = P_o = \frac{\lambda_y}{\lambda_y + \lambda_o}. \tag{3.11}$$

Total demand for young and old workers by incumbents and entrants is given by:

$$L_y^d(\mu, \mu^N, w_y, w_o) = \int N_y(y, o, k, w_y, w_o)\ d\mu(y, o, k) + \int y^H\ d\mu^N\left(y^H, o^H, k\right), \tag{3.12}$$

$$L_o^d(\mu, \mu^N, w_y, w_o) = \int N_o(y, o, k, w_y, w_o)\ d\mu(y, o, k) + \int o^H\ d\mu^N\left(y^H, o^H, k\right). \tag{3.13}$$

Definition of equilibrium
A stationary equilibrium is given by constant wages for young and old workers in efficiency units w_y^*, $w_o^* \geq 0$, a measure of entering firms μ^{*N} and a measure of incumbent firms μ^* such that (i) $L_y^d(\mu^*, \mu^{*N}, w_y^*, w_o^*) = L_y^s$ and $L_o^d(\mu^*, \mu^{*N}, w_y^*, w_o^*) = L_o^s$, (ii) $T(\mu^*, \mu^{*N}, w_y^*, w_o^*) = \mu^*$, and (iii) $(1+g)\frac{1-\delta}{1+r}v(y', o', 0) - c_E - (c_N + c_T)\left(y^H + o^H\right) \leq 0$ and $(1+g)\frac{1-\delta}{1+r}v(y', o', B) - c_E - (c_N + \beta c_T)\left(y^H + o^H\right) \leq 0 \quad \forall\ y^H, o^H \geq 0$, with equality for those pairs (y^H, o^H) where $\mu^{*N}(y^H, o^H, k) > 0$.

The conditions need not much explanation: Condition (i) demands that labor markets for young and old workers are cleared, condition (ii) demands that the state of the economy replicates itself in each period in a stationary equilibrium, given optimal decision by incumbent firms and entrants, and condition (iii) states that entry in the economy is possible with zero expected profits for entrants. The model is solved by numerical methods as described in more detail in the appendix.

Wages, firm policies, and demographic change
A feature of the case with two types of entrants is that typically the two entrant types will pursue different hiring strategies with respect to the age distribution of the hired workforce. This happens due to the fact that the updating decisions of firms strongly depend on the age structure of their workforces, as will be shown in the next section. In this case, simultaneous labor market clearing for young and old workers is achieved by the adjustment of the masses of entrant types, which results in a block recursive equilibrium as described in Menzio and Shi (2009). This implies that when the masses of young and old workers in the economy change, the distribution of entrant types changes, but not the hiring policies and profits of the entering firms itself. Therefore wages are independent of the masses of young and old workers in the economy.[6] From this follows that firm policies are independent of the distribution of workers. So if the relation of young and old workers changes, firm policies do not change. This feature allows to simulate demographic change by adjusting the inflow of new workers into the economy while firm policy functions remain constant as long as all other parameters including λ_y and λ_o are left unchanged.

3.4 Calibration

Calibration
The model is calibrated to match the German economy and the projected changes in the labor force between 2003–2025 are simulated to analyze the resulting changes in the economy's average

[6]Nevertheless, the wages depend on the exogenous parameters of the model like λ_y, λ_o for example.

distance from the technological frontier. Figure 3.2 shows the projected changes in the old-age ratio for the German population and labor force. The threshold age of 55 years that separates young workers from old workers has been chosen because the participation rate in the labor force drops dramatically after the age of 55 whereas it is rather constant between the age 20–54. That implies that the probability that a worker leaves the firm and exits the labor force is strongly increased once he has reached the age of 55. The expected time to be a young worker is therefore 35 years which gives $\lambda_y = 0.0286$ for a period length of one year.

The change in the age composition of the labor force is not only determined by demographic change but also by changes in the average retirement age of older persons. Figure 3.2 illustrates the change of the labor force composition with and without the latter effect. It can be seen that the increase of the share of old workers in the economy is strongly augmented by the expected increase of the retirement age. Table 3.1 depicts the average retirement age and the corresponding λ_o over the simulation period. Different retirement ages imply different firm policies, whereby firms have to adopt their policies dynamically over time to adjust to the new exit age of old workers. In the scope of this paper, the analysis of these dynamic adjustments is not possible.

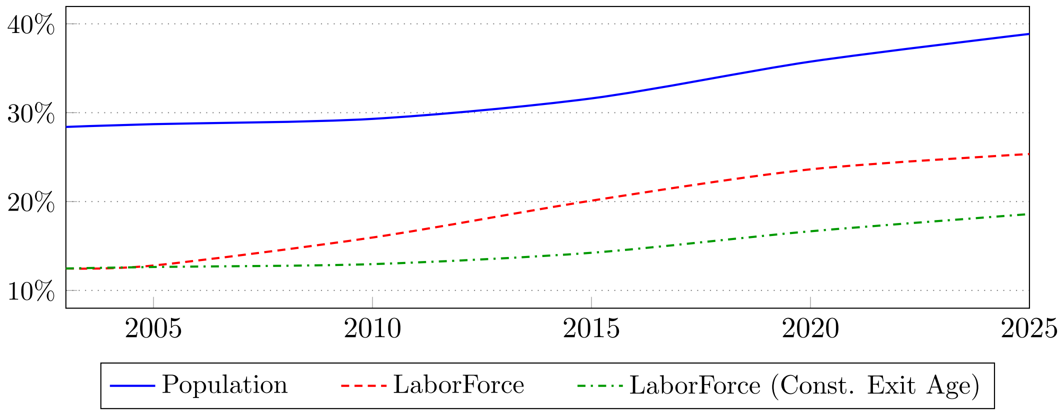

Figure 3.2: Projected share of elderly people in population and labor force in Germany (Source: Carone (2005); OECD (2011), Own calculations)

To take the increase of the average retirement age into account, I divide the simulation period into two periods with relatively constant average retirement age. I use the average of the retirement ages for 2003–2010 and 2015–2025, which gives an average retirement age of 60.8 years with $\lambda_{o,2003} = 0.146$ and 62.8 years with $\lambda_{o,2015} = 0.147$ respectively and assume that the increase of the retirement age in 2015 comes as a shock to the firms.[7]

Table 3.2 provides an overview of the calibration for the model's parameters. The interest rate and rate of exogenous technological progress are standard values. The probability of a firm destruction shock is set to 0.058% to give an expected firm life duration of 17.25 years, which is taken from a study about firm survival and hazard rates for Germany by Fritsch et al. (2006). This number is in line with the age distribution of firms in Germany provided in Wagner

[7]Section 3.6 explains further how the simulation of of demographic change is carried out and how the change of the average retirement age is implemented in the simulation.

	2003	2010	2015	2020	2030	2040	2050
Average Exit Age	60.1	61.8	63.3	63.5	62.1	62.6	62.6
λ_o	0.164	0.128	0.108	0.106	0.124	0.116	0.116

Table 3.1: Expected retirement age and corresponding λ_o (Source: Carone (2005); OECD (2011), Own calculations)

Parameter	Value	Target
r	0.04	annual interest rate
g	0.02	annual rate of technological progress
δ	0.058	expected firm life duration (Fritsch et al., 2006)
q_y	0.05	job mobility (Zimmermann, 1998)
q_o	0.0	job mobility (Zimmermann, 1998)
c_E	19.27	capital share
c_N	$\frac{0.7}{12}\bar{w}$	average recruitment costs (Muehlemann and Pfeifer, 2012)
c_T	0.4	resources for innovation (Aschhoff et al., 2005)
β	0.8	share of trained workers per period $\approx$ 12.7% (Eurostat, 2013)
B	2	firm productivity dispersion (Pfeifer and Wagner, 2012)

Table 3.2: Calibration to German economy

(2005). The exogenous job separation probability of young workers is set to $q_y = 0.05$. This value is taken to match the separation rate of workers given in Zimmermann (1998). This study distinguishes between intra-firm and inter-firm job-to-job transitions. For this paper, only the latter are of interest, yielding an annual transition probability of 4.36% for workers aged 20–55. Adding the average EU-transition rate, the annual firm-separation probability amounts to 10.5%. This gives an average job duration of 9.6 years, which is in line with the reported numbers in Bergemann and Mertens (2004) and OECD (2012). From the age of 55, the EE-transition rates go down remarkably and inter-firm transitions become nearly zero. Given the firm destruction job and the high exit probability of old workers, the quit probability is set to $q_o = 0$.

The recruitment cost for new workers is set to 70% of the monthly average wage, which is taken from a recent study for skilled workers in Germany by Muehlemann and Pfeifer (2012).[8] The entry cost c_E is calibrated to yield a capital share of 30% in the model.[9] The three technology parameters c_T, B and β are chosen to match the total resources used for introduction of new technology as a share of firms' turnover, taken from Aschhoff et al. (2005), the productivity dispersion of firms given in Pfeifer and Wagner (2012), and the share of workers that receive training per year, taken from Eurostat (2013). The calibration procedure for the entry cost and the technology-cost parameters is explained in more detail in the appendix.

[8]The recruitment cost is in line with Chen and Funke (2003) and Bentolila and Bertola (1990) for Germany. It is also similar to the calibration in Mortensen and Pissarides (1999), which is supported by survey results in Hamermesh (1996).

[9]The production function does not include variable capital. Capital is only needed to set up the firm.

The production function takes the form

$$F(y, o) = (y + o)^{\alpha},$$

where $\alpha = 0.71$ is calibrated to give an average firm size of 12.5 employees (OECD, 2010).

3.5 Stationary Equilibrium

This section provides an overview of the firms' technology decisions and technology diffusion in a stationary equilibrium without changes in the age structure of the labor force. Figure 3.3 shows the firms' equilibrium technology decision with respect to their workforce and current technology. The graphic depicts the distance from the technological frontier at which firms update their technology:

$$k^*(y, o) = \min(k | X(y, o, k) \in \{0, B\}) \; \forall \; y, o \geq 0.$$

It turns out that the distance from the technological frontier at which a firm decides to update its technology depends primarily on the age structure of a firm's workforce and to a lower extent on the firm's size. Adding old workers strongly increases the distance to the technological frontier at which a firm decides to update. Adding young workers, on the other hand, does not increase the updating distance, except for very small firms. For heterogeneous firms, increasing the number of young workers can even lower the updating distance as the average age of the workforce in the firm becomes lower. The reason for this is that firms with old workers prefer to delay training their workers for a new technology because they expect them to retire soon, making the investment unprofitable. A higher number of old workers increases the updating distance irrespective of the age structure of the firm. This happens because firms with many old workers wait with technology updating to give old workers a chance to drop out of the labor market first. If these firms finally update, they lay-off some of their old workers in the process, as it is unprofitable to invest training cost for all of them.

For very small firms, the distance from the technological frontier at which they decide to upgrade becomes dramatically smaller. This is caused by the fact that these firms want to increase their workforce to the optimal level. When a firm hires new workers, it has to invest in training cost for the new hires. However, if a firm has to pay training cost for the new hires anyway, it prefers to train them for the newest technology and train its few already existing employees as well, instead of training the new hires for the vintage technology that the firm currently uses and having to train them again some periods later when the firm finally updates its technology. So, hiring new workers complements technology renewal and the smaller a firm is, the greater are the incentives to hire new workers and to update the firm's technology at the same time.

Firms do not only differ in their distance to the technological frontier at which they decide to update but also choose different technologies when updating, depending on the age structure of their workforce. Figure 3.4 illustrates which kind of firms choose to update to the newest

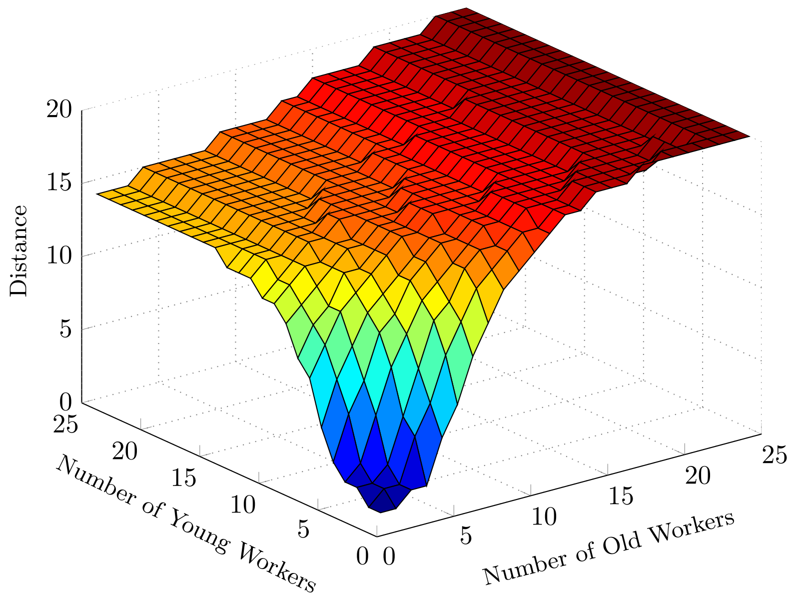

Figure 3.3: Distance from the technological frontier at updating

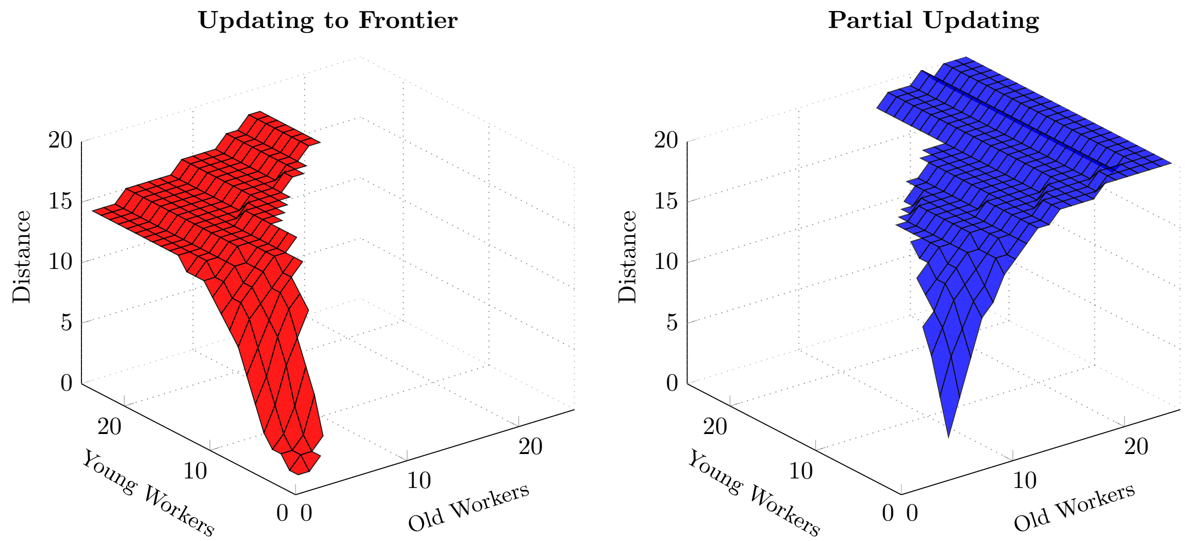

Figure 3.4: Technology choices of updating firms

technology $A_{(0)}$ and which firms prefer to update only to the non-state-of-the-art technology $A_{(B)}$ at a lower updating cost. As expected, firms with a larger share of old workers prefer to upgrade to the older technology to reduce investments in their elderly workers who may otherwise retire before the training cost for the high technology is recovered. An exception are very small firms that are close to the technological frontier. These firms that use an in-between technology $A^i \in (A_{(0)}, A_{(B)})$ update to the highest level in order to hire new workers in the process even if they have only old workers. Nevertheless, if such small old-worker firms are further away from the frontier, they would update to the lagged technology instead. However, as the graphic shows only the first time a firm updates for a given workforce, this is not depicted in the figure.[10]

With regard to the aggregate level, the distribution of firms over technologies in the economy given in Figure 3.5 shows that firms with an older-than-average workforce lag further behind the technological frontier. This replicates the results of the empirical studies at the firm level. In addition, another well-known empirical result in terms of technology utilization by firms is evident in the firm distribution. Firms that are larger than the average use newer technologies than small firms. This may come as a surprise as the analysis of the optimal firm policy above indicated, that small firms updated their technology earlier than large firms. However, firms that update use this opportunity to hire new workers and hence firms that use the newest technology always have the largest workforce.

Comparative Statics

In this part I analyze how firm policies and the firm distribution of the model in steady state are affected by parameter changes. The results provided here do not only apply for the calibrated version, but seem to be fairly general as the the equilibrium variables behave monotonically when confronted with different parameters.

An increase in the training cost for workers c_T enlarges the distance to the technological frontier at which firms decide to update their technology. This is true for all types of firms, however,

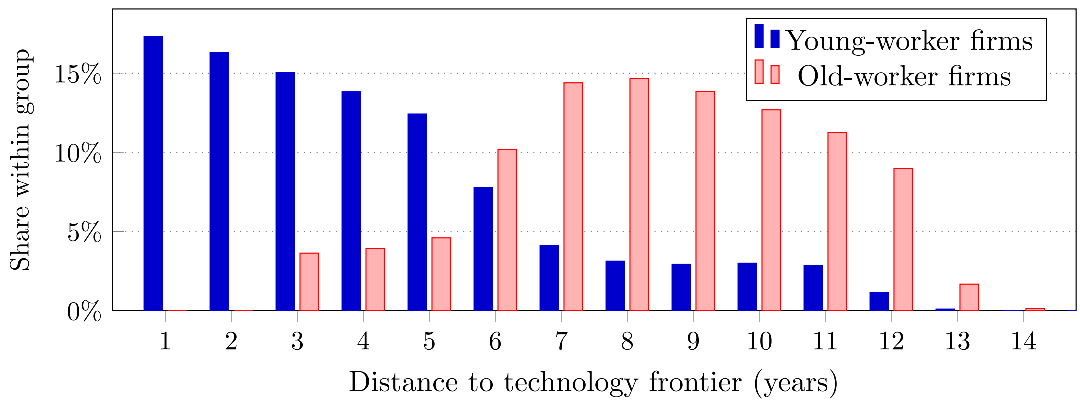

Figure 3.5: Technology distribution for young and old worker firms

[10]Of the two entrant types, those that choose the high technology mainly employ young workers whereas the entrants that start with the lower technology hire mainly old workers. This implies that old-worker firms are never close to the technological frontier.

the effect is stronger for firms with an older workforce. For smaller training costs, the updating policies converge until all firms update their technology in every period when c_T becomes very low and all firms produce at the technological frontier. Increasing the difference B between the newest technology and the non-state-of-the-art technology to which firms can update increases the distance from the technological frontier of old-worker firms and expands the dispersion of productivity in the economy. The interplay of c_T, B and β together determines the share of firms that update in each period, the average distance to the technological frontier and the technology dispersion in the economy.

Increasing the exogenous rate of technological progress g reduces the distance to the technological frontier at which firms decide to update their technology since the gains from updating rise and the pressure from increasing wages is higher. Raising the entry cost of firms c_E on the other hand has little effect on the technology decision and mainly lowers wages. The hiring cost c_N reduces the firm's employment adjustment capabilities and thus leads firms with old workers to postpone the updating process, however, the effect is not very strong.

An increase of the expected worklife duration of an old worker, that is a lower λ_o, has two opposing effects. At the firm level, it reduces the distance to the technological frontier at which firms with older workers update. On the other hand, a lower λ_o increases the share of old workers in the economy. At the aggregate level, this effect moves the entire economy away from the technological frontier as more firms with old workers exist, which update later than firms that employ a younger workforce. This effect is illustrated in Figure 3.6. For the calibrated example, the second effect is stronger, so that an increase in the average retirement age increases the economy's average distance from the technological frontier, however, no general statement can be made here.

Changes in the exogenous separation probabilities q_y, q_o affect young workers stronger than old workers. As the expected worklife of old workers is short in any way because of their upcoming retirement, an additional increase of the separation probability does not have a great effect. For young workers on the other hand, who have a long worklife horizon, an increase in the separation probability reduces their profitability for firms and the distance at which young-worker firms

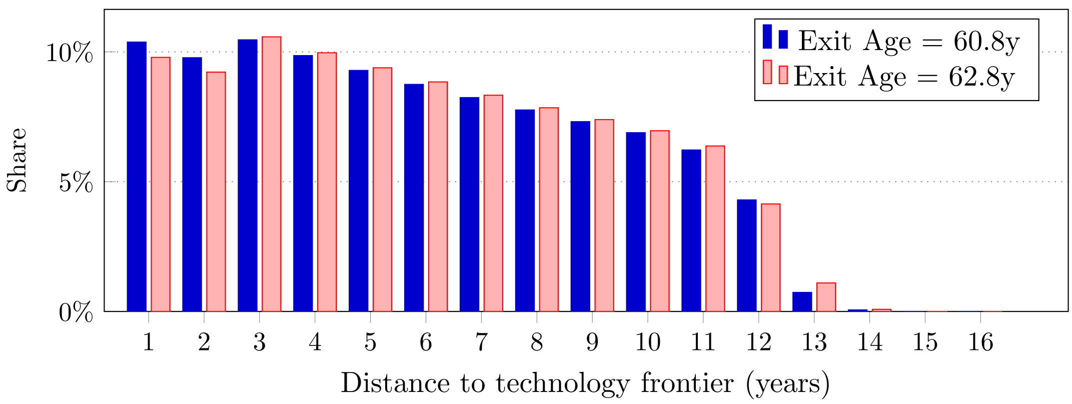

Figure 3.6: Technology distribution for different average retirement ages

decide to update their technology increases. If q_y becomes very large compared to q_o, the expected job duration of young workers would become shorter than that of old workers. This extreme case would reverse most results with regard to the updating decision presented before. In this case, firms with young workers would delay technology updating, since they expect their workers to leave the firm soon anyway.

Empirical studies regarding worker mobility typically find that separation rates decline with worker age. The reason for this is that young workers that entered the labor marked switch their jobs often as they move to better and better jobs. Over time, this matching process slows down and workers become settled in their job. For Germany, Zimmermann (1998) finds that the EE-transition rate of workers aged 15–25 is nearly double that of workers aged 25–55 and decreases further for workers aged 55 and above. Similar results can be found for other economies: for US employees, Menzio et al. (2012) estimate a monthly job-to-job transition rate of 5% for workers aged 18, which declines dramatically until the age of 35. At this age, the estimated job-to-job transition rate is 1.8% and the further decline is only marginal. Similar results can be found in Marotzke (2014). Nevertheless, Zimmermann (1998) shows that a high share of the job-to-job transitions take place within the firm as workers are appointed to better jobs. For Germany, these intra-firm transitions make up for 60–70% of all EE transitions whereas firm separation make up only the smaller part.

These results imply, that middle-aged workers have the lowest separation rate whereas old workers and very young workers have a shorter worklife horizon. This can explain the empirical findings by Feyrer (2007); Werding (2008) and Schneider (2008), which show that the share of workers aged 35–50 has a positive influence on growth and the innovative activity withing the firm. Workers aged above 50 years have a negative influence on growth, but this is also true for very young workers. The study on training in Germany by Kuwan et al. (2006) also shows that the group of employees aged 40–44 received the most on-the-job training of all age categories, whereas the group aged 60–64 received the lowest amount of training.

3.6 Simulation of Demographic Change

In the calibrated model, it turns out, that firm policies are independent of the share of young and old workers in the economy.[11] This allows to use the steady state firm policies for the simulation of demographic change. The simulation is undertaken by deriving the steady-state firm distribution of the economy and then adjusting the number of new workers that enter the economy in the simulation such that the labor force age composition follows exactly the projected development in Germany as depicted in Figure 3.2. From 2015 on, the new $\lambda_{o,2015}$ as well as the new firm policies are used, while the simulation of demographic change in the economy is carried on. That is, I continue the simulation with the firm distribution as it has developed until 2015 given the initial firm policies and $\lambda_{o,2003}$. The firm distribution in the economy then

[11] The calibrated model features two entrant types with different employment policies. Therefore, firm policies are independent of the age structure of the labor force (see section 3.5).

adjusts slowly, given the new firm policies and the ongoing change in the age-structure of the labor force under demographic change.

In the simulation I focus on the effect of demographic change on the economy's average distance from the technological frontier and on the resulting productivity growth. The distance from the technological frontier is measured as the average relative productivity lag, that is the actual output of the simulated economy is compared to an economy where all firms produce at the technological frontier. Denote the actual output of the economy, which is given by the accumulated gross output of all firms, by y and the counterfactual output of the economy where all firms use the newest technology by $\tilde{y}$. Then the distance D is defined by

$$D = \frac{\tilde{y} - y}{\tilde{y}} \tag{3.14}$$

Figure 3.7 illustrates how the projected demographic change affects the economy's average distance from the technological frontier. The solid line depicts the impact of demographic change alone for a constant average retirement age of 60.8 years, leaving out the increase of the average retirement age. The curve follows the pattern of demographic change given in Figure 3.2. As the share of old workers in the labor force increases, the economy moves away from the technological frontier. This happens because the number of firms that employ old workers and update their technologies less often increases which skews the technology distribution away from the frontier. Between 2010–2025, when the magnitude of demographic change is greatest, the economy's relative productivity gap increases by about 1.6 percentage points.

The dashed line takes the increase in the average retirement age into account. In 2015, the higher retirement age of 62.8 years together with the new firm policies is plugged into the simulation. It turns out, that the increase of the retirement age, which results in an additional increase in the share of old workers in the economy (see Figure 3.2), reinforces the negative effect of demographic change and the movement of the economy away from the technological frontier is further amplified. Now the relative productivity gap increases by about 2.5 percentage points between 2010–2025. This implies that the positive effect of a higher retirement age at the micro level, which induces firms with old workers to update their technology more often is smaller here than the negative effect at the macro level, a higher share of old workers.

The economy's movement away from the technological frontier implies lower productivity growth during that period.[12] This is illustrated in Figure 3.8 where the deviation of the realized productivity growth from the long-run trend is plotted. As indicated above, the effect of demographic change alone, depicted by the solid line, is much less pronounced than the case with the actual projected retirement age, illustrated by the dashed line. It turns out that demographic change has a strong negative impact on realized productivity growth. As the share of old workers in the economy increases, realized productivity growth decreases with a negative peak in 2017 where productivity growth is about 0.2 percentage points below the long-run trend

[12] As long as the distance to the technological frontier remains constant, productivity is growing at the exogenous rate. If the relative productivity lag increases, growth is lower than the exogenous productivity growth and vice versa.

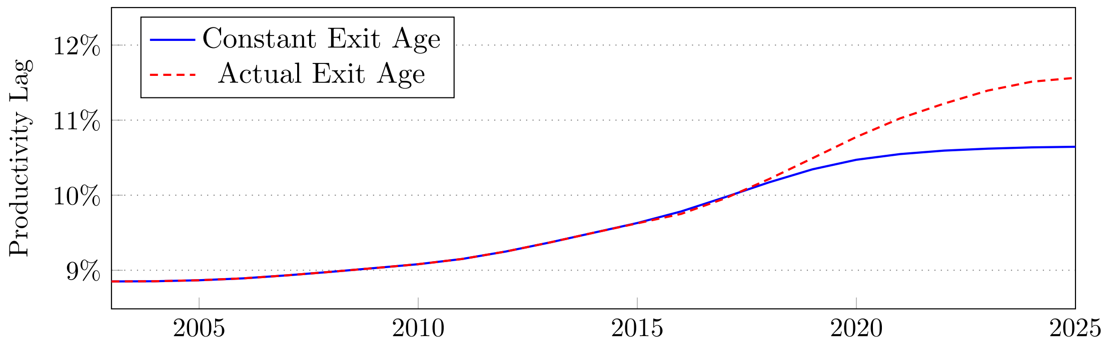

Figure 3.7: Effect of demographic change on the economy's distance from the technological frontier

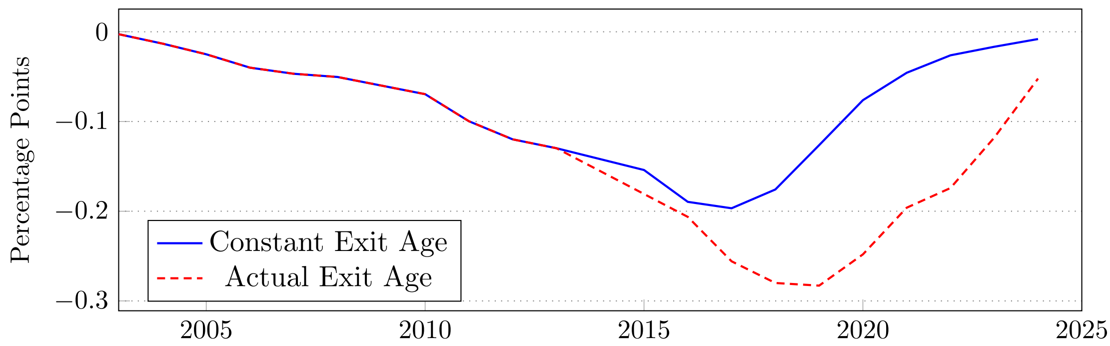

Figure 3.8: Productivity growth: Deviation from the trend

for the case with constant retirement age. When the projected simultaneous increase of the average retirement age is taken into account as well, this loss rises to nearly 0.3 percentage points. As demographic change slows down, productivity growth returns to its long-run trend.

Between 2010–2025, the average rate of realized productivity growth is 0.17 percentage points below the long-run trend when the projected change in the average retirement age is accounted for and 0.11 percentage points when the average retirement age of 2003–2010 is held constant. These numbers translate into a GDP loss of about 416bn Euro in constant prices of 2005 for the case of constant retirement age and 550bn Euro with the actual changes in the retirement age.[13] The loss of GDP under the actual retirement regime is larger than for the case with constant average retirement age for two reasons. First, the loss of productivity growth due to demographic change is higher. Second, as the average retirement age increases, the total labor force of the economy increases, which increases the economy's output. Consequently, a given loss of productivity growth translates into a higher value of lost GDP.

As a benchmark, the quantitative results of the simulation can be compared to the results in Werding (2008) who computes forecasts for productivity and output growth for various OECD countries based on regression estimates. The evolution of productivity growth in his forecast for

[13]The loss of GDP is derived by accumulating the German GDP of 2010 over the period 2010–2025 given the growth rate of the simulated economy and comparing it to the cumulated GDP of the counterfactual economy that grows at the exogenous rate of technological progress.

Germany for the same period is very similar to the results presented here, only the magnitude of the effect is higher. For the period 2010–2025, Werding's estimates indicate an average loss of productivity growth of 0.4 percentage points. So the model's mechanism is able to explain nearly 50% of the estimated effect of demographic change in Germany.

Effect of an Additional Increase of the Retirement Age
As a policy experiment, the effect of an additional increase in the average retirement age by three years is simulated. Such an increase can be achieved by raising the statutory retirement age as it is done in Germany and many other European countries at the very moment, or by reducing the number of people who drop out of the labor force early. For the simulation, the three additional years are added to the average retirement age that is projected for 2015 onward, assuming that the increase in the retirement age is unexpected by the firms. This gives an average retirement age of 65.8 years.

Figure 3.9 illustrates how demographic change affects the economy with a higher exit age. As before, it turns out that the overall effect is negative, moving the economy even further away from the technological frontier. At the peak of demographic change in 2025, the economy's relative productivity lag with the experimental retirement age is about 0.7 percentage points higher compared to the case with the actual projected retirement age. This shows that the additional increase of the average retirement age has a very strong negative effect, resulting in a growth reduction of about 0.43 percentage points in 2017. For the period 2010–2025, the average annual growth loss amounts to 0.21 percentage points, compared to 0.17 percentage points for the actual projected average retirement age.

Effect of a Lower Technology Updating Cost
As a second experiment, I analyze how the economy is affected by demographic change for a lower training cost, that is updating to a new technology becomes cheaper due to better training methods. Figure 3.10 illustrates how the distance of the technological frontier changes, when the training cost is reduced by 10%. For both lines, the constant average retirement age of 60.8 years is used. It can be seen, that the lower updating cost moves the economy in general closer to the technological frontier as all firms tend to update more often. Furthermore, it turns out that the negative effect of demographic change is slightly reduced. As labor force aging sets in, the economy moves away from the frontier, however, the magnitude of this result is lower than for the original training cost. This is in line with the comparative static results in Section 3.5, which showed that firms with older workers are more sensitive towards the updating cost. Over the period 2010–2025, the average annual growth loss now amounts to 0.09 percentage points compared to 0.11 percentage points before. This implies that the growth loss during that time is reduced by about 18%.

3.7 Robustness Tests

As a first robustness check, I test whether the model is consistent in the way that the choice of the cutoff value that separates young from old workers does not affect the model's aggregate

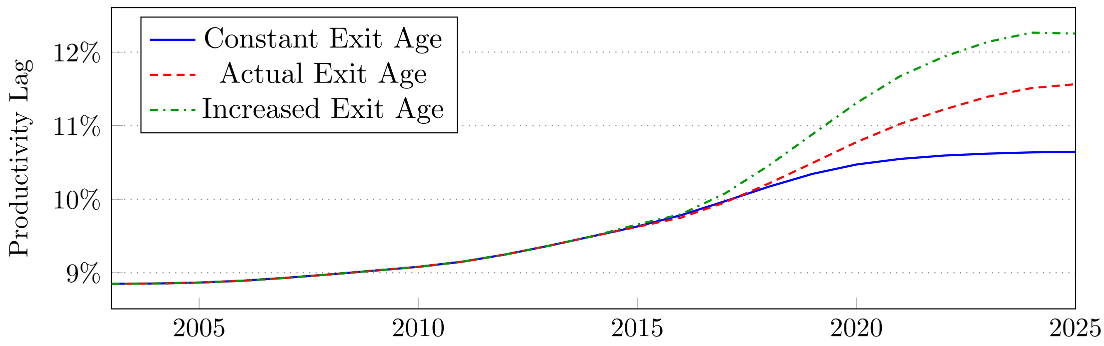

Figure 3.9: Demographic change and increased retirement age

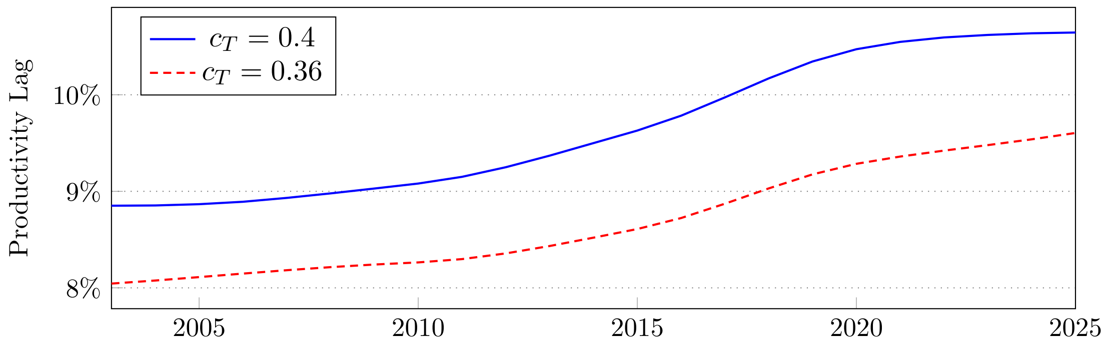

Figure 3.10: Demographic change and lower updating cost (constant retirement age)

results in the steady state. For the standard calibration with early retirement, workers are young for 35 years and old for 6.8 years. I reduce the duration of the young period and add the time to the old period. Consequently, the total worklife duration remains unchanged. This implies that the total worklife horizon of young workers does not change. As a result, the updating policies of firms that employ only young workers should remain unchanged but firms that employ old workers should update their technology in a shorter time interval. Nevertheless, the economy's distance from the technological frontier for the static case (that is without demographic change) should remain the same, as the earlier updating of firms with old workers is balanced by the higher share of old workers and the economy's fundamentals remain the same.

Furthermore, total resources used for technology updating in terms of turnover should remain unchanged. The wage of young workers should remain constant as their expected worklife time does not change whereas the wage of old workers should increase, so the wage differential decreases as well. The mean wage of the economy on the other hand, together with hiring and entry cost should remain unchanged.

Figure 3.11 illustrates the technology updating decision of firms for different cutoff values for young and old workers. As expected, there is basically no change for firms that employ only young workers, because their expected total worklife remains unchanged. On the other hand, firms that employ old workers reduce there updating distance as the expected worklife duration of old workers increases. The longer the expected worklife duration of old workers becomes, the flatter the updating profile of the firms becomes.

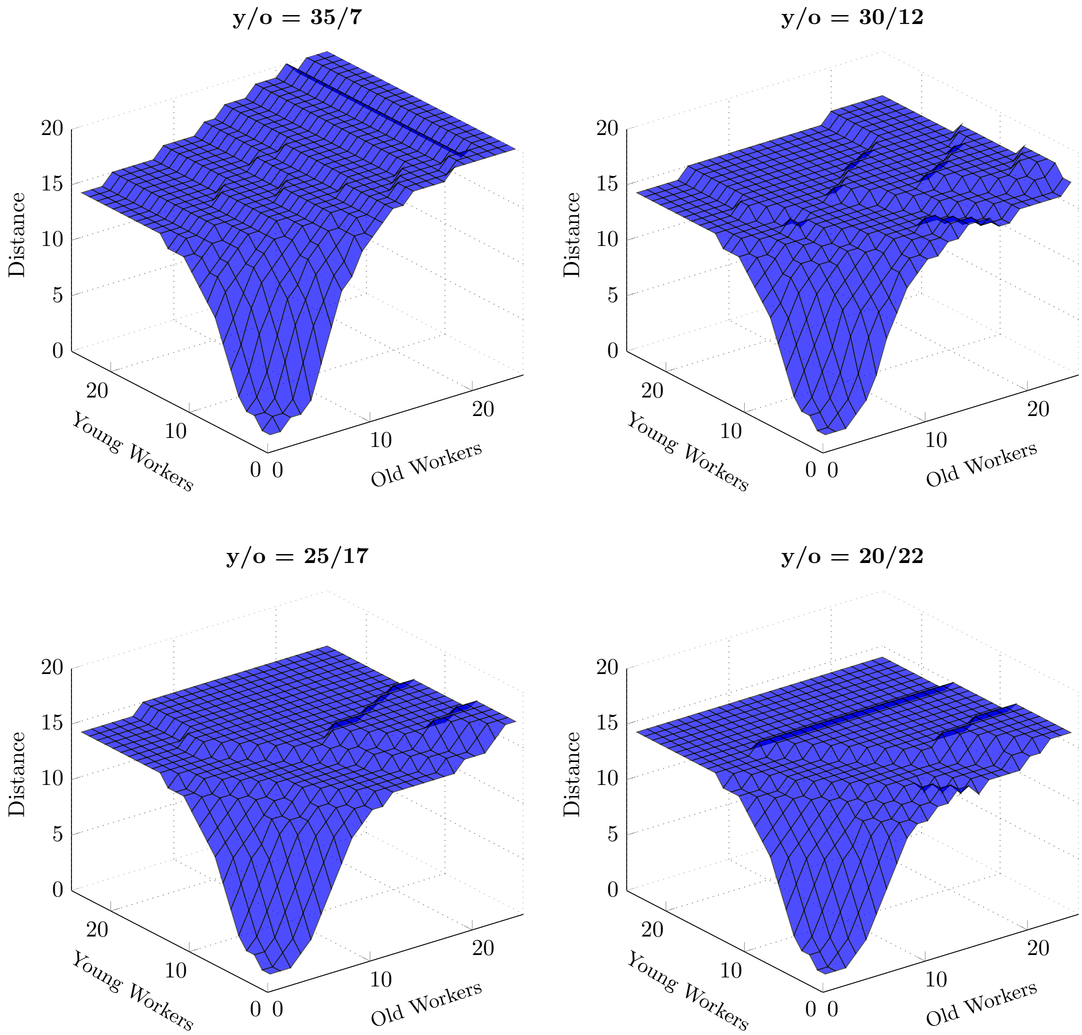

Figure 3.11: Updating distance for different cutoff values

Nevertheless, the aggregate variables of the economy remain unchanged, which is illustrated in Table 3.3. Even though the individual technology decisions of firms change, the distance of the economy from the technological frontier and resources used for innovation remain the same. Wages for young workers also remain constant whereas wages for old workers increase, as the increased expected worklife duration makes them more valuable for firms. However, the mean wage and therefore total wage payments remain constant. These results imply that also the economy's total output is unchanged.

As another robustness check, I test how sensitive the results are toward a change in the hiring cost and the entry cost. For this, I calibrate versions of the model with a 50% lower hiring cost and a 50% lower entry cost. Figure 3.12 shows the results. It turns out that the impact of each of these changes is very low with a small reduction of the growth loss over the period.

As a final robustness test, I analyze how the model would develop given that exogenous productivity growth would be higher by 50%, so $g = 3\%$. With higher exogenous growth, firms do update their technologies at a shorter interval for two reasons. First, the higher growth

	Duration Young / Duration Old			
	35/7	30/12	25/17	20/22
w_y	0.221	0.219	0.218	0.218
w_o	0.136	0.180	0.195	0.200
$\bar{w}$	0.21	0.21	0.21	0.21
Distance from Frontier	11.3%	11.2%	11.2%	11.3%
Resources for Updating	0.024	0.024	0.025	0.025

Table 3.3: Change of the cutoff value for young and old workers

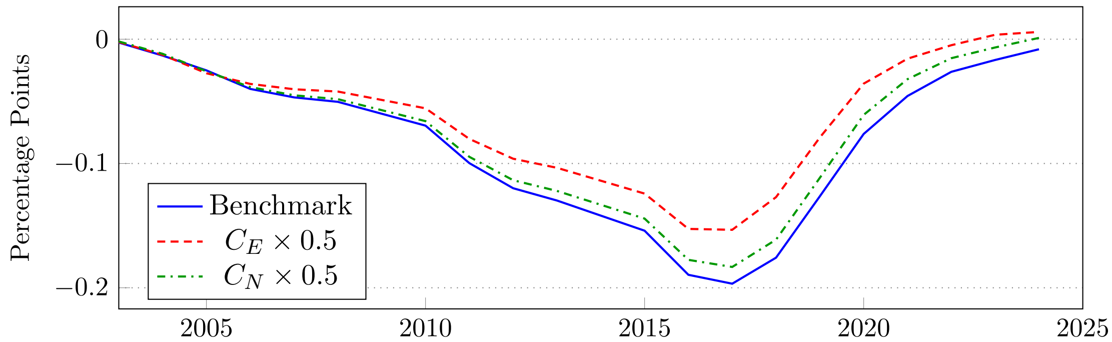

Figure 3.12: Demographic change with lower hiring and entry cost

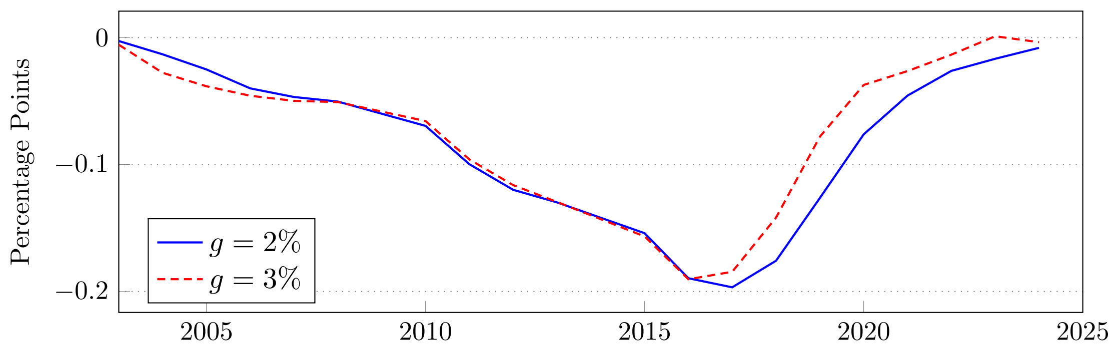

Figure 3.13: Productivity growth with higher exogenous productivity growth

rate makes updating more profitable, as it implies a larger productivity gain. Second, as wages increase at the rate of technological progress, firms are forced to update their technologies more often, as workers become otherwise too expensive, given their output with the current technology. The simulation results are provided in Figure 3.13 whereby the constant retirement age scenario is used. It turns out that the absolute loss of productivity growth in percentage points is very similar for the two rates of exogenous productivity growth. However, the relative loss of productivity growth is lower by a third for the high growth scenario.

3.8 Conclusions

Demographic change in the industrialized countries during the first half of the 21st century leads to a steep increase in the share of elderly persons in the labor force. In this paper, I develop a quantitative dynamic model that analyzes firms' technology decisions with respect to the age of their workforce and allows to determine the effect of labor force aging on the economy's technology distribution and productivity growth.

I calibrate the model to match the German economy and simulate the projected changes in the labor force age composition for the period 2003–2025. The results show that labor force aging increases the average relative productivity lag and thereby lowers aggregate productivity growth. Over the period 2010–2025, demographic change lowers the average annual rate of realized productivity growth by about 0.11 percentage points below the long-run trend. The increase in the average retirement age by about 2 years during that time further increases the negative effect, leading to an average annual growth loss of 0.17 percentage points between 2010–2025. A comparison of the simulation results to other studies indicates that the model results are in a plausible range.

For future work, the model could be applied to other countries as well to quantify the effect of demographic change on productivity growth. One problem that may arise when doing so, is that in countries with very high job mobility, the expected job duration of young and middle-aged workers could possibly be lower than that of eldery employees. Nevertheless, it is very well possible, that similar to Germany, a large share of job-to-job transitions take place within the firm, so that even with short job durations, worker-firm relationships are more stable.

Another possibly fruitful extension of the model is to use three age groups for workers. With this, the very high job-to-job transitions rates of young workers that have just entered the labor market could be taken into account explicitly. Middle-aged workers would then have the longest expected worker-firm relationship whereas it will be shorter for very young and very old workers. With this extension, the model could possibly create the hump-shaped relationship between workforce age and innovative activities of firms that have been found in the data.

3.9 Appendix

Numerical Solution Procedure

The numerical solution of the stationary equilibrium is split into two steps: the derivation of firm policies and wages, and the simulation of the stable firm distribution. As explained below, depending on parameters both steps are repeated multiple times until the stationary equilibrium is found.

The first part, the derivation of firm policies and wages is an iterative procedure. First, for given wages w_y, w_o, firm policies are derived by value function iteration. Then the free entry conditions (3.8) and (3.9) have to be checked in order to adapt the wages. As pointed out in Section 3.3, there are two possibilities for firm entry in equilibrium: either two entrant types exist and both free entry conditions are binding for a certain pair (y^H, o^H) of hired workers, or only a single entrant type exist, i.e. only one of the free entry conditions is binding, the other is strictly negative for all hiring possibilities. If two entrant types exist and these entrant types hire workforces with different age structures, the two labor markets can be cleared by adjustment of the entering firms, resulting in a block recursive equilibrium in which firm policies do not depend on the distribution of workers and firms in the economy. The wages for young and old workers are adapted until both free entry conditions are binding. For every change in the wages, firm policies have to be derived anew until the equilibrium is found. Once the wages have been found, the firm distribution can be simulated. This is done by populating the economy with a constant flow of young workers in every period and allow firms to enter that hire these workers. This simulation runs until the firm distribution, represented by the measure $\mu(y, o, k)$ has become stationary.

If it is not possible for both free entry conditions to be binding, then only one entrant type exist. In this case the wages for young and old workers have to be adapted to have one of the free entry conditions binding and to clear both labor markets simultaneously by the single entrant type while the other free entry condition is strictly negative. The single entrant type must hire exactly the ratio of young and old workers that becomes unemployed in a period and is not directly hired by existing firms in equilibrium. To find this solution, the firm distribution is simulated every time a new pair of wages is chosen and policy functions are derived and it is checked whether labor markets are cleared in equilibrium. In the case of a single entrant type, wages and firm policies are not independent of the share of young and old workers in the economy. This implies that a change in the relation of young and old workers (by demographic change) demands for a different hiring policy of entrants and different wages.

Calibration of Entry Cost c_E:

The model features no variable capital that is needed for production, hence capital appears only indirectly in the fixed cost for firm creation c_E. Therefore, the entry cost is interpreted as the capital share in the economy, which is set to 30%. The labor share is given by the total amount of wages that a firm expects to pay in its lifetime, calculated as present value at the time of firm entry. With a survival probability of $(1 - \delta)$ for a firm, an average workforce of 12.5 workers, and the average wage in the economy given by $\bar{w} = \frac{\lambda_o w_y + \lambda_y w_o}{\lambda_y + \lambda_o}$, the free entry cost is given by:

$$c_E = \frac{0.3}{0.7} \cdot 12.5 \cdot \sum_{t=0}^{\infty} (1-\delta)^t \left(\frac{1+g}{1+r} \right)^t \cdot \bar{w}.$$

Calibration of Technology Parameters: c_T, B, β:
The training cost is derived by calibrating c_T to match total resources for innovative activities as a share of total turnover of German firms, which equals 2.93% for the period 2002–2004 as collected in the German Innovation Survey 2005 by the Centre for European Economic Research (ZEW), based on the harmonized methodology of the Fourth Community Innovation Survey (CIS IV) of the European Union.(Aschhoff et al., 2005) The survey comprises more than 100,000 enterprises and covers all kind of innovative activities that lead to the adoption of new technologies or processes and the introduction of new products. For this definition it does not matter, if the introduced technology is novel to the market or already established at other enterprises, it must only by new for the adopting firm.

As B defines the lag between the newest technology and the non-state-of-the-art technology that is mainly chosen by old-worker firms, it increases the technology spread over the firms and thus increases the productivity dispersion among firms in the economy. As a target for the productivity dispersion, data from Pfeifer and Wagner (2012) is used, who calculate a normalized average standard deviation of labor productivity over firms within industries over the period 2003–2006 of 0.21, which is taken as target for productivity dispersion in the model. In interplay with the other parameters, β determines the total updating frequency or the share of workers receiving training in each period respectively for a given average lag of the economy and a given productivity dispersion. As a target for β, I use data on the share of workers in the labor force that received on-the-job training over the duration of one year which is provided in Eurostat (2013) and gives an average of 12.7% for 2003.

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