Essays on Parental Leave, Global Disinflation and Non-Renewable Resources

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Introduction

This thesis consists of three independent chapters. Chapter 1 is joint work with Juliane Parys and focusses on the allocation of parental leave between spouses. We modify a model of collective rationality developed by Pierre-André Chiappori and coauthors (such as Browning and Chiappori (1998)) to explicitly account for parental leave. The model predicts that the ability of spouses to influence the allocation of parental leave depends on personal characteristics such as age and income. Using representative data of households with young children from Germany we show that a high relative age or income allows a spouse to reduce his or her share in childcare. Chapter 2 is joint work with Mouhamdou Sy. We analyze the influence of increasing international trade on inflation. Increasing international trade makes firm competition more fierce and leads to improving productivity through firm selection. All else being equal, this reduces inflation. Chapter 3 is joint work with Martin Stürmer. In this research project we link geological evidence to the historic developments of non-renewable resource prices and its production in a model of endogenous growth to suggest that a range of non-renewable resources could be considered inexhaustible. If the deterioration of resource deposits in terms of ore grade and investments into extraction technology offset each other, the total resource extraction cost per unit of the resource would stay constant. This could explain the historic pattern of exponentially growing resource consumption at constant prices.

Even though the chapters are not related by content, they have a common approach. All three chapters use an economic model to understand the underlying problem and test the results empirically. Thus they contribute to the respective policy discussions by improving the understanding of the problem and by empirically supporting the theoretical statements.

Chapter 1 is a topic from labor economics. It takes a microeconomic approach as it analyzes the interaction of two individuals. It can have macroeconomic implications, however, as it contributes to the understanding of why young parents stay in or leave the labor market, with potentially large effects on the size and qualification of the labor force. Chapters 2 and 3 take macroeconomic approaches. Chapter 2 is a project in international economics and chapter 3 combines growth and resource economics.

In the following the three chapters are described individually.

Chapter 1. The class of collective rationality models, which makes only minimal assumptions on the decision making process within the family and includes other decision-making models like the axiomatic bargaining models. Since our research question does not necessitate theoretical restrictions on the specific form of household decision-making, we use this model class and adapt it to childcare allocation.

Small children must be in the custody of either one of the parents or of professional care such as daycare centres or nannies. A parent can only work when he or she is not taking care of the child. We consider the case of a country where the government pays parental benefits so that no income loss results from childcare during the first year of the child. In this situation, a parent does not need to be concerned about an immediate income loss. However, his or her long-term income and career is affected, and as future income depends on the spouse's own human capital, long-term considerations will motivate the spouse to work as much as possible and keep childcare low.

In a collective model spouses are assumed to have individual utility functions. This is in contrast to unitary models and implies that there is a certain conflict of interest between the spouses. The ability of an individual to influence the allocation of utility within the household, sometimes termed the "bargaining power" of an individual, depends on individual characteristics or "distribution factors". Using survey data from Germany, we found that those characteristics include relative income and age. Higher relative incomes and larger age differences shift the conditional leave allocation towards the relatively poorer and younger partner, respectively. In addition, we find that the share of professional childcare increases with total household income.

The chapter has a potential policy relevance in that it contributes to the understanding of the functioning of a government parental benefit scheme. It highlights the fact that long-term career considerations play a role in the decision of childcare allocation and that a spouse's initial income may influence the couple's decision even when there is no direct income loss from interrupting the career.

Chapter 2. This chapter is motivated by a remarkable empirical observation: In the twenty years from 1990 to 2010, trade openness increased worldwide while inflation levels decreased. Changes in inflation levels would normally be explained by changes in monetary policy, and indeed, monetary policy changed much throughout this period. Rogoff (2003) lists a number of substantial central bank measures which ended the Latin American hyperinflations at the beginning of the period under consideration and decreased inflation generally.

Taking a closer look at the figures, we searched for a more complete explanation of the cause of the "Global Disinflation" as the phenomenon of decreasing inflation is referred to. First, the trend cannot be explained by a dramatic change in a few economic "heavyweights". The entire distribution of openness and inflation across countries moved towards more openness and lower inflation, respectively. As tables 2.1 and 2.2 show the development started around 1990 and continued throughout the entire timespan without sudden jumps.

We build a model based on Melitz (2003) to analyze the link between disinflation and globalization. Falling tariff rates reduce the effective transport costs faced by (potential) exporters allowing them to ship a greater share of their production abroad. This increased competition shifts a larger share of production towards more productive firms as very unproductive firms leave the market and additional firms start exporting. Higher productivity lowers the relative price of goods as the same amount of goods can be produced with less labor input. A cash-in-advance constraint connects this change in relative prices to changes in the price level: If the money supply does not systematically offset the effect of increasing productivity, then inflation falls ceteribus paribus.

To verify the theoretical result empirically, we construct a new dataset of 123 countries from various sources. As opposed to previous studies such as Chen et al. (2009) who find this effect in regionally limited industry data, we are thus able to show the global scale of the link between globalization and inflation. Controlling for openness and productivity, we demonstrate the theoretical effect by interacting the two variables. The productivity variable alone shows the effect of innovation activity while the interaction effect demonstrates which contribution was made by the increased productivity caused by globalization.

This chapter highlights that globalization has an effect on inflation and that this effect is temporary since it is the *change* in trade openness which accelerates the productivity increase. The temporary nature of this particular effect of globalization may thus be of some relevance to monetary policy.

Chapter 3. The last chapter is motivated by the apparent discrepancy between the predictions of mainstream growth theory with respect to non-renewable resources and the empirical evidence on the historic evolution of non-renewable resource prices and production. Geological evidence shows that many important non-renewable resources are available in large quantities in the earth's crust. Deposits with ever decreasing resource density or "ore grade" are exploited. Yet, growth models continue to work with the basic assumption of the model by Hotelling (1931), where a fixed resource stock is exploited at an increasing price and decreasing consumption of the resource. Historic evidence is at odds with this and shows constant prices and increasing production and consumption in the long term.

These standard models can be found in standard textbooks on growth, take a very theoretical approach: Since the earth is finite, non-renewable resources are finite and thus the global economy has to consume ever decreasing amounts of it if it wants to avoid the point where nothing of the resource is left. Our claim is that this point of view is no useful description for historic patterns and the foreseeable future. The total amount of unexploited resources is so immense that its current consumption rate could be maintained for centuries, millennia or, in some cases, millions of years. This, however, does not imply that resources can be used carelessly. The extraction comes along with large negative externalities, above all for the environment. This aspect, however, is excluded from our research project as we focus on the availability of the resource.

From the geological evidence we conclude that resources are available in principle, but at different ore grades and difficulty of accessing them. This raises the question of extraction costs. To analyze this question we consider two relationships. The first is the distribution of a resource over ore grades. It answers the question of how many tonnes of a given resource are available at a density of x percent of the resource per tonne of sediment. The second relationship is between investments into extraction technology and ore grade that can be profitably exploited. Our hypothesis is that these two relationships trade off such that the cost of investment per tonne of the resource stays roughly constant over time.

Using this hypothesis in a model of economic growth, we are able to explain the historic developments on resource consumption and prices: If the cost of the resource for extraction and innovation in terms of capital stays constant over time, then a growing economy will extract increasing amounts of it while the price remains stable.

This chapter may enrich our understanding of resource production and use by a combination of geological evidence and economic modelling. The supply of many resources may not be the main concern for future economic growth. This insight should shift the focus even more on the negative side effects of its use.

Chapter 1

Intra-Household Allocation of Parental Leave

1.1 Introduction

Long labor market absence after the birth of a child causes a durable income and career penalty due to forgone growth of human capital and a negative work commitment signal to the employer for example.[1] Traditionally, this has mainly been borne by mothers.[2] However, the allocation of childcare time, as far as it conflicts with market work, is increasingly subject to change - especially in countries with a generous paid leave legislation. In this study, we propose a model of how parents share parental leave and the income and consumption drawbacks involved.

Treating a multiple-person household as a rational entity with a single set of goals has been rejected by many economists.[3] This is especially important for our study as it aims to gain insight into the process that determines how parents share the time they spend on doing childcare instead of working on the labor market. As an alternative to unitary household models, Chiappori (1988, 1992) and Apps and Rees (1988) are the first to propose the most

[1] Some of the early references are Mincer and Polachek (1974) as well as Corcoran and Duncan (1979). The importance of work experience for each spouse's acquisition of human capital is formalized in chapter 6 of Ott (1992).

[2] Ruhm (1998) reveals that brief parental leave periods (3 months) have little effect on women's earnings, but lengthier leave (9 months or more) is associated with substantial and durable reductions in relative wages within Western European countries. Erosa et al. (2002) find that fertility decisions generate important long-lasting gender differences in employment and wages that account for almost all the U.S. gender wage gap that is attributed to labor market experience.

[3] A convincing empirical example is Lundberg et al. (1997).

general form of a collective model of household behavior. The key assumption is that, however household decisions are made, the outcome is Pareto efficient. Browning and Chiappori (1998), Chiappori et al. (2002) and Chiappori and Ekeland (2009) extend this model by including distribution factors that affect household decisions even though they do not have an impact on preferences or on budgets directly. The existence of distribution factors is crucial for the model's testability. Blundell et al. (2005) interpret the solution to the household problem as a two-stage process, where household members share what is left for private consumption after purchasing a public good.

The collective framework nests any axiomatic bargaining approach that takes efficiency as an axiom. For instance, the Nash bargaining solution can be expressed as a maximization of the product of individual surpluses. Each agent's surplus involves the agent's status quo value which varies with personal characteristics and distribution factors. As pointed out in Bourguignon et al. (2009), any efficient intra-household allocation can be constructed as a bargaining solution for well-chosen status quo points.

There are very few theoretical examinations of the allocation mechanism between spouses in the literature. One example is Amilon (2007), who analyzes temporary leave sharing in Sweden using a Stackelberg bargaining model with a first-mover advantage for men due to an unexplained "cultural factor". In the empirical literature, the effect of different parental benefit schemes across countries on parents' childcare time contributions has been analyzed. Ekberg et al. (2005), for example, evaluate the introduction of a "daddy month" in Sweden and find an increase of fathers' childcare time contribution, but no learning-by-doing effect for childcare.

In this study, we introduce childcare sharing into a collective model of household behavior with public consumption as in Blundell et al. (2005). Our model does not assume any innate asymmetry between partners per se. It intends to explain the intra-household allocation of childcare time and consumption while assuming Pareto optimality of the outcome. Couples maximize a weighted household utility function. The Pareto weights have a clear interpretation as "distribution of power" parameters. Bourguignon et al. (2009) provide testable restrictions based on the presence of distribution factors which we exploit to empirically test for collective rationality in parental leave sharing.

Parents can purchase professional childcare in order to reduce the total leave duration of the household. This allows parents to work and thus invest in their human capital, which increases consumption of both partners in the future. In this sense, it can be thought of as a "public good". The household decision process can be imagined to happen in two stages. Parents first agree on how much professional childcare to purchase, and then, conditional on the level of public good consumption and the budget constraint stemming from stage one, determine their individual levels of private consumption and labor market participation at the second stage. The model predicts that households with higher incomes purchase more professional childcare.

Our model predicts that once the level of public consumption is set, the weaker spouse takes more leave time than the partner with more power. The more one contributes to household income and the older a partner is relative to the spouse, the larger is his or her intra-household power translating into less parental leave and a larger consumption share. Although income during leave is mainly replaced through parental benefit, both parents value labor market work as an input to human capital positively impacting their relative income and therefore their private consumption shares later in life.

If we consider for example an increase in the income of one partner, this strengthens that partner's power in the household and allows him or her to shift some leave time to the spouse. The net effect on the spouse's leave duration is not straightforward. On the one hand, there is a wealth effect stemming from the household income increase, which allows the couple to purchase more professional childcare. On the other hand, the change in Pareto weights leads to a redistribution of leave time between parents.

Generous parental leave benefits as introduced in many European countries keep household income stable after the birth of a child, no matter who stops working in the market in favor of childcare. Parents are therefore motivated to work mainly out of concern for their human capital. This determines their future income and also their power to influence decisions. This endogenization of gender power has been theoretically explored by Basu (2006), Iyigun and Walsh (2007a) and Iyigun and Walsh (2007b). We apply these theoretical concepts in a basic form.

Our model's empirical restrictions are tested using survey data on young German families. The German legislation allows both parents to go on paid leave and receive generous benefits replacing 67-100 percent of the average monthly net income from before the child's birth. The law allows leave time allocation between parents to be relatively flexible. We cannot reject Pareto efficiency in leave sharing. The data also confirm the income effects predicted by the collective model.

The chapter is organized as follows. Section 1.2 introduces a collective model of intra-household childcare and consumption sharing. An overview of the legal parental benefit situation in Germany in 2007 and a data description are provided in Section 1.3. In Section 1.4, we empirically test our collective model and its predictions. The last section concludes.

1.2 A Collective Model of Parental Leave Sharing

1.2.1 Unitary, Non-cooperative and Collective Household Models

For decades, most theoretical and applied microeconomic work involving household decision-making behavior has assumed that a household behaves as if it had a single set of goals. Following Browning and Chiappori (1998) we refer to them as *unitary* models. In the unitary household model, the partners' utility functions represent the same preferences such that their joint utility is maximized under a budget constraint. More precisely, a weighted sum of utilities is maximized, but the weights are fixed. This does not take into consideration that spouses might have conflicting interests and that the degree to which they can influence household decisions might depend on individual characteristics.

Factors that enter neither individual preferences nor the overall household budget constraint but do influence the decision process are known as distribution factors. A model with a weighted sum of individual utility functions is formally a unitary model as long as the weights do not depend on these distribution factors.

In order to study the intra-household decision process on parental leave allocation we apply a *collective* setting as in Blundell et al. (2005) to explicitly model the conflict of interests between partners. Let us consider an increase in income for the woman to illustrate how the two models react differently. The additional income increases the household income. Through this wealth effect the couple can afford more, including professional childcare. In the unitary model, both partners share this gain equally, so that both would do less childcare. The collective model considers a bargaining effect in addition. The woman increases her bargaining weight, so she gets a greater share of the increased wealth. Both effects are to her advantage. The man, however, benefits from the increased wealth, but suffers from a loss in bargaining power. The net effect of the woman's increase in earnings may be positive or negative for him, depending on specific functional forms. Thus only the collective model is able to explain a decrease in childcare of one partner as a result of an increase in income for the other partner.

But even if we accept a certain conflict of interest and bargaining weights that depend on distribution factors, the class of models to be chosen is not obvious. Non-cooperative models do not assume efficiency as the collective model does and instead assume that each household member maximizes his or her own utility without regard for the utility of the spouse. This potential way of resolving conflict in the household has been advanced by Konrad and Lommerud (1995), for example. But unlike the collective model, this theoretical concept hasn't been shown empirically. It is not motivated as a general concept, but for specific uses such as threat points in a cooperative model as suggested by the authors. Another application is illustrated in the "semi-cooperative" model of Konrad and Lommerud (2000) where there is a non-cooperative period before the family is formed and a cooperative period after it is formed. We therefore follow Konrad and Lommerud (2000) when they say "Fully non-cooperative behavior, we hope, is rare in family contexts...", and model family decision-making after the birth of a child as cooperative.

1.2.2 Model Setup

Resources to be allocated in the household are time and money, whereby the latter is translated into consumption. Time allocation has a central role in our model of household behavior. It concerns working time during the period right after the birth of a child, called period 1. During working hours there are only two possible activities for parents: market work and childcare. A parent not being on leave is free for market work. Therefore, shortening leave time is equivalent to extending work time.[4] Work experience is valued as an input to human capital accumulation. It increases income and consequently the individual consumption share in the second period. In addition, a long leave period might imply career drawbacks as it signals weak work commitment to the employer and promotion rounds might be missed.

Our model focusses on two main trade-offs involved with the intra-household allocation of parental leave: One trade-off concerns the consumption allocation between partners. Childcare provided by a parent him- or herself reduces that parent's market working time. Although income is replaced to a large extent through parental benefit during the leave period itself, parenthood-related job absence still involves an income penalty after returning to work

[4] The basic form of the model does not include any explicit measure of leisure, because we focus on the extensive margin of labor supply. See section 1.2.4 for a model including leisure.

compared to a situation without any career interruption.

The second major trade-off is between consumption during the period right after birth, when the child is very young and needs intensive care, and later. Parents can hire professional childcare such as nannies, daycare facilities, etc, in order to reduce the total household parental leave time.[5] The more professional childcare parents purchase, the more it reduces the household's level of private consumption in period 1, but the more it also allows partners to reduce parenthood-related income and consumption drawbacks for the second period. The amount of public expenditures therefore determines the total amount of leave time the household needs to take. Given the central role of time use we begin by defining its allocation.

Time Constraints

In period 1, which are the T_1 months after delivery, each parent i has to allocate time between market work h_i and leave b_i:

$$T_1 = h_i + b_i, \quad i \in \{m, w\} \ . \tag{1.1}$$

Men are indexed $i = m$ and women $i = w$. Permanent childcare needs to be guaranteed either by parents providing childcare themselves, denoted b_m and b_w, or by hiring professional childcare, denoted b_p, such that

$$T_1 = b_m + b_w + b_p \ . \tag{1.2}$$

This equation ensures that someone takes care of the newborn at any time. Market work and childcare time are restricted by zero below and by T_1 above. For future reference, note that a woman can work on the labor market whenever she is not on leave, i.e. $h_w = T_1 - b_w$, and that a man's work time can be expressed as the time when either the woman is at home or professional childcare is hired, i.e. $h_m = b_w + b_p$.

Income and Budget Constraint

Monthly net income is denoted w_{it}, where $i \in \{m, w\}$ denotes the spouse concerned and $t \in \{1, 2\}$ is the time period. Total net income of partner i in period t is consequently given by $w_{it}T_t$. In the first period, parents have two ways of spending income: They can either consume private goods, or purchase professional childcare at a monthly rate w_p. The latter is

[5] Modeling different childcare qualities is interesting, but not the focus of the current model. Therefore, we assume all three sources of childcare to be perfect substitutes.

considered a public good that shortens the cumulative leave duration of both partners. The level of public good consumption is denoted b_p. The couple's budget constraint is thus

$$c_{m1} + c_{w1} + b_p w_p = (w_{m1} + w_{w1})\, T_1 \, . \tag{1.3}$$

The right-hand side of the above equation implies that parental benefit is assumed to compensate for the most part of the immediate income loss parents encounter from going on leave. Consequently, our model focusses on the long-term drawbacks from parenthood-related job absence. It applies especially to countries with generous paid leave regulations. However, direct income reductions during leave could be easily incorporated through multiplying monthly net income of the parent on leave by an income-reduction factor λ, where $0 \leq \lambda < 1$. $\lambda = 0$ reflects the situation of countries with unpaid parental leave, whereas our model assumes full income replacement, i.e. $\lambda = 1$.

Utility and Human Capital

Parents derive utility from consumption and from the well-being of their child. The utility derived from having a kid and its well-being explains a couples' demand for children. However, once the decision for a child has been made, the derived utility is constant[6] given that at least one appropriate person takes care of it. Thus, we model consumption in each of the two periods as the variable to be maximized. The utility function is given as

$$U_i = U(c_{i1}, c_{i2}) \tag{1.4}$$

with the standard properties of positive but diminishing returns to consumption in both periods.

Our model incorporates public and private consumption. As in Blundell et al. (2005), partners share what is left for private consumption after purchasing a public good. We argue that relative incomes and the age difference between partners strongly influence the intra-household distribution of power and therefore determine the individual private consumption shares. The higher a partner's relative income or the older a partner is compared to the spouse, the more private goods he or she can consume.

The level of public consumption implicitly determines the amount of time parents can work on the market in order to accumulate human capital and raise future earnings. Since utility from the child's wellbeing is constant, professional childcare impacts utility only in-

[6] See Chiappori and Weiss (2007) for an example of this assumption in the literature.

directly via the budget constraint. For the allocation of consumption, we focus on private consumption for two reasons: First, private consumption is especially important to both partners as it remains to a large extend even after a potential marital dissolution. Second, we want to investigate the impact of the intra-household distribution of power on consumption shares, and public consumption is not affected by changes in the power allocation.

Pareto Weights

Partners maximize a weighted sum of utilities. The resulting allocation of household resources is assumed to be Pareto optimal. The man's Pareto weight is denoted by $\mu(\mathbf{z}) \in [0, 1]$, that of the woman by $1 - \mu(\mathbf{z})$.[7] The weights reflect the power of each partner and depend on a Q-dimensional vector of distribution factors $\mathbf{z}$. Examples for observable and unobservable distribution factors from the literature include relative incomes, age difference, relative physical attractiveness, and the local sex ratio. In the context of childcare, custody allocation and alimony transfers from the custody to the non-custody parent after divorce are further examples.

Assuming that $\mu(\mathbf{z})$ is known to be increasing in z_1, which could be the man's relative income or relative physical attractiveness for example, and decreasing in z_2, the negative age difference between partners [-(male minus female age)] for example, we can write $\partial\mu(\mathbf{z})/\partial z_1 > 0$ and $\partial\mu(\mathbf{z})/\partial z_2 < 0$. The man's relative income w_{m1}/w_{w1} as a distribution factor implies c.p. the Pareto weight $\mu(\mathbf{z})$ to be increasing in the man's monthly contribution to total household income w_{m1} and to be decreasing in the woman's contribution w_{w1}, i.e. $\partial\mu(\mathbf{z})/\partial w_{m1} > 0$ and $\partial\mu(\mathbf{z})/\partial w_{w1} < 0$.

First-Period consumption

We allow parents to hire professional childcare during working hours in period 1. This lowers the current level of private consumption, but shortens the period of parenthood-related labor market absence in period 1 thus increasing the level of private consumption in period 2. Therefore, the level of expenditures on professional childcare in period 1 is equivalent to an intertemporal consumption allocation within the household.

[7] If $\mu(\mathbf{z}) = 1$ the household behaves as though the man always gets his way, whereas if $\mu(\mathbf{z}) = 0$ it is as though the woman were the effective dictator. For intermediate values, the household behaves as though each person has some decision power.

Second-Period consumption

First-period monthly net income w_{i1} reflects the level of human capital from schooling and work experience acquired up to the child's birth. The income level in period 2 depends on first-period income w_{i1}, on the labor market experience from period 1, h_i, and on the initial level of human capital from before period 1, h_{i0}. For all $i \in \{m, w\}$, we write

$$w_{i2} = (h_i + h_{i0})w_{i1} \; . \tag{1.5}$$

Second-period household income $(w_{w2} + w_{m2})T_2$ is allocated between partners and spent individually on private consumption. The allocation underlies the same collective decision-making process as in the first period. Any change in the distribution of parental leave has, via second-period income, a WE as well as a BE in the second period. The motivation of spouses to reduce own leave time comes from the intention to (i) increase own future income, (ii) c.p. increase relative income, i.e. strengthening the own bargaining weight in period 2, and (iii) ultimately increase own future consumption. Labor market work in the first period is thus an investment into the future bargaining weight. See 1.A.1 for an analytical solution of the collective decision in period 2.

Dynamic household bargaining models are complex to solve analytically. Modeling a bargaining process in both periods renders the model dynamic. Mazzocco (2004) and Mazzocco (2005) model two periods, but the bargaining weight of the spouses is assumed to be fixed over time. In Mazzocco (2007) the weights are only influenced by random exogenous shocks. Basu (2006), Iyigun and Walsh (2007a) and Iyigun and Walsh (2007b) do have endogenous bargaining weights. The complexity of the models however allows only for quite general results.

In order to obtain analytical solutions, which we can test empirically, we take a shortcut and model consumption in period 2 directly as a function increasing in work experience and income from the first period:

$$c_{i2} = c_2(h_i, w_{i1}) = w_{i2}T_2 = (h_i + h_{i0})w_{i1}T_2 \; , \tag{1.6}$$

Maximization

The utility functions of the partners are assumed to take a Cobb-Douglas form and be given through

$$
\begin{aligned}
U_m &:= \log[(w_{m1} + w_{w1})T_1 - w_p b_p - c_{w1}] + \log[(b_w + b_p + h_{m0}) w_{m1} T_2] \\
U_w &:= \log[c_{w1}] + \log[(T_1 - b_w + h_{w0}) w_{w1} T_2] \ ,
\end{aligned}
$$

where h_{i0} is work experience of spouse i from before period 1.

Partners maximize a weighted sum of utilities

$$
\mathbb{L}(b_w, c_{w1}, b_p) = [\mu(\mathbf{z})\, U_m + (1 - \mu(\mathbf{z}))\, U_w] \ . \tag{1.7}
$$

The household problem reads

$$
\max_{b_w, c_{w1}, b_p} \mathbb{L}(b_w, c_{w1}, b_p) \tag{1.8}
$$

s.t.

$$
b_w \geq 0, \quad b_p \geq 0, \quad \text{and} \quad b_m = T_1 - b_w - b_p \geq 0 \ .
$$

In what follows, asterisks indicate solutions to the household maximization problem. Assuming for the moment that the non-negativity constraints are nonbinding, the first-order conditions can be solved:[8]

$$
\begin{aligned}
b_w^* &= (1 + \mu(\mathbf{z}))\, \frac{T_1 + h_{w0}}{2} - (1 - \mu(\mathbf{z}))\, \frac{(w_{m1} + w_{w1})T_1 + w_p h_{m0}}{2 w_p} && (1.9) \\
c_{w1}^* &= (1 - \mu(\mathbf{z}))\, \frac{(w_{m1} + w_{w1})T_1 + w_p (T_1 + h_{m0} + h_{w0})}{2} && (1.10) \\
b_p^* &= -\frac{T_1 + h_{m0} + h_{w0}}{2} + \frac{(w_{m1} + w_{w1})T_1}{2 w_p} && (1.11) \\
b_m^* &= T_1 - b_w^* - b_p^* \\
&= (2 - \mu(\mathbf{z}))\, \frac{T_1 + h_{m0}}{2} - \mu(\mathbf{z})\, \frac{(w_{m1} + w_{w1})T_1 + w_p h_{w0}}{2 w_p} \ . && (1.12)
\end{aligned}
$$

1.2.3 Results

We start our analysis with the effect of distribution factors. The proofs for this section can be found in 1.A.2

[8] See 1.A.2 for the explicit expressions and details on the non-negativity constraints.

Proposition 1.1 *A distribution factor z_1 that increases a partner's Pareto weight decreases this partner's optimal leave duration and increases the leave duration of the spouse. The inverse holds for a distribution factor z_2 that decreases a partner's Pareto weight:*

$$\text{(i)}\ \frac{\partial \mu(\mathbf{z})}{\partial z_1} > 0 \quad \Rightarrow \quad \frac{\partial b_w^*}{\partial z_1} > 0 \text{ and } \frac{\partial b_m^*}{\partial z_1} < 0$$

$$\text{(ii)}\ \frac{\partial \mu(\mathbf{z})}{\partial z_2} < 0 \quad \Rightarrow \quad \frac{\partial b_w^*}{\partial z_2} < 0 \text{ and } \frac{\partial b_m^*}{\partial z_2} > 0$$

This proposition shows that the intra-household parental leave allocation depends on the distribution of power between partners and therefore on distribution factors. Quite intuitively, the leave allocation changes in favor of the spouse who gains power.

Proposition 1.2 *The optimal leave duration of each parent decreases when his or her own income increases.*

$$\text{(i)}\ \frac{\partial b_w^*}{\partial w_{w1}} < 0 \qquad \text{(ii)}\ \frac{\partial b_m^*}{\partial w_{1m}} < 0$$

The optimal leave duration of each parent increases when the partner's income increases iff the change in the "distribution of power" parameter is stronger than the effect on the household's budget, i.e.

$$\text{(iii)}\ \frac{\partial b_w^*}{\partial w_{m1}} > 0 \quad \Leftrightarrow \quad \frac{\partial \mu(\mathbf{z})}{\partial w_{m1}} > \frac{1-\mu(\mathbf{z})}{w_{m1} + w_{w1} + w_p(1 + \frac{h_{m0}+h_{w0}}{T_1})}$$

$$\text{(iv)}\ \frac{\partial b_m^*}{\partial w_{w1}} > 0 \quad \Leftrightarrow \quad -\frac{\partial \mu(\mathbf{z})}{\partial w_{w1}} > \frac{\mu(\mathbf{z})}{w_{m1} + w_{w1} + w_p(1 + \frac{h_{m0}+h_{w0}}{T_1})}$$

An increase in one partner's income has the following two effects. On the one hand, the level of public expenditures increases due the increase in household income, which reduces the total parental leave duration of the household. Spouses agree on the amount of professional childcare they want to hire based on their symmetric preferences with respect to the intertemporal private consumption allocation. This effect is reflected in Proposition 1.3. On the other hand, the power allocation inside the household, and therefore the parental childcare allocation, shifts in favor of the partner whose contribution to household income has increased. The cut-off parameter constellation for a longer leave duration of one partner as a net response to an increase in the other partner's income is provided in Proposition 1.2.

Proposition 1.3 *The amount of professional childcare hired increases with total household income and is independent of distribution factors* $\mathbf{z}$*, i.e. for all* $q = 1, \ldots, Q$ *we have*

$$\text{(i)} \quad \frac{\partial b_p^*}{\partial(w_{m1} + w_{w1})} > 0 \qquad \textit{and} \qquad \text{(ii)} \quad \frac{\partial b_p^*}{\partial z_q} = 0 \; .$$

The previous propositions focus on changes in the composition of childcare sources. Proposition 1.4 states, in theoretical terms, how relative parental childcare shares compare depending on the intra-household distribution of power. When initial work experience from before period 1 and Pareto weights are equal, symmetric preferences imply an equal sharing of childcare responsibilities. If, however, one partner has more power inside the household, this partner turns out to bear the smaller share of parenthood-related income and career penalties.

Proposition 1.4 *Consider a situation in which both partners have the same initial market work experience from before period 1, i.e.* $h_{m0} = h_{w0}$*. In this case the mother takes a longer leave period than the father whenever* $\mu(\mathbf{z}) > \frac{1}{2}$*.*

Conditional on the level of household expenditures on professional childcare parents agreed on, the Pareto weight $\mu(\mathbf{z})$ determines the sharing rule of parental childcare between partners. If we assume $\mu(\mathbf{z})$ to be increasing in relative income, that is $z_1 = w_{m1}/w_{w1}$, and decreasing in the amount of alimony transfers after separation, then women are likely to take longer leave periods than men, i.e. $b_w^* > b_m^*$, (i) if women contribute relatively less than men to total household income, and (ii) if the alimony legislation does not enforce full compensation of custody mothers for expenses on professional childcare and for negative impacts on their future incomes from long leave periods.

1.2.4 Extension: Leisure

Up to now, we assumed that life with an infant does not grant any leisure time to the parents. We now soften this assumption and allow for three uses of time: childcare, market work and leisure. We keep the notation used so far and add a variable l_{it} for leisure of spouse $i \in \{l, m\}$ and period $t \in \{1, 2\}$.

The parental time budget now reads

$$T_1 = h_i + b_i + l_{i1}. \tag{1.13}$$

Equation 1.2 continues to hold:

$$T_1 = b_m + b_w + b_p \; . \tag{1.14}$$

On the side of expenses, there are no changes. On the side of revenues, the family earns market income w_i from work h_i and government benefit w_i for childcare b_i:

$$c_{m1} + c_{w1} + b_p w_p = w_{m1}(h_m + b_m) + w_{w1}(h_w + b_w) \; . \tag{1.15}$$

Utility now depends on consumption and labor:

$$\begin{aligned} U_i &= U(c_{i1}, c_{i2}, l_{i1}, l_{i2}) && (1.16) \\ &= \log(c_{i1}) + \log(c_{i2}) + \log(l_{i1}) + \log(l_{i2}) && (1.17) \end{aligned}$$

The second line is our choice of function, which we use to obtain an analytical solution.

Consumption in the second period is given by

$$c_{i2} = (T_1 - b_i + h_{i0}) w_{i1} (T_2 - l_{i2}). \tag{1.18}$$

Proposition 1.5 *Under the assumptions of this subsection the optimal values for consump-*

tion, childcare time and leisure are:

$$
\begin{aligned}
b_w &= \frac{1}{3w_p}[-T_1(w_{m1}+w_{w1}) + (-h_{m0} + 2(h_{w0}+T_1))w_p \\
&\quad +((h_{m0}+b_{w0})w_p + T - 1(w_{m1}+w_{w1}+w_p))\mu(\mathbf{z})] \\
b_p &= \frac{1}{3w_p}[T_1(w_{m1}+w_{w1}] \\
c_{w1} &= (1-\mu(\mathbf{z}))\ \frac{(w_{m1}+w_{w1})T_1 + w_p(T_1+h_{m0}+h_{w0})}{3} \\
l_{w1} &= (1-\mu(\mathbf{z}))\frac{1}{3w_{w1}}((h_{m0}+h_{w0})w_p) + T_1(w_{m1}+w_{w1}+w_p) \\
l_{m1} &= \mu(\mathbf{z})\frac{1}{3w_{m1}}((h_{m0}+h_{m0})w_p) + T_1(w_{m1}+w_{w1}+w_p) \\
l_{w2} &= \frac{T_2}{2} \\
l_{m2} &= \frac{T_2}{2}
\end{aligned}
$$

It becomes apparent from the results that the propositions in Section 1.2.3 continue to hold.

1.3 Legal Background and Data

1.3.1 The German Parental Benefit Legislation

In 2007 a modified parental benefit legislation has been introduced in Germany. The new law is known as “Elterngeld”. The benefit is now directed to the parent going on leave in order to take care of the child and not, as it has been the case until 2006, to the household. In addition, both parents have become eligible for the benefit independent of the individual and household income. No parent is excluded for passing an income threshold. The main eligibility conditions are residency in Germany, less than 30 hours of weekly working time, and legal guardian status for the child concerned.

Under the new law, 67-100 percent of the average monthly net income over the previous 12 months before applying for parental benefit is paid as a tax-free benefit to a parent on leave. A minimum monthly benefit amount of EUR 300 is paid even on top of unemployment benefits. An upper bound of EUR 1,800 per month corresponds to a monthly net income of EUR 2,700. The amount of parental benefit is calculated from the individual income, so that two parents with different incomes receive different amounts. If a parent chooses to go on leave only part time, the monthly benefit is calculated based on the amount of net-income reduction. When a parent's net income is less than EUR 1,000, the percentage paid as benefit exceeds 67 percent, and reaches 100 percent for low incomes. The maximum total benefit duration per family is 14 months, but each parent can at most go on paid leave for 12 months. Unpaid leave with job protection is possible thereafter for another 24 months. In order to exploit the full 14 months of paid leave, each parent has to stay at home for at least two months.[9]

Before 2007, the amount of parental benefit was not relative to net income. It also provided only one parent per birth with a fixed amount of EUR 300 per month, and only if the household's income was below a certain threshold. We do not observe whether only one or both parents went on leave. As a consequence, pre-2007 parental benefit data do not contain individual income information. In addition, there is no information available on the parent who did not apply for benefit.

1.3.2 Data

In Germany in 2007, 675,886 women gave birth to 684,862 children, including multiple births. Since it is the country of domicile of the legal parents that determines entitlement to parental benefit, this figure gives a close estimate of the number of households who are eligible for paid leave. For 658,389 births and 669,139 children a parental benefit application has been approved, meaning that at least one month of paid leave has been taken. Therefore, about 97.5 percent of all births in 2007 appear in the Parental Benefit Statistic 2007. However, the statistic contains information about both parents of a child only if both received parental benefit. Reasons why parents might not go on paid leave is that they continue working with more than 30 hours per week or that the family moved abroad after having given birth in Germany.

Tables 1.1 to 1.4 provide an overview of parental benefit use for children having been born in Germany in 2007. Based on a random 65 percent subsample of the Parental Benefit Statistic 2007, provided by the Federal Statistical Office of Germany (2008), we find that in only 35,938 out of 417,832 households, i.e. 8.6 percent, both parents go on paid leave for at least one months (Table 1.1). In 86.7 percent of the families only the mother takes

[9] Single parents with exclusive custody for the child can go on paid leave for up to 14 months.

leave. Not only do few fathers take paternity leave, fathers on leave also take shorter periods off than mothers. Only 5.3 percent of total parental benefit time is taken by fathers. The corresponding distribution of parental leave time is provided in Table 1.2. Corner solutions (2 or 12 months) are a favorite for both genders. However, it also becomes clear that a considerable number of parents do not opt for a corner solution.

One drawback of the administrative data is that households with applications for both parents are likely to be different from those in which only one parent goes on leave. Also, the data contain only indirect and censored income information through the benefit amount. Income is not informative if the option to reduce income is used, which allows parents to reduce working hours to less than 30 hours per week. The benefit is then calculated from the amount by which income has been reduced, and income cannot be calculated from the benefit. Another shortcoming of the statistic is that it does not contain socioeconomic background information on, for example, the employment sector, educational attainment, or the use of daycare facilities. This is in contrast to the dataset the remainder of the chapter is based on.

For our analysis, we use a survey on young families provided by the Rhine-Westphalia Institute for Economic Research Essen (2008). Between May and June 2008 and 2009 the survey was conducted on parents whose youngest child has been born between January and April 2007. Mothers were interviewed and provided information on themselves and on their partners if applicable. The survey contains direct information on individual monthly net income, employment sector, educational attainment, and on the use of daycare facilities as components of a rich set of personal characteristics. The RWI survey also provides information on parents who did not receive any benefit. It covers 4,177 randomly selected married and cohabiting hetero- and homosexual couples.

Using the survey data, Table 1.3 shows that leave duration is shorter for higher income groups. This picture is clear for mothers and fathers. For comparability with the previous two tables, which are based on the Parental Benefit Statistic, we restrict the sample used in Table 1.3 to persons who took at least one month of paid leave. Summary statistics of all variables used in the subsequent analysis are provided in Table 1.4. A comparison of Table 1.3 with the bottom part of Table 1.4 reveals that reported paternity leave length in the RWI survey is higher on average than can be concluded from the administrative data. For the average maternity leave duration the two datasets give similar results.

1.4 Empirical Results

1.4.1 Econometric Method

In order to investigate the intra-household allocation of parental leave, we regress maternity and paternity leave durations on a number of individual and household characteristics. Importantly, we assume the underlying variables to be continuous while we only observe a discrete number of full parental benefit months. These numbers are non-negative integers with an upper bound at 12 in the considered cohort of cohabiting or married couples.

We follow an approach by Papke and Wooldridge (1996), who introduce a quasi-maximum likelihood estimator (QMLE henceforth) based on the logistic function in order to estimate fractional response models. This estimator is consistent and $\sqrt{N}$-asymptotically normal regardless of the distribution of the dependent variable, conditional on the regressors. The explained variable can be continuous or discrete, but is restricted to the unit interval $[0, 1]$. Wooldridge (2002) points out that rescaling a variable that is restricted to the interval $[l, u]$, where $l < u$, using the transformation $(h_{in} - l)/(u - l) =: \widetilde{h}_{in}$, does not affect the properties of their QMLE approach. Hereby, $i \in \{w, m\}$ and $n = 1, 2, \ldots, N$ is a household index. For the subsequent logit QMLE regressions we rescale the leave durations setting $u = 12$ and $l = 0$. For comparability, also in the benchmark OLS estimations leave durations are rescaled.

$\mathbf{x}_{in}$ is the $1 \times K$ vector of explanatory variables from observation i with one entry being equal to unity. Although in practice, $\mathbf{x}_{wn}$ might be different from $\mathbf{x}_{mn}$, we assume equality of the two for simplicity. Papke and Wooldridge (1996) assume that, for all n,

$$\mathbb{E}[\widetilde{h}_{in}|\mathbf{x}_n] = G(\mathbf{x}_n\delta) \ . \tag{1.19}$$

The linear specification assumes $G(\mathbf{x}_n\delta) = \mathbf{x}_n\delta$ whereas in the non-linear fractional response model $G(\cdot)$ is chosen to be the logistic function $G(\mathbf{x}_n\delta) = \exp\{\mathbf{x}_n\delta\}/(1 + \exp\{\mathbf{x}_n\delta\})$ that satisfies $0 < G(\cdot) < 1$. QMLE is shown to be consistent as long as the conditional mean function (1.19) is correctly specified. For the non-linear fractional response model Papke and Wooldridge (1996) suggest to maximize the Bernoulli log-likelihood function

$$l_{in}(\delta) \equiv \widetilde{h}_{in} \log[G(\mathbf{x}_n\delta)] + (1 - \widetilde{h}_{in}) \log[1 - G(\mathbf{x}_n\delta)] \ .$$

We begin our empirical analysis with the linear model as a benchmark, which we estimate by OLS with White (1980) heteroskedasticity-robust standard errors. We then estimate non-linear fractional response models based on the logistic function.

1.4.2 Tests of Collective Rationality in Childcare Sharing

Bourguignon et al. (2009) provide a characterization of testability in the collective framework when only cross-sectional data without price variation is available. They develop a necessary and sufficient test of the Pareto-efficiency hypothesis, where the presence of distribution factors is crucial. Their influence on behavior provides the only testable restrictions of the collective model. The collective setting encompasses all cooperative bargaining models that take Pareto optimality of allocations as an axiom.

Our study considers a version of the collective model where professional childcare use is considered a collective good that reduces total household leave time. Both parents try to minimize the time they stay absent of the labor market, because their incomes in period 2 negatively depend on their leave time, see Section 1.2.2 and equation (1.5), in particular. Since there is no price variation in professional childcare in our data, we normalize w_p to unity in the budget constraint (1.3). Each partner has preferences represented by (1.4). The arguments of the utility function affect preferences directly and are referred to as "preference factors" as in Bourguignon et al. (2009). Observable preference factors in the following estimations include parents' employment sector and educational attainment, regional location, citizenship, and the number and age of children.

The literature on collective models has paid considerable attention to relating the within-household sharing of resources to distribution factors such as relative incomes and the age difference between spouses; see, for example, Browning et al. (1994) and Cherchye et al. (2011). We follow this approach and consider relative income and age difference (male minus female) as observable distribution factors. Unobservable preference and distribution factors go into the statistical error term ε_{in} and are assumed to be orthogonal to all observable characteristics.

The solution to maximization problem (1.8) implies that both partners have a demand for the good "working time in period 1" as an input to future consumption. As a consequence, partners want to minimize the "bad" leave time in period 1, denoted b_{mn} and b_{wn}. Parents' leave duration and professional childcare use are estimated as functions of the observable distribution factors relative income (of the man) and age difference (male minus female) while controlling for monthly household income y_n,[10] of total parental leave duration $b_{\text{tot}n} = b_{mn} + b_{wn}$, and of further individual and household characteristics such as parents' employment sector, education, number of children in the household, twins, foreign mother, parents living in East Germany, and living in a big city, denoted by vector $\mathbf{a}_n$, i.e. for all $i \in \{m, w, p\}$ we estimate:

$$\mathbb{E}[\widetilde{h}_{in}|\mathbf{x}_n] = G\left(\alpha_{i0} + \alpha_{i1}\frac{w_{m1n}}{w_{w1n}} + \alpha_{i2}\text{agediff}_n + \alpha_{i3}y_n + \alpha_{i4}b_{\text{tot}n} + f_i(\mathbf{a}_n)\right) . \tag{1.20}$$

Importance of Distribution Factors

The first testable implication comes from Proposition 1.1 in Bourguignon et al. (2009) and is a generalization of the income-pooling hypothesis that has been tested and rejected by Browning et al. (1994) and Lundberg et al. (1997) among others. It comes from the implication of the collective model that, without price variation, a model of collective decision making is observationally equivalent to a unitary setting as long as the weights of the individual utilities in the household utility function do not depend on distribution factors. On cross-sectional data without price variation, testing for collective rationality therefore requires the presence of distribution factors.[11]

The demands for leave time are compatible with unitary rationality if and only if

$$\alpha_{i1} = 0 \text{ and } \alpha_{i2} = 0 \qquad \forall\, i \in \{m, w, p\} .$$

This means that in the unitary framework, the impact of distribution factors on parental leave durations and professional childcare use are zero once we control for total household income and preference factors.

Table 1.5 shows that the impact of the distribution factors on maternity and paternity leave duration is individually and jointly different from zero in each of the two estimations. If leave time was split between parents based on unitary rationality, the source of income for example should not affect the sharing rule once we control for the level of household income. Table 1.5 therefore provides first evidence for collective rationality in parental leave sharing.

The decision to hire professional childcare, however, does not depend on distribution factors, but only on total household income as can be seen in Table 1.9. This finding confirms the expression we obtained for b_p^* in equation (1.11), where only joint household income but no

[10] As we only observe two sources of income, we have $y_n = w_{m1n} + w_{w1n}$.
[11] See Bourguignon et al. (2009, p. 509) for further discussion.

distribution factors enter. Although all decisions happen simultaneously, one can think about the decision mechanism as the following: Somebody needs to take care of the child at all times. We consider maternal, paternal, and professional childcare as possible, substitutable sources. Based on their total household income, parents first decide whether to purchase professional childcare in order to reduce the amount of total parental leave $b_m + b_w$. By choosing the amount of professional childcare, the amount of the public good "total labor market working time" is determined at the same time. Once the optimal total leave duration has been chosen, the between-parents leave sharing then depends on the intra-household distribution of power.

A relevant concern is that relative income provides a measure for potential drawbacks from job absence of both partners and therefore enters preferences directly. So far we are not able to completely rule this argument out. In the following we therefore consider the age difference between partners as a second distribution factor and provide further pieces of evidence for the plausibility of collective rationality in parental leave sharing.

Testing for Pareto Optimality

The central assumption for the allocation of private goods in collective models is that the intra-household decision process leads to a Pareto-efficient outcome. This is what Bourguignon et al. (2009) refer to as collective rationality. The main testable prediction based on variation in distribution factors follows from Proposition 1.2 of Bourguignon et al. (2009, p. 510), which has become know as the *proportionality condition.* The authors show that the condition is necessary and sufficient for collective demands in cross-sectional data without price variation in the sense that any demand function satisfying it is compatible with collective rationality.

The test is based on the idea that, by definition, distribution factors do not affect the Pareto set. If they influence the intra-household allocation of goods, then only through their one-dimensional impact on Pareto weights, which in turn determines the final location on the Pareto frontier. In order to test whether the impact of distribution factors on the final allocation is indeed one-dimensional, at least two distribution factors need to be present.

Intuitively, the proportionality condition implies that the effect of distribution factors on the optimal leave duration is proportional to the influence of the distribution factors on the intra-household distribution of power function, i.e.

$$\frac{\partial\, \mu(\mathbf{z})/\partial\, \frac{w_{m1n}}{w_{w1n}}}{\partial\, \mu(\mathbf{z})/\partial\, \text{agediff}_n} = \frac{\alpha_{i1}}{\alpha_{i2}} \qquad \forall i \in \{m, w\}\ .$$

Since the proportionality condition holds for both, maternity and paternity leave durations, the ratio of partial derivatives needs to be equal for both partners.

The proportionality condition implies that the ratio of partial derivatives of each good with respect to each distribution factor conditional on aggregate household resources is equal across all goods. If we additionally assume the man's weight $\mu(\mathbf{z})$ to be increasing in his own income w_{m1}, and to be decreasing in his partner's income w_{w1}, then the demand functions consistent with any bargaining model are such that

$$\frac{\alpha_{m1}}{\alpha_{m2}} - \frac{\alpha_{w1}}{\alpha_{w2}} = 0\ . \tag{1.21}$$

Bourguignon et al. (2009) have recently shown that the proportionality condition is necessary and sufficient for Pareto efficiency. Table 1.5 shows that a 95 percent bootstrap confidence interval of the left-hand side of equation (1.21) contains the zero. Therefore, the proportionality hypothesis cannot be rejected. In addition, the ratios are negative in both models. These results provide further evidence for collective rationality in parental leave sharing. The parent who contributes more to household income does c.p. have more intra-household power which puts him or her in the position to shift a bigger leave time share to the partner. For couples with a larger age difference leave sharing is shifted towards the younger partner.

Testing the impact of distribution factors on parental leave durations and the proportionality condition requires the joint estimation of the system of parental leave equations which allows for disturbance term correlations across equations. We then need to test linear and nonlinear cross-equation restrictions over the parameter estimates of the distribution factors. Unfortunately, Wald tests tend to overreject the null hypothesis in system OLS and seemingly unrelated regression models. In addition, nonlinear Wald test statistics are invariant to reformulations of the null. We follow Bobonis (2009) for both issues. First, we present p values from the bootstrap percentile interval of the test statistic when testing across models (see Table 1.6), which has been shown to significantly reduce the overrejection bias in this setting. Second, we assess the robustness of our inferences by constructing linear Wald tests as described below.

Robustness Check 1: Log Incomes and Income Effects

By considering log incomes, we can test for Pareto optimality in leave sharing in an alternative way. For all $i \in \{m, w\}$, we estimate:

$$\mathbb{E}[\widetilde{h}_{in}|\mathbf{x}_n] = G\left(\beta_{i0} + \beta_{i1}\log(w_{m1n}) + \beta_{i2}\log(w_{w1n}) + \beta_{i3}\text{agediff}_n + \beta_{i4}b_{\text{tot}n} + f_i(\mathbf{a}_n)\right)$$

If we assume that only relative income matters for the leave time sharing rule, then we can check the proportionality condition by testing whether the sum of the log income coefficients equals zero, i.e. whether

$$\beta_{i1} + \beta_{i2} = 0 \qquad \forall\, i \in \{m, w\}\ .$$

This hypothesis cannot be rejected - neither individually nor jointly across models. Therefore, Table 1.6 provides further pieces of evidence for Pareto optimality in parental leave sharing as the Wald tests can again not reject the proportionality hypothesis.

In addition, we present estimates of Tobit models with a lower censoring at 0 and an upper censoring at 12 months of paid leave. The magnitudes of the income effects are larger in absolute terms than in the fractional logit regressions as the Tobit models focus on interior solutions.[12] Families who do not opt for a corner solution, i.e. where each partner takes a strictly positive leave time, are likely to react stronger to a change in relative incomes as compared to partners opting for a corner solution. This is because the decision to temporarily drop out of the labor market has been already taken by both parents.

Robustness Check 2: z-Conditional Demands

Further testable implications come from an alternative demand system that is consistent with collective rationality. It follows from the effect of distribution factors on the intra-household allocation being one-dimensional, which is implied by the proportionality condition. Independent of the number of distribution factors, they can influence the parental leave allocation among parents only through a single, real-valued function $\mu(\mathbf{z})$. The demand for one good can therefore be expressed as a function of the demand for another good.

Bourguignon et al. (2009) introduce z-conditional demands which are useful to resolve, e.g., the empirical difficulty of nonlinear Wald test statistics being noninvariant to reformulations of the null hypothesis. We follow Bobonis (2009) and construct linear Wald tests based on parametric versions of the z-conditional demand functions in order to assess the robustness of our previous results to reformulations of the null hypotheses.

The idea of z-conditional demands is demonstrated in the following for $G(\cdot)$ being the logistic function. Under the assumption that relative income w_{m1n}/w_{w1n} has a strictly mono-

[12] Note that the dependent variables in columns 2 and 4 of Table 1.6 are not rescaled. Therefore, coefficients do not need to be multiplied by 12 as in the other tables.

tone influence on optimal leave sharing, we can invert (1.20):

$$\frac{w_{m1n}}{w_{w1n}} = \frac{1}{\alpha_{i1}} \log\left(\frac{\widetilde{h}_{in}}{1-\widetilde{h}_{in}}\right) - \frac{\alpha_{i0}}{\alpha_{i1}} - \frac{\alpha_{i2}}{\alpha_{i1}} \text{agediff}_n - \frac{\alpha_{i3}}{\alpha_{i1}} b_{\text{tot}n}$$
$$-\frac{1}{\alpha_{i1}} f_i(\mathbf{a}_n) - \frac{1}{\alpha_{i1}} \varepsilon_{in} \qquad \forall\, i \in \{m, w\} \; .$$

As total household leave duration is simply the sum of maternity and paternity leave time, we can replace b_{tot} by $b_{in} + 12\widetilde{h}_{jn}$. For parent j with $j \in \{m, w\}$ and $j \neq i$, we can substitute the above equation into (1.20) to obtain[13]

$$\mathbb{E}[\widetilde{h}_{jn}|\mathbf{x}_n] = G\left(\frac{1}{\alpha_{i1}(1-12\alpha_{j3})+12\alpha_{i3}\alpha_{j1}}\,\big[\,(\alpha_{i1}\alpha_{j0}-\alpha_{i0}\alpha_{j1}) + (\alpha_{i1}\alpha_{j2}-\alpha_{i2}\alpha_{j1})\ \text{agediff}_n\right.$$
$$\left. + (\alpha_{i1}\alpha_{j3}-\alpha_{i3}\alpha_{j1})\ b_{in} + \alpha_{j1}\ \log\left(\frac{\widetilde{h}_{in}}{1-\widetilde{h}_{in}}\right) + (\alpha_{i1}\ f_j(\mathbf{a}_n) - \alpha_{j1}\ f_i(\mathbf{a}_n))\,\big]\right) \; .$$

Benchmark OLS and fractional logit regression results are provided in Table 1.7. As expected we find that the mother's contribution to total household income has no significant impact on either maternity or paternity leave duration anymore once we control for the partner's leave duration. This must be true if the collective model is correct as the father's contribution to household income as one distribution factor already absorbs the one-dimensional effect of all distribution factors together on parental leave sharing.

Robustness Check 3: First Births and Tobit Estimations

A concern might be that in families, who already had children before the most recent one, parents might have specialized in different activities. Mothers might have provided the larger share of childcare already for the older children and are therefore relatively more productive in childcare provision than fathers. In this sense the lower market income of women reflects their specialization in household production and not their lower intra-household power.

In order to address this concern we restrict our sample to families without any older children, which reduces the sample to about 57 percent of the full sample. We redo the fractional

[13] Note that, if $G(\cdot)$ is linear, total household leave duration becomes redundant once we control for the partner's leave duration and

$$\mathbb{E}[\widetilde{h}_{jn}|\mathbf{x}_n] = \frac{1}{\alpha_{i1}(1-12\alpha_{j3})+12\alpha_{i3}\alpha_{j1}}\,[\,(\alpha_{i1}\alpha_{j0}-\alpha_{i0}\alpha_{j1}) + (\alpha_{i1}\alpha_{j2}-\alpha_{i2}\alpha_{j1})\ \text{agediff}_n$$
$$+ (\alpha_{i1}\alpha_{j3}-\alpha_{i3}\alpha_{j1})\ b_{in} + (\alpha_{i1}\ f_j(\mathbf{a}_n) - \alpha_{j1}\ f_i(\mathbf{a}_n)) + (\alpha_{i1}\ \varepsilon_{jn} - \alpha_{j1}\ \varepsilon_{in})\,] \; .$$

logit estimations of Table 1.5 and find a similar picture as before. As in Table 1.6 we compare the estimates of our previous analysis with the results of Tobit model estimations and can completely confirm our findings from before.

Concerns and Limitations

The variation in relative income and age difference between households could be correlated with unobservable characteristics of couples like varying separation probabilities. In this case couples with a lower risk of divorce may have different preferences for childcare sharing than partners with a high risk of separation. The considered distribution factors would then have an indirect effect on the sharing rule through the effect on divorce probabilities. However, Bobonis (2009) points out that tests of the proportionality condition are not invalidated by this possibility since the ratio of the direct and indirect effects of changes in relative income and/or age difference on Pareto weights does not involve anything specific to either maternity or paternity leave durations. Effects of changes in those factors on leave durations are again equally proportional to the distribution factors' influence on the intra-household power distribution.

Another concern addresses unobserved heterogeneity in distribution factor effects on individual leave durations, which involves the possibility of differences in estimated coefficients stemming from heterogeneity in individuals' preferences rather than from differences in individuals' intra-household power. Changes in the age difference might for example affect total household leave durations mainly in the lower range of the distribution between 0 and 12 months if age difference mainly affects maternity leave duration in a way that in couples with a small age difference women rather take paid leave for less than the maximum duration. Men's relative income, on the other hand, might affect more the upper range of the leave distribution between 12 and 14 months because relatively better earning men, i.e. relative to their spouses, mainly decide whether to participate in parental leave at all and are unlikely to take more than the minimum requirement of two months.

The main consequence would be that Pareto optimality tests, which rely on testing condition (1.21), may consider significant differences between the ratios of distribution factor coefficients in the demand for different goods as evidence against the predictions of the collective model. In fact, however, rejections of the proportionality condition could be caused by heterogeneity in household demand functions. As we cannot reject Pareto efficiency in parental leave sharing, this concern does not seem to be harmful in our application.

Finally, if individuals' preferences for leisure are not separable from those for leave time or childcare, respectively, the estimated income effects may suffer from an omitted variable bias. We therefore assume that conditioning on employment status before birth, employment sector, and additional socioeconomic and demographic variables, preferences for leisure are separable from those for childcare. A related limitation of relative income as a distribution factor is that labor incomes may be endogenous to households' childcare allocation decisions. Due to a lack of observed non-labor income or exogenous variation in incomes, we need to focus on correlations of relative incomes with household demands.

1.4.3 Empirical Intra-Household Allocation of Parental Leave

Concerning Proposition 1.1

Proposition 1.1 addresses the importance of distribution factors that do not enter individual preferences, but influence the decision process. The presence of such variables is not consistent with the unitary framework. Examples of distribution factors in the absence of price variation that have been suggested in the literature, include relative incomes, age difference, relative physical attractiveness, and local sex ratio. In the context of leave sharing, custody allocation after divorce and alimony transfers from the custody to the non-custody parent are also examples of distribution factors. Due to a lack of substantial variation in the other potential distribution factors between the 16 German states,[14] for the empirical analysis we need to focus on relative income and age difference changes while controlling for the level of household income. A unitary model would predict that only the level and not the sources of household income matter.

Table 1.5 provides evidence for collective rationality in parental leave sharing by confirming the impact of relative income changes on individual leave durations. A higher relative income of the father and a larger age difference are correlated with longer maternity leave and shorter paternity leave. Once we include relative income, the level of household income does not have a significant impact on parental leave durations anymore. This finding provides evidence for the WE on paid leave durations being weaker than the BE.

Concerning Proposition 1.2

Proposition 1.2 predicts that each spouse's leave share is decreasing in own income. Em-

[14] Unfortunately, we do not observe smaller geographical regions than states.

pirical support for this prediction is presented in Table 1.6.[15] The magnitudes of the Tobit parameter estimates from Table 1.8 tell us that doubling the mother's income leads to a 1.4 months decrease of her own parental benefit duration. For fathers the corresponding coefficient from the last column of Table 1.6 is a little bit larger in absolute terms: it corresponds to a month and a half decrease.

Additionally, doubling the mother's earnings involves an increase in the father's leave time of about four fifth of a month. If the father's income is doubled, the coefficient is more than twice as big, i.e. mothers go on leave for 1.6 months longer. The magnitude of the coefficients might even be expected to become larger in absolute terms in the future if we consider that the most recent data available are from the first third of 2007 - the four months after the new parental benefit legislation has been introduced in Germany.

Tables 1.1 and 1.2 demonstrate a strong asymmetry between maternity and paternity leave durations on an aggregate level. Table 1.1 tells us that, based on the Parental Benefit Statistic, for 95.3 percent of the children born in 2007 the mother went on leave for at least one month. This number needs to be compared to only 13.3 percent of fathers who took at least one month off. Table 1.2 then shows that fathers take only 5.3 percent of the total leave duration.

However, if we look at the development of fathers' participation rate in parental leave in Scandinavian countries, who introduced generous parental leave legislations much earlier, paternity leave durations in Germany can be expected to increase in the future.

Concerning Proposition 1.3

Proposition 1.3 predicts that professional childcare use increases with household income, but is independent of distribution factors. The consumption of the public good determines the amount of household leave time which is then shared between parents.

Some descriptive facts from RWI survey data are that 30.7 percent of parents with a monthly household net income below EUR 2,000 plan to hire professional childcare. This percentage rises with income until it reaches 55.4 percent for parents with a household income of more than EUR 5,000. Marginal effects from logit QMLE in Table 1.9 suggest that only household income and not relative income or age difference matter for the decision to hire professional childcare. In particular, a family is roughly 2.4 percent more likely to hire professional childcare if monthly household net income exceeds the average income of house-

[15] See also Tables 1.5 and 1.8.

holds by EUR 1,000.[16]

Concerning Proposition 1.4

Proposition 1.4 states that the mother's leave share is relatively larger if the father's Pareto weight is relatively stronger. This theoretical result is difficult to bring to the data, as the exact functional form of the power function is unknown. A multiplicity of factors are likely to determine the exact intra-household "distribution of power" out of which we observe substantial variation only in two distribution factors (relative income and age difference).

We still provide suggestive empirical evidence for women to be represented in childcare relatively stronger than their partner in couples where the woman's Pareto weight is relatively weaker, i.e. when $1 - \mu(\mathbf{z}) < \mu(\mathbf{z})$. We construct a dummy variable which equals one if the woman takes more leave time than the man. A second dummy equals one if the man's contribution to household income is bigger than the woman's. Then, families in which the latter dummy variable equals one are 5.1 percent more likely that the woman takes relatively more leave time than families where the man's relative income is less than 1.[17]

However, while in 65 percent of the observed households from the RWI survey the man's relative income is larger than 1 and in 73 percent the man is older that the woman, in more than 89 percent of households the woman's relative leave time is larger than 1. This means that, as the effect of all distribution factors on the intra-household allocation of leave time is one-dimensional, we are able to infer the effect of changes in the observed distribution factors on relative leave times to happen through changes in relative Pareto weights. Still, we cannot credibly predict the exact magnitude of the man's and the woman's Pareto weight in a given household without knowing the exact functional form and without observing all arguments of the power function.

1.5 Conclusion

This chapter aims to gain insight into the process that determines how parents share the time they spend on doing childcare instead of working on the labor market. Lengthy parental leave periods involve long-term income and career penalties even in countries with a generous

[16] As the dependent variable is a dummy, logit QMLE simplifies to a usual logit estimation. We calculate marginal effects with all variables at means. Qualitative results for different covariate values are similar and available from the authors upon request.

[17] The t statistic of the marginal effect is 4.2 when regressing the leave-time dummy on the relative-income dummy in a logit regression while using the same remaining controls as in Table 1.5.

paid leave legislation. Therefore, both parents value labor market work as an input to their human capital that positively impacts their individual incomes later in life - which translates into a higher level of future private consumption.

We introduce parental leave sharing in a collective model of household behavior with public consumption. The model's restrictions are tested on survey data of young German families. The collective model is identified through the existence of distribution factors that affect household decisions even though they do not impact preferences nor budgets directly.

Although all decisions happen simultaneously, the leave allocation can be imagined to happen in a two-stage process: Parents first agree on public expenditures on professional childcare use. Then, and conditional on the amount of public good consumption, partners choose the time they spend on childcare and their levels of private consumption. Each partner's leave time is the shorter and private consumption is the higher, the stronger a partner's power initially is. Market work is valued as an investment in human capital which increases expected future income. A higher personal income c.p. increases the household income and the relative income. It therefore translates into a higher consumption level for the household and a larger personal consumption share through a stronger Pareto weight. Households face one trade-off concerning the allocation of childcare time conflicting with work time between partners, and a second trade-off related to an intertemporal private consumption allocation between the nearer and the farther future by choosing the amount of professional childcare to hire.

To summarize, parental leave time and the involved income and career penalties are allocated strongly towards women. This is correlated to men usually contributing relatively more to household income and being older than their partner. Possibly, the economically weak outside option for women as a single mother even boosts the inequality in leave time sharing.[18] Still, as we observe in the data, the childcare allocation is sensitive to relative incomes and age differences. It is more equal in households where the woman contributes relatively more to household income and where the woman is relatively older.

[18] Alimony transfers by the father help to reduce the inequality after divorce, but DiPrete and McManus (2000) and Bartfeld (2000) among others find that the economic situation of custodial-mother families is still dramatically worse than the economic situation of fathers after separation.

Appendix to Chapter 1

1.A Mathematical Appendix

1.A.1 The Collective Model in Period 2

In this section, we describe analytically how the collective model in the second period would look like. The maximization problem reads:

$$\max_{c_{w2},c_{m2}} [\mu(z_2)U_{m2} + (1-\mu(z_2))U_{w2}]$$

with budget constraint

$$c_{w2} + c_{m2} = (w_{w2} + w_{m2})T_2 \ .$$

For a concrete illustration we assume utility to be logarithmic:

$$U_{i2} = \log(c_{i2}) \ .$$

The resulting maximization leads to the following expression for second period consumption:

$$\begin{aligned} c_{w2} &= (1-\mu(z_2))(w_{w2} + w_{m2})T_2 \\ c_{m2} &= \mu(z_2)(w_{w2} + w_{m2})T_2 \ . \end{aligned}$$

Each spouse thus obtains a fraction of household income equal to his/her bargaining weight. This highlights the bargaining and wealth effect of any change in income. Since the bargaining weight includes relative income among other distribution factors, any improvement in own education or work experience thus leads to an increase in own consumption. This aspect is captured by our shortcut formulation for consumption in the second period. We abstract from the effect of the other spouse's education and work experience on own future consumption, since in this case bargaining and wealth effect work in opposite directions.

1.A.2 FOC, SOC, Non-negativity Constraints and Proofs

First- and Second-Order Conditions

Assuming for the moment that the non-negativity constraints are nonbinding,[19] the FOCs are

$$\begin{aligned}
\mathbb{L}^{(1,0,0)} &= \frac{\mu(\cdot)}{b_w+b_p+h_{m0}} - \frac{1-\mu(\cdot)}{T_1-b_w+h_{w0}} &\equiv 0\\
\mathbb{L}^{(0,1,0)} &= -\frac{\mu(\cdot)}{(w_{m1}+w_{m1})T_1-w_pb_p-c_{w1}} + \frac{1-\mu(\cdot)}{c_{w1}} &\equiv 0\\
\mathbb{L}^{(0,0,1)} &= \mu(\cdot)\left(\frac{1}{b_w+b_p+h_{m0}} - \frac{w_p}{(w_{m1}+w_{m1})T_1-w_pb_p-c_{w1}}\right) &\equiv 0
\end{aligned}$$

This is a linear equation system in three variables. Results are given in Section 1.2.2.

The Hessian of $\mathbb{L}$ is given by

$$H = \begin{bmatrix} L^{(2,0,0)} & L^{(1,1,0)} & L^{(1,0,1)} \\ L^{(1,1,0)} & L^{(0,2,0)} & L^{(0,1,1)} \\ L^{(1,0,1)} & L^{(0,1,1)} & L^{(0,0,2)} \end{bmatrix}$$

with

$$\begin{aligned}
\mathbb{L}^{(2,0,0)}(b_w^*, c_{w1}^*, b_p^*) &= -\frac{\mu}{(b_w^*+b_p^*+h_{m0})^2} - \frac{1-\mu}{(T_1-b_w^*+h_{w0})^2} < 0\\
\mathbb{L}^{(0,2,0)}(b_w^*, c_{w1}^*, b_p^*) &= -\frac{\mu}{((w_{m1}+w_{w1})T_1-w_pb_p^*-c_{w1}^*)^2} - \frac{1-\mu}{(c_{w1}^*)^2} < 0\\
\mathbb{L}^{(0,0,2)}(b_w^*, c_{w1}^*, b_p^*) &= -\mu\left(\frac{1}{(+b_w^*+b_p^*+h_{m0})^2} + \frac{w_p^2}{((w_{m1}+w_{w1})T_1-w_pb_p^*-c_{w1}^*)^2}\right) < 0\\
\mathbb{L}^{(1,1,0)}(b_w^*, c_{w1}^*, b_p^*) &= 0\\
\mathbb{L}^{(1,0,1)}(b_w^*, c_{w1}^*, b_p^*) &= -\frac{\mu}{(b_w^*+b_p^*+h_{m0})^2} < 0\\
\mathbb{L}^{(0,1,1)}(b_w^*, c_{w1}^*, b_p^*) &= -\frac{\mu\, w_p}{((w_{m1}+w_{w1})T_1-w_pb_p^*-c_{w1}^*)^2} < 0
\end{aligned}$$

The first minor is negative, the second is $|\mathbb{H}_2| = \mathbb{L}^{(2,0,0)}\mathbb{L}^{(0,2,0)} > 0$. The determinant of the Hessian at the maximum is

[19] See next section for details on the non-negativity constraints.

$$|\mathbb{H}_3(b_w^*, c_{w1}^*, b_p^*)| = \mathbb{L}^{(2,0,0)}(b_w^*, c_{w1}^*, b_p^*)\ \mathbb{L}^{(0,2,0)}(b_w^*, c_{w1}^*, b_p^*)\ \mathbb{L}^{(0,0,2)}(b_w^*, c_{w1}^*, b_p^*)$$

$$-\mathbb{L}^{(2,0,0)}\ \left(\mathbb{L}^{(0,1,1)}(b_w^*, c_{w1}^*, b_p^*)\right)^2 - \mathbb{L}^{(0,0,2)}(b_w^*, c_{w1}^*, b_p^*)\ \left(\mathbb{L}^{(1,0,1)}(b_w^*, c_{w1}^*, b_p^*)\right)^2 < 0\ .$$

Therefore, the Hessian is negative definite at (b_w^*, c_{w1}^*, b_p^*) and $\mathbb{L}(b_w^*, c_{w1}^*, b_p^*)$ is a maximum.

The Non-negativity Constraints

When solving the maximization problem (1.8), we consider only the case where the non-negativity constraints are nonbinding. We then use the resulting solutions to derive our propositions. In order for this to be meaningful, we have to show that there exists a range of parameters, for which the non-negativity constraints are indeed nonbinding.

From equation (1.9) and (1.12) it can be seen that if the Pareto weight of one spouse equals zero, this leads to an excessive leave duration for the other spouse, i.e. $\mu(\cdot) = 0 \Rightarrow b_m^* \geq T_1$ and $\mu(\cdot) = 1 \Rightarrow b_w^* \geq T_1$. The interpretation is that if the utility of one spouse has no importance, then this partner would be overly exploited in favor of the other. The non-negativity constraints therefore only hold for an intermediate range of weights $\mu_{\min}(\cdot)$ to $\mu_{\max}(\cdot)$ with $0 < \mu_{\min}(\cdot) < \mu_{\max}(\cdot) < 1$. Outside of this range, a corner solution with $b_m = 0$ or $b_w = 0$ maximizes the household's utility. In the following, we show that all constraints can hold at the same time, so that we are not in a degenerate case.

The non-negativity constraints for the duration of maternity and paternity leave can be written:

$$\begin{aligned}
& b_w^* && \geq\ 0 \\
\Leftrightarrow\quad & (1+\mu(\cdot))\,\frac{T_1 + h_{w0}}{2} - (1-\mu(\cdot))\,\frac{(w_{m1}+w_{w1})T_1 + w_p h_{m0}}{2w_p} && \geq\ 0 \\
\Leftrightarrow\quad & \frac{(w_{m1}+w_{w1})T_1 - w_pT_1 + w_p(h_{m0}-h_{w0})}{(w_{m1}+w_{w1})T_1 + w_pT_1 + w_p(h_{m0}+h_{w0})} && \leq\ \mu(\cdot) \qquad \text{and}
\end{aligned}$$

$$\begin{aligned}
& b_m^* && \geq\ 0 \\
\Leftrightarrow\quad & (2-\mu(\cdot))\frac{T_1 + h_{m0}}{2} - \mu(\cdot)\,\frac{(w_{m1}+w_{w1})T_1 + w_p h_{w0}}{2w_p} && \geq\ 0 \\
\Leftrightarrow\quad & \frac{2w_p(T_1 + h_{m0})}{(w_{m1}+w_{w1})T_1 + w_pT_1 + w_p(h_{m0}+h_{w0})} && \geq\ \mu(\cdot)
\end{aligned}$$

The non-negativity constraints for b_m^* and b_m^* can be simultaneously fulfilled only if

$$\begin{aligned}
\frac{2w_p(T_1+h_{m0})}{(w_{m1}+w_{w1})T_1+w_pT_1+w_p(h_{m0}+h_{w0})} &\geq \frac{(w_{m1}+w_{w1})T_1-w_pT_1+w_p(h_{m0}-h_{w0})}{(w_{m1}+w_{w1})T_1+w_pT_1+w_p(h_{m0}+h_{w0})}\\
\Leftrightarrow \qquad w_{m1}+w_{w1} &\leq 2w_p+\left(1+\frac{h_{m0}+h_{w0}}{T_1}\right)w_p\ .
\end{aligned}$$

In addition, the duration of professional childcare use needs to be nonnegative, i.e.

$$\begin{aligned}
b_p^* &\geq 0\\
\Leftrightarrow \quad \frac{(w_{m1}+w_{w1})T_1-w_pT_1-w_p(h_{m0}+h_{w0})}{2w_p} &\geq 0\\
\Leftrightarrow \quad w_{m1}+w_{w1} &\geq \left(1+\frac{h_{m0}+h_{w0}}{T_1}\right)w_p\ .
\end{aligned}$$

Let us consider, e.g., parameter values such that $w_{m1}=w_{w1}=w_p$ and $h_{m0}=h_{w0}=0$. In this case, all non-negativity constraints hold simultaneously if $1/3 \leq \mu(\cdot) \leq 2/3$. An interior solution is reached as long as one partner does not have more than twice the power of the other.

Proof of Proposition 1.1

We have

$$\frac{\partial b_w^*}{\partial z_1}=\frac{\partial\ \mu(\mathbf{z})}{\partial\ z_1}\frac{(w_{m1}+w_{w1}+w_p)T_1+w_p(h_{m0}+h_{w0})}{2w_p}$$

and

$$\frac{\partial b_w^*}{\partial z_2}=-\frac{\partial\ \mu(\mathbf{z})}{\partial\ z_2}\frac{(w_{m1}+w_{w1}+w_p)T_1+w_p(h_{m0}+h_{w0})}{2w_p}$$

The signs of these expressions depend in an obvious way on $\operatorname{sign}\big(\partial\ \mu(\mathbf{z})/\partial\ z_q\big)$ for $q=1,2$. □

Proof of Proposition 1.2

(i) $$\frac{\partial b_w^*}{\partial w_{w1}}=\frac{\partial\ \mu(\mathbf{z})}{\partial\ w_{w1}}\frac{(w_{m1}+w_{w1}+w_p)T_1+w_p(h_{m0}+h_{w0})}{2w_p}-\frac{(1-\mu(\mathbf{z}))T_1}{2w_p}$$

(ii) analogous

(iii) $$\frac{\partial b_w^*}{\partial w_{m1}}=\frac{\partial\ \mu(\mathbf{z})}{\partial\ w_{m1}}\frac{(w_{m1}+w_{w1}+w_p)T_1+w_p(h_{m0}+h_{w0})}{2w_p}-\frac{(1-\mu(\mathbf{z}))T_1}{2w_p}$$

(iv) analogous

□

Proof of Proposition 1.3

$$\frac{\partial b_p^*}{\partial(w_{m1}+w_{w1})} = \frac{T_1}{2w_p} \qquad \text{and} \qquad \text{(ii)} \quad \frac{\partial b_p^*}{\partial z_q} = \frac{\partial b_p^*}{\partial \mu(\mathbf{z})} \frac{\partial \mu(\mathbf{z})}{\partial z_q} \quad \forall\, q = 1, \ldots, Q\,.$$

□

Proof of Proposition 1.4

$$b_w^* > b_m^* \qquad \text{iff} \qquad \mu(\mathbf{z}) > \tfrac{1}{2}\,.$$

□

Proof of Proposition 1.5

We use (1.13) to solve (1.15) for c_{m1}:

$$\begin{aligned} c_{m1} &= w_{m1}(h_m + b_m) + w_{w1}(h_w + b_w) - c_{w1} - b_p w_p \\ &= w_{m1}(T_1 - l_{m1}) + w_{w1}(T_1 - l_{w1}) - c_{w1} - b_p w_p\,. \end{aligned}$$

We use (1.14) to solve (1.18) for c_m2:

$$\begin{aligned} c_{m2} &= (T_1 - b_m + h_{m0}) w_{m1}(T_2 - l_{m2}) \\ &= (b_w + b_p + h_{m0}) w_{m1}(T_2 - l_{m2}) \end{aligned}$$

Utility of the individual spouses can now be written as

$$\begin{aligned} U'_m &= \log(w_{m1}(h_m + b_m) + w_{w1}(h_w + b_w) - c_{w1} - b_p w_p) \\ &\quad + \log((b_m + b_p + h_{m0}) w_{i1}(T_2 - l_{i2})) + \log(l_{m1}) + \log(l_{m2}) \\ U'_w &= \log(c_{w1}) + \log(c_{w2}) + \log(l_{w1}) + \log(l_{w2}) \end{aligned}$$

The function to be maximized is

$$\mathbb{L}'(b_w, c_{w1}, b_p, l_{w1}, l_{m1}, l_{w2}, l_{m2}) = \mu(\mathbf{z})\, U_m + (1 - \mu(\mathbf{z}))\, U_w$$

The partial derivatives of $\mathbb{L}'$ with respect to the seven endogenous variables is a linear equation system with the solution indicated in the proposition statement. □

1.B Tables

Table 1.1: Composition of Households that Use Parental Benefit

Case	Frequency	Fraction
Only the mother made use of the parental benefit	362,368	86.7%
Only the father made use of the parental benefit	19,526	4.7%
Both mother and father made use of the parental benefit	35,938	8.6%
Total	417,832	100.0%

Source: Authors' calculations from the Parental Benefit Statistic 2007.

Table 1.2: Duration of Parental Benefit Use by Gender

	Women		**Men**	
Duration in months	**Frequency**	**Fraction**	**Frequency**	**Fraction**
1	133	0.03%	886	1.6%
2	1,337	0.34%	34,323	61.9%
3	506	0.13%	1,578	2.8%
4	655	0.16%	1,250	2.3%
5	774	0.19%	944	1.7%
6	1,419	0.36%	1,513	2.7%
7	1,659	0.42%	1,348	2.4%
8	1,904	0.48%	949	1.7%
9	2,341	0.59%	833	1.5%
10	5,426	1.36%	1,284	2.3%
11	5,473	1.37%	1,751	3.2%
12	357,335	89.71%	8,501	15.3%
13*	7,051	1.77%	205	0.4%
14*	12,293	3.09%	99	0.2%
Total	398,306	100.0%	55,464	100.0%

Source: Authors' calculations from the Parental Benefit Statistic 2007. *Only single parents eligible.

Table 1.3: Average Benefit Duration among Leave Takers by Monthly Net Income and Gender

		Women			**Men**	
Income	**Mean**	**Std.Err.**	**Obs.**	**Mean**	**Std.Err.**	**Obs.**
300 or less	11.47	0.05	932	6.49	0.39	146
301 - 1,000	11.13	0.06	849	4.71	0.36	120
1,001 - 1,500	10.85	0.06	736	3.85	0.30	143
1,501 - 2,000	10.75	0.10	379	3.49	0.23	169
2,001 - 2,699	10.50	0.16	220	3.69	0.25	158
2700 or more	9.67	0.30	110	3.13	0.28	84
Total	11.03	0.03	3,226	4.27	0.13	820

Source: Authors' calculations from the RWI survey. Only leave takers (benefit duration $\geq$1 month).

Table 1.4: Summary Statistics

RWI Survey of Children Born in January till April 2007				
Variable	**Description**	**Mean**	**Std.Dev.**	**Obs.**
Number of benefit months: Mother	parental benefit duration in	10.15	3.45	4,177
Number of benefit months: Father	months (range: 0-12)	1.03	2.63	4,177
Household benefit duration	(range: 0-14)	11.18	2.98	4,177
No benefit use: Mother	dummy (d) =1 if the num-	0.08	0.27	4,177
No benefit use: Father	ber of benefit months = 0	0.76	0.43	4,177
Professional childcare	d=1 if used	0.36	0.48	4,151
Mother's income	(range: 0.08-6.0)	0.98	0.81	3,536
Father's income	(range: 0-6.0)	1.72	1.11	3,228
Household income	(range: 0.3-12)	2.78	1.44	3,130
Net monthly income in tEUR, means from categories				
= EUR 225 for below EUR 300 income category; = EUR 6,000 for above EUR 5,000 category				
Age difference	(range: -25 - +35)	3.00	4.85	4,131
(Father's) Relative income	(range: 0-59)	3.10	3.85	3,130
Mother in public sector	d=1 if working in	0.06	0.25	4,017
Father in public sector	public sector	0.07	0.24	3,523
Mother in private sector	d=1 if working in	0.53	0.50	4,017
Father in private sector	private sector	0.71	0.45	3,523
Mother is self-employed	d=1 if self-employed	0.04	0.20	4,017
Father is self-employed		0.11	0.31	3,523
Mother secondary school	d=1 if highest education	0.46	0.50	4,177
Father secondary school	level is secondary school	0.47	0.50	4,177
Mother high school	d=1 if highest education	0.24	0.43	4,177
Father high school	level is high school	0.18	0.39	4,177
Mother college/university	d=1 if highest education	0.26	0.44	4,177
Father college/university	level is college/university	0.28	0.45	4,177
Age of the oldest child	(range: 0-24)	2.44	3.83	4,149
Children	number (range: 1-11)	1.75	0.95	4,177
Twins	d=1 if multiple births	0.02	0.14	4,177
Mother is foreign	d=1 if not German	0.11	0.31	4,142
East	d=1 if living in the East	0.09	0.28	4,078
Big city	d=1 if $\geq$ 100T inhabitants	0.27	0.45	3,868
Parental Benefit Statistic 2007 (Couples)				
Number of benefit months: Mother	parental benefit duration in	11.15	3.09	35,938
Number of benefit months: Father	months (range: 1-12)	2.69	2.05	35,938
Household leave duration	(range: 2-14)	13.83	0.72	35,938
Only leave takers considered, i.e. persons who receive benefit for at least one month.				
Mother's income	(range: 0.3-2.7)	1.18	0.75	34,936
Father's income	(range: 0.3-2.7)	1.43	0.82	28,481
In tEUR, calculated from parental benefit amount, left-censored at 0.3, right-censored at 2.7				
Mother's income = 300	d=1 if income = EUR 300	0.23	0.43	34,936
Father's income = 300		0.22	0.41	29,168
Mother's income = 2,700	d=1 if income = EUR 2,700	0.05	0.22	34,936
Father's income = 2,700		0.12	0.32	29,168

Note: Unweighted data.

Table 1.5: Tests of Collective Rationality in Parental Leave Sharing

Leave duration of the	**Mother**		**Father**	
Estimation Method	Logit QMLE	OLS	Logit QMLE	OLS
Father's relative income	0.0063*	0.0047*	-0.0046*	-0.0047*
	(0.0015)	(0.0010)	(0.0012)	(0.0010)
Age difference	0.0028*	0.0032*	-0.0019*	-0.0032*
	(0.0011)	(0.0012)	(0.0008)	(0.0012)
Household income (in tEUR)	-0.0012	0.0015	0.0014	-0.0015
	(0.0036)	(0.0042)	(0.0023)	(0.0042)
Total household leave duration	0.0378*	0.0596*	0.0303*	0.0237*
	(0.0011)	(0.0019)	(0.0016)	(0.0019)
SER a)	0.72	0.20	1.34	0.20
R^2	0.44	0.37	0.24	0.13
Testing joint significance				
of sector dummies b)	31.25	5.27	29.13	5.27
p value	[0.00]*	[0.00]*	[0.00]*	[0.00]*
of education dummies b)	5.19	1.42	6.56	1.42
p value	[0.52]	[0.20]	[0.36]	[0.20]
Distribution factor tests (based on logit QMLE estimations)				
distribution factor ratio = 0 c)	4.85	4.91	4.24	4.91
p value	[0.03]*	[0.03]*	[0.04]*	[0.03]*
95% CI for difference in ratios d)	[-0.21, 0.23]			

Regression results from the RWI survey with robust standard errors in parentheses. Sample size is 2,408. The dependent variables are the number of parental benefit months divided by 12. For logit QMLE marginal effects with all variables at means are shown. Control variables for parents in public sector, self-employed, not working (reference group is private sector), parents' education, number of children in the household, twins, foreign mother, parents living in East Germany, and living in a big city are included.

a: Standard error of the regression; for QMLE the SER is defined in terms of weighted residuals.
b: Wald statistic from F distribution (OLS) and chi-square distribution (QMLE).
c: Nonlinear Wald test on significance of the ratio of distribution factor coefficients.
d: Bootstrapped confidence interval for the difference between the ratios of distribution factor coefficients across models.
*: Significantly different from zero on the 5% level (two-sided test).

Table 1.6: Income Effects

Leave duration of the	**Mother**		**Father**	
Estimation Method	Logit QMLE		Tobit	
Log(father's income)	0.0240*	-0.0138*	0.8029*	-1.5015*
	(0.0050)	(0.0036)	(0.1841)	(0.2427)
Log(mother's income)	-0.0386*	0.0204*	-1.4137*	1.6227*
	(0.0084)	(0.0054)	(0.2797)	(0.3184)
Age difference	0.0024*	-0.0018*	0.0942*	-0.1340*
	(0.0011)	(0.0008)	(0.0355)	(0.0538)
Total household leave duration	0.0376*	0.0302*	1.5502*	1.7100*
	(0.0011)	(0.0016)	(0.0697)	(0.1953)
SER a)	0.73	1.18		
R^2 / Pseudo R^2	0.45	0.25	0.14	0.11
Proportionality test b)	2.00	1.10	3.15	0.09
p value	[0.16]	[0.29]	[0.08]	[0.76]
Joint proportionality test c)	$\chi^2(2) = 2.77$		$\chi^2(2) = 8.17$	
p value	[0.73]		[0.31]	

Regression results from the RWI survey with robust standard errors in parentheses. Sample size is 2,361. The dependent variables are the number of parental benefit months divided by 12. For logit QMLE marginal effects with all variables at means are shown. Control variables for parents in public sector, self-employed, not working (reference group is private sector), parents' education, number of children in the household, twins, foreign mother, parents living in East Germany, and living in a big city are included.

a: Standard error of the regression; for QMLE the SER is defined in terms of weighted residuals.

b: Testing the hypothesis: log(mother's income) + log(father's income) = 0. μ is assumed to be increasing in father's income and decreasing in mother's income.

c: Test log(mother's income) + log(father's income) = 0 jointly across models [bootstrapped p value].

d: Tobit estimations with a lower limit at 0 and an upper limit at 12 parental benefit months.

*: Significantly different from zero on the 5% level (two-sided test).

Table 1.7: z-Conditional Demands

Leave duration of the	**Mother**		**Father**	
Estimation Method	Logit QMLE		Logit QMLE	
Sample size	632 Obs.		841 Obs.	
Father's relative income		0.0009		-0.0052
		(0.0040)		(0.0027)
Age difference	0.0020		-0.0006	
	(0.0021)		(0.0013)	
Household income (in tEUR)	-0.0079	-0.0075	-0.0128*	-0.0125*
	(0.0063)	(0.0064)	(0.0055)	(0.0055)
Partner's leave duration	-0.1503*	-0.1476*	-0.1118*	-0.1138*
	(0.0396)	(0.0395)	(0.0203)	(0.0203)
Partner's leave duration measure [a)]	0.2591*	0.2529*	0.1742*	0.1801*
	(0.0969)	(0.0967)	(0.0460)	(0.0459)
SER [b)]	0.52	0.52	0.52	0.52
R^2	0.51	0.51	0.57	0.57

Regression results from the RWI survey with robust standard errors in parentheses. The dependent variables are the number of parental benefit months divided by 12. For logit QMLE marginal effects with all variables at means are shown. Controls for parents' in public sector, self-employed, not working (reference group is private sector), parents' education, number of children in the household, twins, foreign mother, parents living in East Germany, and living in a big city are included.

a: log[(partner's leave duration/12) / (1 - (partner's leave duration/12))].
Defined for leave durations > 0 and < 12.

b: Standard error of the regression defined in terms of weighted residuals.

*: Significantly different from zero on the 5% level (two-sided test).

Table 1.8: First Birth Restricted Sample and Tobit Estimations

Leave duration of the	**Mother**		**Father**	
Estimation Method	Logit QMLE		Tobit estimations c)	
Sample size	First births (1,367 Obs.)		Full sample (2,408 Obs.)	
Father's relative income	0.0080*	-0.0060*	0.1952*	-0.3666*
	(0.0035)	(0.0024)	(0.00503)	(0.0767)
Age difference	0.0027*	-0.0025*	0.1077*	-0.1617*
	(0.0013)	(0.0011)	(0.0355)	(0.00543)
Household income (in tEUR)	-0.0060	0.0048	-0.0734	-0.2092
	(0.0047)	(0.0035)	(0.1193)	(0.1584)
Total household leave duration	0.0383*	0.0316*	1.5686*	1.7563*
	(0.0014)	(0.0021)	(0.0703)	(0.2014)
R^2 / Pseudo R^2	0.43	0.26	0.13	0.11
Distribution factor tests (based on logit QMLE estimations)				
distribution factor ratio = 0 a)	2.05	2.42	5.56	5.95
p value	[0.15]	[0.12]	[0.02]*	[0.01]*
95% CI for difference in ratios b)	[-0.66, 0.32]		[-0.19, 0.53]	

Regression results from the RWI survey with robust standard errors in parentheses. The dependent variables are the number of parental benefit months. For logit QMLE leave durations are divided by 12 (not for Tobit estimations). Marginal effects with all variables at means are presented. Controls for parents' in public sector, self-employed, not working (reference group is private sector), parents' education, number of children in household, twins, foreign mother, parents living in East Germany, and living in a big city are included.

a: Nonlinear Wald test on significance of the ratio of distribution factor coefficients.
b: Bootstrapped confidence interval for the difference between ratios of distribution factor coefficients.
c: Tobit estimations with a lower limit at 0 and an upper limit at 12 parental benefit months.
*: Significantly different from zero on the 5% level (two-sided test).

Table 1.9: Professional Childcare Use Estimations

	Professional childcare use	
Estimation Method	Logit QMLE	OLS
Father's relative income	-0.0022	-0.0026
	(0.0032)	(0.0029)
Age difference	0.0037	0.0034
	(0.0023)	(0.0021)
Household income (in tEUR)	0.0204*	0.0210*
	(0.0092)	(0.0089)
Total household leave duration	-0.0111*	-0.0104*
	(0.0041)	(0.0039)
SER [a)]	1.00	0.46
R^2	0.09	0.09
Testing joint significance		
of sector dummies [b)]	32.45	5.51
p value	[0.00]*	[0.00]*
of education dummies [b)]	39.50	6.73
p value	[0.00]*	[0.00]*
Distribution factor tests (based on logit QMLE estimations)		
distribution factor ratio = 0 [c)]	0.44	0.64
p value	[0.51]	[0.42]

Regression results from the RWI survey with robust standard errors in parentheses. Sample size is 2,408. The dependent variable is a dummy equal to 1 if professional childcare is used. For logit QMLE marginal effects with all variables at means are shown. Control variables for parents in public sector, self-employed, not working (reference group is private sector), parents' education, number of children in the household, twins, foreign mother, living in East Germany, and living in a big city are included.

a: Standard error of the regression; for QMLE the SER is defined in terms of weighted residuals.

b: Wald statistic from F distribution (OLS) and chi-square distribution (QMLE).

c: Nonlinear Wald test on significance of the ratio of distribution factor coefficients.

*: Significantly different from zero on the 5% level (two-sided test).

Chapter 2

The Non-Monetary Side of the Global Disinflation

2.1 Introduction

The fact that inflation has fallen everywhere - even in countries with weak institutions, unstable political systems, thinly staffed central banks, etc. - invites us to open our minds to the possibility that other factors have also been significant. Kenneth S. Rogoff, (2003)

During the early 1990s the world wide patterns of openness to trade and inflation have changed dramatically. All regions of the world increased openness to trade strongly bringing the world average from 39% in 1990 to 54% in 2005. In a parallel development, inflation saw an even more dramatic change, coming down from a world average of 26% in 1990 to only 3.8% in 2005. As Rogoff (2003) points out, a number of possible approaches can explain this fall in inflation, among them improved monetary policy, technological development and globalization. We argue in this chapter that globalization in the form of increasing openness to trade is a driving force of falling inflation.

Transport cost have fallen strongly since 1990 as illustrated by World Bank (2009). This table shows a fall in unweighted average tariff rates from 23.9% in 1990 to 8.6% in 2009.[1] The subsequent reallocation of production has an obvious effect on openness, defined as imports plus exports over GDP. Since consumers have a taste for variety and firms diversify their

[1] All tariff rates are based on unweighted averages for all goods in ad valorem rates, or applied rates, or MFN rates whichever data is available in a longer period.

inputs (see Marin (2006)), more products from abroad are imported. And as falling transport cost allows more home producers to export, imports and exports increase.

As openness benefits consumers, it also increases competition. The empirical and theoretical literature (Pavcnik (2002), Bernard et al. (2003), Syverson (2004), Bernard et al. (2006)) shows that this increase in competition forces the least productive firms out of the market and production is reallocated towards more productive firms. Industries, even if narrowly defined show a large variety of productivity. When competition increases, the least productive firms can no longer make positive profits and have to quit the market.

Inflation is affected via productivity. As more trade increases competition, some firms that could operate profitably in a more closed market, are no longer able to do so. They have to stop production and leave the market. As a consequence, average productivity in the economy increases. This in turn leads to lower average prices, which reduces inflation. In addition, more open countries consume more goods from abroad, which reduces average consumption prices since only the most productive foreign firms export.

Productivity and its reaction to transport cost play a vital role in this concept. So we use the framework of Melitz (2003), where productivity is endogenously determined. We modify it to analyze the interaction of productivity with openness and inflation.

Romer (1993) finds that openness and inflation are negatively related. This is based on Rogoff (1985) which finds that a surprise monetary expansion causes the real exchange rate to depreciate and that the depreciation is larger in more open economies. The same amount of inflation will thus require a larger monetary expansion in a more open economy. The Central Bank of a more open economy thus has a lower incentive to create a surprise inflation. Rogoff (2003) also finds the incentive structure for the central bank to provide the link between globalization and disinflation. His argument however is that more competition from abroad makes prices and wages more flexible.

Chen et al. (2004) investigate the effect of increased trade on prices, productivity and markups in the EU. Inter alia, they find that for the period 1988 to 2000 increased openness in the EU reduced inflation. Similarly, Chen et al. (2009) estimates a version of Melitz and Ottaviano (2008) and obtain directly estimable equations. So these papers find the same qualitative results, but focus on one world region, the European Union, for which they are able to use disaggregated data on the manufacturing sectors.

The effect of openness on inflation has been investigated in the framework of the New

Keynesian Phillips Curve (NKPC) by Woodford (2007), Sbordone (2007), Milani (2010), Calza (2009) and Barthelemy and Cleaud (2011) for example. This literature aims at finding a permanent effect of openness on inflation through a structural change in the economy, notably the Phillips Curve. Finally, there are papers such as Auer and Fischer (2010) which quantify the effect of low-price imports on the inflation of individual countries.

On the theoretical side our contribution is the modification of the Melitz model with monetary variables. In addition we decompose productivity into two driving factors, openness-induced and "normal" productivity growth. Using the empirical plausibility for the Pareto distribution in firm productivity levels provided by Luttmer (2007) we use this distribution to get specific predictions from the model concerning the effect of globalization. Using a cash-in-advance constraint we obtain an *extended* quantity equation which identifies the effect of openness on inflation via productivity. This provides an alternative perspective to the NKPC literature on the nexus of globalization and inflation. Unlike the NKPC literature, the effect described here is transitory and affects inflation as long as openness keeps increasing. This has necessarily different policy implications.

While the empirical literature explores the monetary side as well as productivity, markups and import prices on the real side as causes of disinflation, none of the studies above attempts to answer to Rogoff's challenge to explain disinflation *worldwide*, including countries with "thinly staffed central banks". This chapter links productivity and a precise measure of globalization to inflation, using a macroeconomic dataset of 123 countries from all world regions. It attempts to shed light on the concentration of the cross-country distribution of inflation rates around 3 percent, in other words on the global dimension of global disinflation.

We will illustrate our thesis of a fundamental and important link between trade globalization and global disinflation in three steps. Section 2 will give an intuitive approach, illustrating the astounding comovement between openness and inflation and its context graphically as well as in descriptive statistics. Section 3 provides the theory which informes us on why we should expect a strong link between openness and inflation. Section 4 explores causility with a detailed econometric analysis. Section 5 concludes.

2.2 Descriptive Evidence

Economists are largely familiar with the general phenomenon of globalization and disinflation. In this section we pin down these phenomena in time and describe a number of details which are much less well known. First, all world regions are affected, so the development is not driven only by a few economic "heavyweights". Second, the change occurs continuously over the entire period of 1990 to 2010, there is no jump in levels. Third, the year 1990 marks a true turning point for the growth rate of both variables, suggesting a strong interaction. The econometric analysis follows in section 2.4.

One of the most important manifestations of globalization is trade openness. Since the early 1990s, the trend towards more trade has been rapid. As Table 2.1 illustrates, openness as measured as (import plus export)/GDP has increased by almost 16 percentage points in the 15 years to 2005, reaching 54%. This trend has been truly global as it occurred in the developed and developing world, climbing steeply in every single continent.

Table 2.1: Openness, measured as (Import + Export)/GDP

Year	World	Developed	Developing	Asia	Africa	Latin America
1980	38.52	36.00	32.70	33.64	62.65	27.60
1985	37.39	36.32	31.38	33.14	53.76	27.62
1990	38.30	34.90	39.41	47.22	51.76	31.52
1995	42.04	37.35	47.29	58.67	57.61	37.33
2000	49.10	44.87	52.97	66.85	63.20	41.28
2005	54.04	46.41	62.85	86.86	66.64	46.13

Source: World Development Indicators, authors' calculation

As the sum of imports and exports has climbed quickly, the distribution of imports and exports has diverged equally quickly. Open borders have allowed countries to have unbalanced current accounts, a possibility that was used increasingly. Figure 2.1 shows the cross country distribution of current accounts around the world. In 1980 we still find a sharp peak of current accounts around zero. In the following 10 years, not much changed, so that roughly the same pattern can be found in 1990. But as globalization takes hold during the 1990s, a strong trend towards a more dispersed distribution emerges. The peak declines significantly and more mass moves to the tails: The excess supply of goods can flow freely and creates surpluses on the side of exporters (such as China) and deficits on the side of importers (such as the United States). This ultimately exerts a downward pressure on inflation, see the theoretical part. The trend continues well into the 2000s, as ever more mass wanders to the tails.

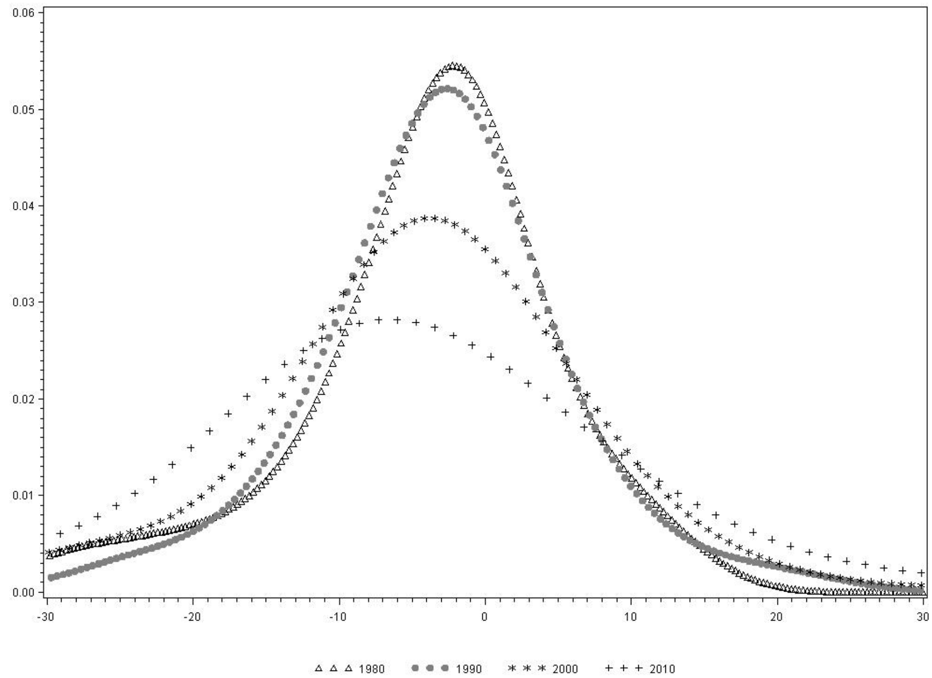

Figure 2.1: World Cross Country Distribution of Current Accounts.
Kernel density plots of the CA balance of countries without missing data.
Source: World Economic Outlook (IMF) and authors' calculation.

A mirror image of this trend is found for inflation, see Table 2.2. World wide, inflation has fallen from more than 26% in 1990 to a mere 3.8% in 2005, with most of this drop having occured in the 1990s.[2] In developed countries it was already low in 1990 and has fallen reliably below 3% since 1995. Impressive advances have been made in developing countries, where inflation has come down from very high numbers to single-digit values.

[2]For calculating the average, inflation in each country is weighted by the country's GDP.

Table 2.2: Inflation (% per year)

Year	World	Developed	Developing	Asia	Africa	Latin America
1980	17.28	12.9	28.30	11.95	16.80	53.76
1985	14.87	5.41	40.92	8.48	12.78	134.1
1990	26.10	5.16	74.27	6.13	13.81	474.1*
1995	14.61	2.63	39.56	12.62	36.25	41.34
2000	4.55	2.24	8.61	1.93	11.78	7.84
2005	3.76	2.22	5.86	3.80	7.11	6.19

Sources: World Economic Outlook (IMF), authors' calculation.

** This figure excludes Argentina and Brazil. Including these two countries gives an even higher value: 1805.24*

The disappearance of hyperinflations, especially in Latin America, must of course be credited to improved monetary policy. Table 2.2 therefore reflects two effects on a descriptive basis: The disappearance of very high values of inflation (especially in Latin America after 1990) on the one hand and the universality of the trend to lower inflation on the other hand. These two effects are disentangled theoretically in the next chapter: Inflation can be written as the difference between the growth rate of the money supply and the growth rate of productivity, see equation (2.46).

This trend towards lower inflation has given rise to an opposite movement to that found in Figure 2.1 for openness: The distribution of inflation levels around the world has become increasingly concentrated, see Figure 2.2. In 1980 the peak of the distribution is well above 10%, with values of more than 20% being no rarity. By 1990 the distribution has shifted to the left with the peak now around 5%. As globalization takes hold the distribution becomes strongly concentrated around a peak below 3%.

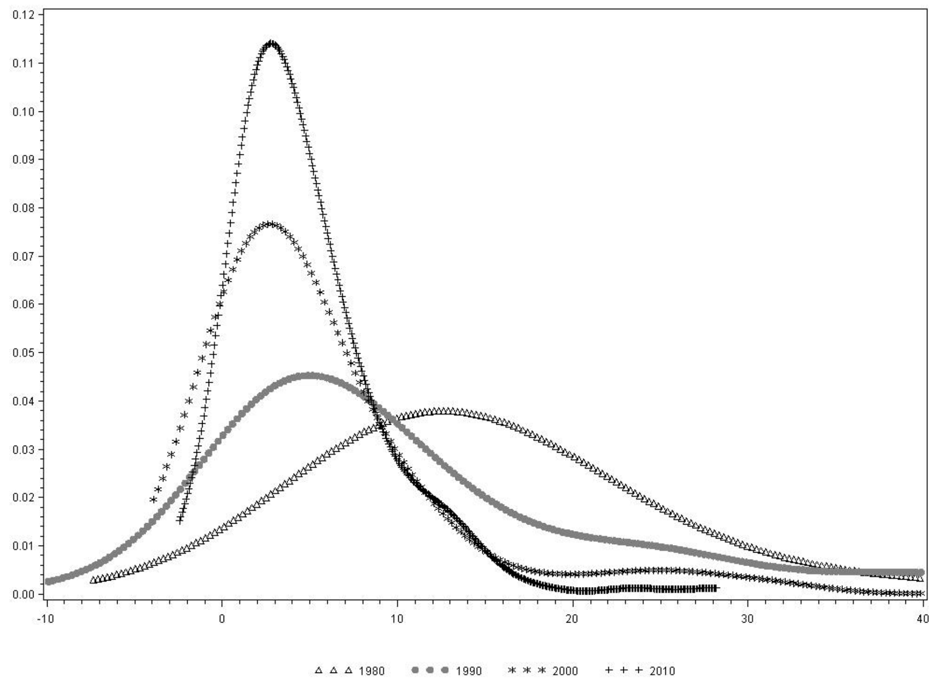

Figure 2.2: World Cross Country Distribution of Inflation.
Kernel density plots of inflation of countries without missing data.
Source: World Economic Outlook (IMF) and authors' calculation

2.3 The Model

As we laid out in the empirical evidence, openness has an important effect on declining inflation. But what caused openness to rise in the first place? It seems striking that measures of openness show a sudden increase in the early 1990s. One effect might have been on the side of technology. It is for example much easier and cheaper to transmit software across large distances than manufactured goods, so that the technological revolution of the 1990s facilitated trade. But an even more important development took place on the political side. The balance of payments crisis brought many countries to look for assistance from the Bretton Wood Institutions. These advised and encouraged policies of the *Washington Consensus*, including more openness. This led countries around the world to leave protectionist policies and lower tariffs. India, as one example, reduced tariff rates from 133 in 1990 to 48 in 1997, as reported in Aghion et al. (2008).

This pattern can best be analysed in the framework of Melitz (2003). We modify it in a way that clearly highlights how lower transport cost increase openness and how greater openness affects inflation via foreign prices and productivity at home.

After making an investment in sunk entry cost new firms draw an initial productivity parameter φ from a common distribution. In the model of Melitz, this distribution is not specified. Results are thus kept as general as possible, but it also strongly limits the ability of the model to make unambiguous predictions. In order to obtain clear statements on the variables of interest for this chapter such as average productivity and prices, we replace the general distribution by the Pareto distribution as in Melitz and Ottaviano (2008), Ghironi and Melitz (2005) and Helpman et al. (2004). Luttmer (2007) provides empirical evidence that the Pareto distribution is a good approximation for firm sizes and thus implicitly for productivity levels.

Using the Pareto distribution, we can analyze the direction of change of the endogenous variables when parameters such as the level of fixed entry costs to the domestic and foreign market or transport cost change. On the side of parameters we concentrate on changes in transport cost. On the side of the variables, we consider some of those which are already defined in the Melitz paper such as average productivity and price levels. In addition we define a measure for openness.

In addition, we introduce money through a cash-in-advance constraint in order to explicitly analyse the effect of changes in relative prices on the price level. This will provide the link between the immediate real effects of trade and the monetary side.

In this section we will briefly present the model, using the Pareto distribution.

2.3.1 Setup of the Model

Demand

Utility is given as a CES function. Since each variety is uniquely characterized by the productivity level φ of the producing firm it can be written as

$$U = \left[\frac{1}{1 - G(\varphi^*)} \int_{\varphi^*}^{\infty} q(\varphi)^{\rho} N g(\varphi) d\varphi \right]^{\frac{1}{\rho}} , \tag{2.1}$$

where the elasticity of substitution is given by $\sigma = \frac{1}{1-\rho} > 1$. After paying an initial entry cost, firms draw a productivity distributed by the Pareto distribution

$$g(\varphi) = k\frac{(\varphi_m(t))^k}{\varphi^{k+1}} \tag{2.2}$$

where $\varphi_m(t)$ is the minimum of productivity draws. But only firms above an endogenous equilibrium cut-off value φ^* are able to stay in the market. (φ^*, ∞) is the interval of producing firms and N indicates the mass of firms and goods. We assume $k > \sigma - 1$ as in Ghironi and Melitz (2005) to assure that the variance of firm size is finite.

The minimum of productivity draws $\varphi_m(t)$ is defined as a function of time. This reflects that the distribution of productivity in an economy changes over time even in the absence of changes in trade volumes. Reflecting the historic trend of increasing productivity, there should be an upward trend in $\varphi_m(t)$. This implies a slow shift of the productivity distribution towards higher productivity. It would be possible at this point to introduce positive and negative productivity shocks, but since the focus of this chapter is on long-term trends, we model technological development as a deterministic and exogenous process improving productivity at a constant rate a:

$$\varphi_m(t) = \varphi_{m0}\, e^{at}\ . \tag{2.3}$$

The set of varieties consumed can be written as an aggregate good $Q = U$ and the aggregate price is given by

$$P = \left[\frac{1}{1-G(\varphi^*)}\int_{\varphi^*}^{\infty} p(\varphi)^{1-\sigma} N g(\varphi) d\varphi\right]^{\frac{1}{1-\sigma}}\ . \tag{2.4}$$

Demand for each individual good will be given by

$$q(\varphi) = Q\left[\frac{p(\varphi)}{P}\right]^{-\sigma} \tag{2.5}$$

and revenue generated by one variety is

$$r(\varphi) = R\left[\frac{p(\varphi)}{P}\right]^{1-\sigma} \tag{2.6}$$

where $R = PQ$.

Production

Firms produce with a constant marginal cost, using only labor as an input. In order to set up the firm and enter the market, firms have to pay a sunk investment cost f_e. The effect of this will be discussed below for the free entry condition. In addition, firms pay a fixed overhead cost f every period. Fixed overhead costs for exporting are $f_x > f$. Productivity is given by φ and wages by w. Labor used can be written as $l = f + \frac{q}{\varphi}$. The investment cost plays no role once the firm is in the market because it is a sunk cost. Investment cost f_e and overhead cost f and f_x are denoted in terms of labor. So the actual price that the firm has to pay is wf_e, wf and wf_x.

Domestic firms therefore optimally set a price of

$$p_d(\varphi) = \frac{w}{\rho\varphi} \ . \tag{2.7}$$

For each exported good, firms have to pay a transport cost τ, which increases their marginal cost. The price setting for export goods is thus

$$p_x(\varphi) = \frac{\tau w}{\rho\varphi} \ . \tag{2.8}$$

Inserting (2.7) into (2.6), we can express revenues as

$$r_d(\varphi) = R(P\rho\varphi)^{\sigma-1} \ . \tag{2.9}$$

Putting (2.8) into (2.6) yields the foreign revenues

$$r_x(\varphi) = R(P\rho\varphi)^{\sigma-1}\tau^{1-\sigma} \ . \tag{2.10}$$

Profits in the home and export market can thus be written as

$$\pi_d(\varphi) = r_d(\varphi) - l(\varphi) = \frac{r_d(\varphi)}{\sigma} - wf \tag{2.11}$$

$$\pi_x(\varphi) = r_x(\varphi) - l(\varphi) = \frac{r_x(\varphi)}{\sigma} - wf_x \ . \tag{2.12}$$

Revenue

From (2.9) domestic revenue can be written as

$$r_d(\varphi) = \left(\frac{\varphi}{\varphi^*}\right)^{\sigma-1} r_d(\varphi^*) \ . \tag{2.13}$$

Recall that φ^* is the marginal productivity at which a firm makes zero profits, $\pi_d(\varphi^*) = 0$. Using (2.11), revenues are thus $r_d(\varphi^*) = \sigma w f$, so that we can write

$$r_d(\varphi) = \left(\frac{\varphi}{\varphi^*}\right)^{\sigma-1} \sigma w f \ . \tag{2.14}$$

Using (2.10) we can write

$$r_x(\varphi) = \tau^{1-\sigma} r_d(\varphi) = \tau^{1-\sigma} \left(\frac{\varphi}{\varphi^*}\right)^{\sigma-1} \sigma w f \tag{2.15}$$

and

$$\frac{r_x(\varphi_x^*)}{r_d(\varphi^*)} = \tau^{1-\sigma} \left(\frac{\varphi_x^*}{\varphi^*}\right)^{\sigma-1} \ , \tag{2.16}$$

where φ_x^* is the cut-off level for exports at which firms make zero profits from exporting.

As above for domestic revenues we have $r_x(\varphi_x^*) = \sigma w f_x$ for export revenues, so that

$$\frac{r_x(\varphi_x^*)}{r_d(\varphi^*)} = \frac{f_x}{f} \ . \tag{2.17}$$

Productivity

Joining (2.16) and (2.17) we obtain

$$\varphi_x^* = \varphi^* \tau f^* \ . \tag{2.18}$$

where $f^* = \left[\frac{f_x}{f}\right]^{\frac{1}{\sigma-1}}$.

The weighted average of productivity is given by (see appendix for details)

$$\begin{aligned}
\tilde{\varphi}(\varphi^*) &= \left[\frac{1}{1-G(\varphi^*)}\int_{\varphi^*}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi\right]^{\frac{1}{\sigma-1}} \\
&= \left[\frac{\varphi^{*k}}{\varphi_m^k}\int_{\varphi^*}^{\infty}\varphi^{\sigma-1}k\frac{\varphi_m^k}{\varphi^{k+1}}d\varphi\right]^{\frac{1}{\sigma-1}} \qquad (2.19) \\
&= k^*\varphi^* \,, \qquad (2.20)
\end{aligned}$$

where $k^* = \left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}}$.

Average productivity abroad is given as

$$\tilde{\varphi}(\varphi_x^*) = k^* f^* \tau \varphi^* \,. \qquad (2.21)$$

We define the share of exporters among domestic firms (which is also the probability of becoming an exporter for a new firm) as

$$p_x = \frac{1-G(\varphi_x^*)}{1-G(\varphi^*)} \,. \qquad (2.22)$$

For the Pareto distribution this is (see appendix for details).

$$p_x = \frac{1}{(\tau f^*)^k} \,. \qquad (2.23)$$

Average total productivity is defined by

$$\tilde{\varphi}_{tot} = \left(\frac{1}{N_{tot}}[N\tilde{\varphi}^{\sigma-1} + N_x(\tau^{-1}\tilde{\varphi}_x)^{\sigma-1}]\right)^{\frac{1}{\sigma-1}} \,, \qquad (2.24)$$

where $N_{tot} = N + N_x$ and $N_x = p_x N$.

In the case of the Pareto distribution, this simplifies to (see appendix for details)

$$\tilde{\varphi}_{tot} = k^*\varphi^*\left(\frac{\tau^k f^{*k} + f^{*\sigma-1}}{\tau^k f^{*k} + 1}\right)^{\frac{1}{\sigma-1}} \,. \qquad (2.25)$$

2.3.2 Equilibrium

It remains to determine average profits, noted $\bar{\pi}$ and the cutoff productivity level φ^*. Average profits are obtained as the sum of the differences between revenues and costs from export and domestic production. The resulting equation is termed zero cutoff profit (ZCP) condition by Melitz (2003). Using this, cutoff productivity is then obtained from the free entry (FE) condition which says that the net value of entry must be zero.

Average profits $\bar{\pi}$ are defined as

$$\bar{\pi} = \pi_d(\tilde{\varphi}) + p_x \pi_x(\tilde{\varphi}_x) \ . \tag{2.26}$$

Using (2.13) for $\tilde{\varphi}$ yields an equation for revenues

$$r_d(\tilde{\varphi}) = \left(\frac{\tilde{\varphi}}{\varphi^*}\right)^{\sigma-1} r_d(\varphi^*)$$

which can be inserted into the profit function (2.11)

$$\pi_d(\tilde{\varphi}) = \left(\frac{\tilde{\varphi}}{\varphi^*}\right)^{\sigma-1} \frac{r_d(\varphi^*)}{\sigma} - wf \ . \tag{2.27}$$

Inserting $r_d(\varphi^*) = \sigma w f$ yields

$$\bar{\pi}_d = \pi_d(\tilde{\varphi}) = wf \left[\left(\frac{\tilde{\varphi}(\varphi^*)}{\varphi^*}\right)^{\sigma-1} - 1\right] . \tag{2.28}$$

Export profits are derived analoguously as

$$\bar{\pi}_x = \pi_x(\tilde{\varphi}) = wf_x \left[\left(\frac{\tilde{\varphi}(\varphi_x^*)}{\varphi_x^*}\right)^{\sigma-1} - 1\right] . \tag{2.29}$$

Inserting (2.28) and (2.29) into (2.26) we get

$$\bar{\pi} = wf \cdot \left(\left[\frac{\tilde{\varphi}(\varphi^*)}{\varphi^*}\right]^{\sigma-1} - 1\right) + p_x w f_x \cdot \left(\left[\frac{\tilde{\varphi}(\varphi_x^*)}{\varphi_x^*}\right]^{\sigma-1} - 1\right)$$

This is the Zero Cutoff Profit condition. For the case of the Pareto distribution it can be expressed as (see appendix for details)

$$\bar{\pi} = \left(wf + \frac{1}{\tau^k} w f^{\frac{-k}{\sigma-1}} f_x^{1-\frac{-k}{\sigma-1}} \right) \frac{\sigma-1}{k-(\sigma-1)} . \tag{2.30}$$

In order to keep notation clear we have so far abstained from using a time index. This was possible since all calculations made so far used only variables of the same period. To calculate the net value of entry however, we must sum over all expected future profits, so that we must introduce explicit time indices at this point. Average profits in period t can be expressed as

$$\bar{\pi}_t = (1+\pi^w_{0,t}) w_0 \left(f + \frac{1}{\tau^k} f^{\frac{-k}{\sigma-1}} f_x^{1-\frac{-k}{\sigma-1}} \right) \frac{\sigma-1}{k-(\sigma-1)} \tag{2.31}$$

where $\pi^w_{0,t}$ denotes wage inflation between 0 and t.

Every period each firm faces a probability δ of a bad shock that forces it to exit. The value of a firm is thus given as

$$\bar{v} = \sum_{t=0}^{\infty} (1-\delta)^t \frac{1}{1+\pi^w_{0,t}} \bar{\pi}_t . \tag{2.32}$$

Firms weight each period by the probability of still being in the market at this point in the future and adjust for inflation. But since $\bar{\pi}_t$ can be written in a way that allows the inflation term to be factored out, the inflation terms cancel and the firm value can be written in real terms as

$$\bar{v} = \frac{1}{\delta} \bar{\pi}_0 . \tag{2.33}$$

The probability of drawing a productivity above the cutoff is denoted with p_{in}. In order to enter the market, firms pay a one-off sunk investment cost of wf_e. The net value of entry is

$$v_e = p_{in}\bar{v} - w_0 f_e = \frac{1-G(\varphi^*)}{\delta} \bar{\pi}_0 - w_0 f_e .$$

In equilibrium there is free entry so that the net value of entry must be zero. The free entry condition is thus

$$\begin{aligned} \bar{\pi}_0 &= \frac{\delta w_0 f_e}{1-G(\varphi^*)} \\ &= \frac{\delta w f_e \varphi^{*k}}{(\varphi_m(t))^k} . \end{aligned} \tag{2.34}$$

Combining FE and ZCP yields

$$\varphi^* = \left[\frac{(\varphi_m(t))^k}{\delta f_e} \left(f + \frac{1}{\tau^k} f^{\frac{-k}{\sigma-1}} f_x^{1-\frac{-k}{\sigma-1}} \right) \frac{\sigma - 1}{k - (\sigma - 1)} \right]^{\frac{1}{k}} . \tag{2.35}$$

Substituting this value into the various expressions above allows to express the variables of the model depending on parameters. The equilibrium mass of domestic, exporting and total firms are given by

$$N = \frac{L}{\sigma(\bar{\pi} + f + p_x f_x)} \tag{2.36}$$

$$N_x = \frac{p_x L}{\sigma(\bar{\pi} + f + p_x f_x)} \tag{2.37}$$

$$N_{tot} = N + p_x N \tag{2.38}$$

where L is aggregate labor.

2.3.3 The Price Level

Up to this point, the focus was on the real side of the economy. As can be expected, all productivity variables do not depend on wages and prices. But in order to link this model to inflation, a monetary side needs to be introduced. For this, we simply impose a cash-in-advance constraint which allows us to analyse inflation in a straightforward way.

The budget constraint is given on a period-by-period basis. Consumers earn wages w and supply labor L inelastically. Revenue R is spent on consumption goods and can be written as the product of average prices $p(\tilde{\varphi})$, the average quantity supplied by each firm $q(\tilde{\varphi})$ and the mass N of active firms:

$$wL = p(\tilde{\varphi})q(\tilde{\varphi})N . \tag{2.39}$$

We impose a cash-in-advance constraint meaning that consumers have to hold money M equal to the total amount of purchases. And since purchases equal revenue, we can write

$$\begin{aligned} M &= R \\ &= p(\tilde{\varphi})q(\tilde{\varphi})N \\ &= w\frac{1}{\rho\tilde{\varphi}}q(\tilde{\varphi})N . \end{aligned} \tag{2.40}$$

2.3.4 Results

Lower transport cost eliminates the least productive domestic firms and increases the weight of high-productivity foreign firms in the domestic productivity index. A decrease in transport cost leads to a new level of cost τ' with $\tau > \tau' > 1$.

Proposition 2.1 *Average productivity in a country increases as the transport cost decreases.*

$$\frac{\partial \tilde{\varphi_{tot}}}{\partial \tau} < 0\ . \tag{2.41}$$

For a given level of wages w average prices in the home country fall when transport costs fall:

$$\frac{\partial \tilde{p}}{\partial \tau} > 0\ .$$

Proof

In equation (2.25), average total productivity is given by

$$\tilde{\varphi}_{tot} = k^* \varphi^* \left(\frac{\tau^k f^{*k} + f^{*\sigma-1}}{\tau^k f^{*k} + 1} \right)^{\frac{1}{\sigma-1}}\ .$$

Denoting $F = \frac{\tau^k f^{*k} + f^{*\sigma-1}}{\tau^k f^{*k}+1}$, the derivation can be written as

$$\frac{\partial \tilde{\varphi}_{tot}}{\partial \tau} = k^* \left[\frac{\partial \varphi^*}{\partial \tau} F^{\frac{1}{\sigma-1}} + \varphi^* \frac{1}{\sigma-1} F^{\frac{2-\sigma}{\sigma-1}} \frac{\partial F}{\partial \tau} \right]\ . \tag{2.42}$$

We now have to determine the sign of each of these terms:

$$\begin{aligned}
\frac{\partial F}{\partial \tau} &= \frac{k\tau^{k-1} f^{*k}(\tau^k f^{*k}+1) - (\tau^k f^{*k} + f^{*\sigma-1}) k\tau^{k-1} f^{*k}}{(\tau^k f^{*k}+1)^2} \\
&= \frac{k\tau^{k-1} f^{*k} - f^{*\sigma-1} k\tau^{k-1} f^{*k}}{(\tau^k f^{*k}+1)^2} \\
&= \frac{k\tau^{k-1} f^{*k}(1 - f^{*\sigma-1})}{(\tau^k f^{*k}+1)^2} \\
&= \frac{k\tau^{k-1} f^{*k}(1 - \frac{f_x}{f})}{(\tau^k f^{*k}+1)^2} < 0
\end{aligned}$$

since $f < f_x \Leftrightarrow 1 < \frac{f_x}{f}$.

Taking derivatives from (2.35), we have $\frac{\partial \varphi^*}{\partial \tau} < 0$. This means that cutoff productivity increases, when transport cost fall.

Substituting $\frac{\partial F}{\partial \tau} < 0$ and $\frac{\partial \varphi^*}{\partial \tau} < 0$ into (2.42) we have

$$\frac{\partial \tilde{\varphi}_t}{\partial \tau} < 0 \ .$$

This completes the proof for the first statement. The second statement follows almost immediately. By the definition of $\tilde{\varphi}_{tot}$, the average price of firms is given by the price of the firm with average productivity

$$\tilde{p} = p(\tilde{\varphi}_{tot}) \ .$$

Using the equation for prices (2.7) and Proposition 2.1 we have

$$\frac{\partial p(\tilde{\varphi}_{tot})}{\partial \tau} = -\frac{w}{\rho \tilde{\varphi}_{tot}^2} \frac{\partial \tilde{\varphi}_{tot}}{\partial \tau} > 0 \ .$$

□

As the next step we show the theoretical link between transport cost and our measure of openness. Openness is defined as imports plus exports over GDP. But since countries are identical in this chapter, imports are actually equal to exports. We define R_x as the total revenues from export and R_d as total revenues from domestic sales. Openness is then given as

$$Openness = \frac{Imports + Exports}{GDP} = \frac{2 \cdot Exports}{GDP} = \frac{2 \cdot R_x}{R_d + R_x} \ , \qquad (2.43)$$

where

$$\begin{aligned} R_d &= \int_{\varphi^*}^{\infty} r_d(\varphi) N g(\varphi) d\varphi \\ R_x &= \int_{\varphi_x^*}^{\infty} r_x(\varphi) N_x g(\varphi) d\varphi \ . \end{aligned}$$

The integration limits are illustrated by the following list of production and export status:

Interval	**Production Status**	**Total Revenue**
$[\varphi_m, \varphi^*]$	no production	0
$[\varphi^*, \varphi_x^*]$	production for domestic market	$r_d(\varphi)$
$[\varphi_x^*, \infty]$	production for domestic market and export	$r_d(\varphi) + r_x(\varphi)$

Proposition 2.2 *Openness increases as the transport cost decreases.*

$$\frac{\partial Openness}{\partial \tau} < 0 \ . \tag{2.44}$$

Proof Taking derivatives of domestic revenue (2.14) with respect to transport cost, we have

$$\frac{\partial r_d(\varphi)}{\partial \tau} = \varphi^{\sigma-1}\sigma w f(1-\sigma)\frac{\partial \varphi^*}{\partial \tau} > 0 \ ,$$

since $\frac{\partial \varphi^*}{\partial \tau} < 0$ and $\sigma > 1$.

The mass N of firms is given in equation (2.36). An decrease in transport cost τ increases the probability of exporting p_x as given in (2.23), which in turn reduces the equilibrium number of domestic firms N.

In addition, the lower bound of integration for R_d, given by φ^*, increases because of decreasing transport cost. In all, we can conclude

$$\frac{\partial R_d}{\partial \tau} > 0 \ ,$$

meaning that total revenue from domestic sales falls as a consequence of lower transport cost.

Taking derivatives of export revenue (2.15) with respect to transport cost, we have

$$\frac{\partial r_x(\varphi)}{\partial \tau} = \varphi^{\sigma-1}\sigma w f(1-\sigma)(\tau\varphi^*)^{-\sigma}\left(\frac{\partial(\tau\varphi^*)}{\partial \tau}\right) < 0 \ .$$

To see this, note that using (2.35) we get

$$\tau\varphi^* = \left[\frac{\varphi_m^k}{\delta f_e}\left(\tau^k f + f^{\frac{-k}{\sigma-1}} f_x^{1-\frac{-k}{\sigma-1}}\right)\frac{\sigma-1}{k-(\sigma-1)}\right]^{\frac{1}{k}} \ ,$$

which depends positively on τ.

The effect of transport cost on the mass of exporters is given by the derivative of (2.37):

$$\frac{\partial N_x(\varphi)}{\partial \tau} = \frac{L\sigma\bar{\pi} + f}{(\sigma(\bar{\pi} + f + p_z + f_x))^2}\left(-\frac{k}{f^{*k}\tau^{k+1}}\right) < 0 \; .$$

Taking derivatives of the export cut-off level (2.18) with respect to transport cost, we have

$$\frac{\partial \varphi_x^*}{\partial \tau} = f^*\left(\frac{\partial(\tau\varphi^*)}{\partial \tau}\right) > 0$$

meaning that the lower bound of integration for R_x falls when transport costs fall. In all, we have

$$\frac{\partial R_x}{\partial \tau} < 0 \; .$$

Using the expression for openness from (2.43), this yields the result. □

Combining Propositions 2.1 and 2.2 shows the close connection between openness and productivity.

Proposition 2.3 *Every increase in openness implies ceteribus paribus an increase in productivity.*

Proof As Proposition 2.2 illustrates openness is strictly monotonely increasing in transport cost. Every level of openness is thus connected to a unique level of transport cost, the two variables are linked by a one-to-one relationship. Given Proposition 2.1, every increase in openness means that productivity must rise as well. □

The results so far treated the effect of changes in tranport cost on the economy. Next, we turn to the innovative process which increases productivity in a country over time even in the absence of globalization. The first observation is that the average productivity of firms *in the market* increases as the distribution of productivity *draws* moves to the right. This statement is non-trivial since the fraction of firms that is able to stay in the market is endogenously determined.

Proposition 2.4 *The average productivity of firms in the market increases over time*

$$\frac{\partial \tilde{\varphi_{tot}}}{\partial t} > 0 \; . \tag{2.45}$$

Proof From equation (2.25) we can see that average productivity of firms in the market increases linearly in the cut-off level of productivity φ^*. The cut-off level itself depends linearly on the minimum level of productivity draws $\varphi_m(t)$, see equation (2.35). The minimum level of productivity was assumed to grow at a constant rate over time, equation (2.3). □

In analogy to the case of transport cost, we can determine the effect of time via productivity on prices. Given assumption (2.3) quality-adjusted relative prices of goods become cheaper in terms of the wage over time.

Using equation (2.40) we can now summarize our results on the central role of productivity for inflation. The growth rate of a variable x is noted as g_x.

Proposition 2.5 *Inflation can be written as the difference in the growth rate of the money supply and total productivity*

$$\pi = g_M - g_{\tilde{\varphi_{tot}}} \tag{2.46}$$

whereas productivity depends on time as a result of innovation and on openness as a result of firm selection.

Proof From the budget constraint, we have $\frac{1}{\rho\varphi_{tot}}q(\tilde{\varphi})N = L$ which is constant. Using (2.40), this allows to write

$$g_M = g_w \ . \tag{2.47}$$

Inflation can now be written in this way:

$$\begin{aligned} \pi &= g_p \\ &= g_w - g_{\tilde{\varphi_{tot}}} \\ &= g_M - g_{\tilde{\varphi_{tot}}} \end{aligned} \tag{2.48}$$

Given Propositions 2.1 and 2.4, all increases in productivity resulting from innovation or firm selection as a consequence of lower transport cost (resp. higher openness) which are not actively offset by increases in the money supply, decrease inflation. □

If monetary policy is constant $M_t = M_0 \cdot e^{tg_M}$, then all changes in inflation are driven by changes in average productivity. Furthermore, equation (2.46) shows why the model can explain the reduction in world wide inflation *generally* without having to explain the disappearance of hyperinflation such as the one in Latin America in the early 90s: The disappearance of hyperinflations is caused by better monetary policy reflected in the growth of money supply g_M.

However it may be that monetary policy is not independent of productivity. If the central bank wants to keep inflation constant for example it could make the money supply dependent on productivity $M(\tilde{\varphi})$ with $M'(\tilde{\varphi}) < 0$ such that $g_M = g_{\tilde{\varphi}}$. In this case, changes in productivity would be neutralised by monetary policy. For the historic development, this seems implausible since low levels of inflation are generally seen as desirable. It may however be the case of countries which already have low levels of inflation as central banks want to avoid deflation.

Proposition 2.5 gives a new perspective on the effect of openness on the monetary side of the economy. Following papers such as Romer (1993) and Rogoff (2003), the effect of openness on inflation has been investigated in the literature of Woodford (2007), Sbordone (2007) and others. In contrast to this literature we take a new approach and include money in an otherwise standard Melitz model. This puts the focus on the long-term development and the role of productivity. It allows an appreciation of the effect on a global scale as we can use macro data which are available for a large range of countries.

2.4 Estimation and Methodology

In section 2.2 we saw that inflation has fallen strongly as globalization deepened. This might of course be a coincidence only. Many explanations for falling inflation have been put forward, most prominently improved monetary policy. In this section we will seek to establish a causal link, controlling for monetary variables.

2.4.1 Description of the Data

The data used for our regression analysis originates from various sources which we list here. The econometric results in Table 2.3 to 2.9 start with the main regression, followed by the inclusion of additional controls and robustness checks with alternative data sources. The presentation of the data follows this order. We use data for the period following the collapse of the Bretton Woods system in 1973 up to the most recent available data in 2009.

We compiled a dataset of the variables described below for 175 countries. All countries that don't have at least 20 consecutive observations for inflation are deleted. This leaves a final sample of 123 countries with annual data for the period 1973-2009. The panel is balanced. See Table 2.11 for the list of countries included in the sample and Table 2.10 for the summary statistics.

Productivity data are not available for all countries. We therefore approximate productivity growth with growth in GDP per capita. In studies involving a large number of countries, this approximation of productivity is a frequently used procedure (see for example Rodrik (2008) and Rogoff (1996)). The data for real GDP per capita is taken from the Penn World Table (6.2). To illustrate why this is a good approximation, see figure 2.3. The figure plots the growth rate of GDP against that of productivity for all countries where data on productivity is available. Openness, also taken from the Penn World Table (6.2), is imports plus exports over GDP as in the theoretical part.

Our exchange rate regime classification is based on Levy-Yeyati and Sturzenegger (2003)[3]. They use a *de facto* classification of exchange rate regimes based on cluster analysis techniques. Countries are sorted according to three variables: (i) Exchange rate volatility, (ii) Volatility of exchange rate changes, and (iii) Volatility of reserves. They are classified into three categories: 1 = float; 2 = intermediate and 3 = fixed.

Inflation targeting is a dummy variable with value zero when a country does not practice inflation targeting and one when it does. See Table 2.12 for the list of inflation targeting countries and the date they started the practice.

The remaining variables of Table 2.3 are taken from the World Development Indicators (WDI) of the World Bank from September 2010. The consumer price index, the dependent variable, is in the form of annual log differences. Money and quasi money is the total money supply. "It comprises the sum of currency outside banks, demand deposits other than those of the central government, and the time, savings, and foreign currency deposits of resident sectors other than the central government", according to the World Bank.

Table 2.4 introduces two additional control variables. The Political Rights Index of the NGO Freedom House is used as a proxy for quality of institutions. A country receives the highest score if political rights are close to some ideals (free and fair elections, competitive parties, minorities have reasonable self government, etc.)[4]. We transform this index via a logistic transformation to the interval between zero and one, where one is the best possible

[3]Due to the stability of the exchange-rates regime for each country between 2000-2003, we extend the classification in this period to the period 2004-2009

[4]Freedom House, *Freedom in the World*, *http://www.freedomhouse.org*. Last access: January 2011

score for quality of institutions. Since inflation tends to increase during war periods, we control also for war episodes. The data for war episodes is taken from Fearon and Laitin (2003)[5].

Table 2.7 is a robustness check for the productivity variable. The variable used here is total factor productivity (TFP) as in Kose et al. (2009). Similarly, Table 2.8 replaces the exchange rate regime. The data used in this table is the exchange rate regime data from Reinhart and Rogoff (2002). Finally, Table 2.9 replaces the dummy variable for institutional quality. The variable used in this table is the data from the International Country Risk Guide.

2.4.2 Predictions Derived from the Theoretical Model

Proposition 2.5 leads to a testable prediction: Inflation can be written as the difference of the growth rate of the money supply and the growth rate of productivity

$$\pi = g_M - g_{\tilde{\varphi}_{tot}} \, .$$

The growth rate of productivity in turn depends on time (Proposition 2.4) as it evolves as a result of ongoing innovative activity and on increases in openness (Proposition 2.3) which causes firm selection. In order to test our theoretical result, the most straighforward thing to do is therefore to estimate this equation. We implement it empirically as:

$$\begin{aligned} \Delta \ln \mathrm{CPI}_{i,t} \quad = \quad & \beta_0 + \beta_1 \Delta \ln \text{Money-Supply}_{i,t} + \beta_2 \Delta \ln \text{Productivity}_{i,t} \\ & + \beta_3 \underbrace{\Delta \ln \text{Productivity}_{i,t} * \Delta \ln \text{Openness}_{i,t}}_{\text{openness-induced productivity}} \\ & + \beta_4 \Delta \ln \text{Openness}_{i,t} + \beta_5 \Delta \ln \mathrm{CPI}_{i,t-1} + \beta' X_{i,t} + \mu_t + \gamma_i + \epsilon_{i,t} \end{aligned} \tag{2.49}$$

where $i = 1, \cdots, 123$ indexes the countries and $t = 1, \cdots, 37$ indexes the years (from 1973 to 2009). Δ indicates first differences. All variables are set in log differences except the dummies. The dependent variable is the growth rate of the consumer price index. The first explanatory variable is the money supply (M2) followed by the two sources of productivity growth. Productivity is the log difference of GDP per capita and openness is the log difference of the ratio of import plus export over gross domestic product. Control variables are openness and the lagged value of inflation to capture persistence in inflation and potentially mean-

[5] Armed conflict, *http://new.prio.no*. Last access: January 2011

reverting dynamics. Further controls are captured in $X_{i,t}$ including the exchange rate regime dummy (Levy-Yeyati and Sturzenegger (2003)) and inflation targeting dummy. μ_t and γ_i are the time and country-fixed effect and $\epsilon_{i,t}$ the error term.

This regression equation explicitly models the two types of productivity changes: changes that occur independently from trade are captured by β_2 and those occurring as a consequence of greater openness through the mechanism of the model are captured by β_3. At the same time it takes into account the two mechanisms through which globalisation can affect inflation: the first one is the direct channel of openness captured by β_4, the second is the indirect channel via productivity captured by β_3. The derivative of inflation with respect to productivity can be expressed as

$$\frac{\partial \Delta \ln \text{Inflation}}{\partial \Delta \ln \text{Productivity}} = \beta_2 + \beta_3 \cdot \Delta \ln \text{Openness}$$

with $\beta_2 < 0$ and $\beta_3 < 0$. A negative β_3 implies that openness causes an additional increase in productivity which slows down inflation. Given Proposition 2.5 we also expect $\beta_1 > 0$.

2.4.3 Regression Methods

We estimate equation (2.49) with different regression techniques to address the various shortcomings of standard OLS. Table 2.3 is structured as follows. Odd column numbers include only the real variables. Even column numbers each use the same regression technique as the preceding odd column, but adds monetary variables.

Columns (1) and (2) is simple OLS with country fixed effects. Country fixed effects allow to move beyond cross country comparison by investigating within-country variation over time. The OLS analysis is biased since we include lagged values of the dependent variable inflation among the regressors. We nevertheless report the regression results since the bias is inversely proportional to the time period of the panel (see Nickell (1981) and Hsiao (2003)). In our case we have 37 time periods so that the bias is expected to be small.

Columns (3) and (4) is OLS with country fixed effect, robust standard errors and clustered countries. By clustering countries, we allow for intragroup correlation, relaxing the previous hypothesis that the observations are independent across groups but not necessarily within groups.

When using OLS there is a pitfall even when including country fixed effect, robust standard errors and clustered countries: The endogeneity of productivity. One possible source of this is reverse causality: less inflation leads to higher productivity because inflation volatility reduces along with the level thus reducing risk and increasing competition. The second cause of endogeneity is simultaneous causality: an omitted variable – like the quality of institutions – causes productivity to increase and inflation to decrease. To deal with this problem, we use the system of Generalized Method of Moments (GMM)[6], see columns (7) and (8). Following Roodman (2006) we do not include explicit fixed effect dummies in system GMM since it might cause bias. We do not cluster countries because GMM standard errors are robust. For comparison we also show the results for difference GMM, see columns (5) and (6).

2.4.4 Estimation Results

In describing the estimation results we follow the order of the tables. Table 2.3 is our baseline result and is presented in Section 2.4.4. Additional control variables and robustness checks follow in Section 2.4.4

Main results

The sign of each variable is the same across all regression methods described above. Our discussion will thus be limited to column (8) which is the most sound econometric technique and includes all relevant variables[7].

Starting with the control variables, we find that inflation inertia has a positive sign, confirming the notion of the persistence of changes in inflation. In line with monetary theory we find that growth in the money supply has a positive effect on inflation. The exchange rate regime is found to be insignificant in the benchmark regression. This control was included to take into account that a large number of countries use, officially or de facto, the euro or the dollar or have a fixed exchange rate to one of these currencies. The insignificance of this control variable suggests that the use of a common currency does not lead to common inflation levels. Inflation targeting seems to work as intended since it reduces inflation.

Now coming to the variables of interest to our theory we find that an increase in openness reduces inflation. This confirms previously proposed theories for a link between openness and inflation such as the idea of a reduced incentive for surprise disinflations put forward by

[6]These are Difference-GMM and System-GMM, see Blundell and Bond (1999) and Roodman (2006) for example. We focus here on the System-GMM since it reduces the biases associated with the Difference-GMM.

[7]In this chapter, the importance of each variable in the explanation of the right hand side variable matters. This is why we report t-statistics instead of standard errors in each of the regression tables. To save space, we drop the negative sign in front of the value of the t-student when the coefficient is negative

Rogoff (2003). An increase in productivity also lowers inflation, thus supporting the idea that a reduction in *relative* prices for goods does to some extent affect the price *level*. Finally, and crucially for our theory, the interaction term between openness and productivity also has a negative effect on inflation. This confirms the central concept of this chapter that openness-induced productivity changes reduce the price level via lower relative prices for goods.

Alfaro (2005) documents the role of the exchange rate regime on inflation. Without controlling for productivity, she concludes that the exchange rate regime is more relevant than openness as an explanation of inflation. Our results however show that productivity provides the link between openness and inflation. Openness via productivity has a stronger impact on the level of inflation than the exchange rate regime. We find the effect of the exchange rate regime on inflation to be insignificant.

The results are likely to be a lower bound as we only have data for total inflation. De Gregorio et al. (1994) notes that inflation in tradeables is much lower than in non-tradeables. Since our effect of lower inflation through more international competition works mainly on tradeables, the strength of the effect is likely to be even stronger in this sector. It is an important contribution to explain where this difference in inflation rates originates.

Robustness Tests

It is possible that the correlation between changes in productivity and inflation is due to an omitted variable. An improvement in institutions or political leadership might cause both inflation to go down and trade to increase. The idea behind this is that leaders simultaneously stop using inflation taxation and start opening their countries in an attempt to improve economic performance. A sudden change of economic policy like this might be introduced by newly elected leaders. To check if this hypothesis is right we run regression 2.3 and include a control for institutional quality in the set of control variables X_{it}.

It is difficult to measure the quality of institutions directly of course. But we may get a good idea of major changes in institutional quality from an index such as the "Freedom in the World" - index from Freedom House. This index measures the quality of political rights in a country and can be seen as an indicator of a sincere attempt to improve governance. So if the correlation between openness and inflation is indeed driven by institutional quality, the inclusion of a measure for institutional quality should dramatically reduce the significance of productivity and openness in the regressions. Including the index, see Table 2.4, we find that this is not the case. We find that the "Freedom in the World"-index is only weakly significant and does not strongly change the effect of openness, productivity and its interaction.

A similar concern is the effect of wars. Wars might force a country to reduce international trade and drive up inflation. Controlling for this with the inclusion of a war dummy, we find that the dummy is not significant.

Table 2.5 addresses the concern that the results may be sensitive to the choice of periods. We split the sample period in two parts of roughly equal lengths. The split at 1989/1990 follows Kose et al. (2003). Some of the results are less strongly significant in the first period (1972 to 1989), which is likely due to a much slower pace of globalization during that period. Results in the second period (1990 to 2009) however are strongly significant and quite similar to those of the whole sample. Following this temporal split, Table 2.6 shows the results for a geographical split by comparing OECD and non-OECD countries. Among several geographical robustness checks which we do not all report here, this one seems the most interesting since it shows that the effect exists for high and low income countries. Results hold in this analysis.

Table 2.7 is concerned with the possibility that the approximation of productivity growth with growth in per capita GDP is to rough to produce reliable results. The regression therefore includes only the 67 countries for which TFP data are available in Kose et al. (2009). Again, results are similar to the main regression. Tables 2.8 and 2.9 follow the same idea. The variables for exchange rate regimes and institutional quality are replaced by alternative measures. In the case of exchange rate regimes we use data from Reinhart and Rogoff (2002) and in the case of institutional quality we use data from from the International Country Risk Guide. As before results are not strongly affected.

2.5 Conclusion and Policy Implications

This chapter explores the central role of productivity as a link between openness to trade and inflation in a framework of heterogeneous firms. Theoretically, we adapt the model of Melitz (2003) to make explicit statements on the reaction of openness, productivity and relative prices to changes in transport cost. In addition a CIA constraint permits to understand how the relative price changes translate into the price level and affect inflation.

Empirically, we make use of a purpose-made dataset containing all the relevant variables for 123 countries from all regions of the world. Estimation of the central theoretical equation reveals a significant effect of openness-induced productivity increase on inflation. Using GMM and directly controlling for institutional quality we give strong evidence that results are robust to omitted variable bias and reverse causality.

As a consequence of our result the question arises how sustainable the low levels of inflation are. An increase in openness leads to an acceleration in productivity. This however is not a structural change to the economy, it lasts only as long as openness increases. Once openness stabilizes, theory predicts that inflation should rise to a higher level, because productivity growth is no longer aided by firm selection from additional foreign competition. We can draw a policy implication from this. Once openness levels out, the additional downward pressure it had on inflation disappears. Central banks will have to adjust for this if they aim to keep inflation at very low levels.

Appendix to Chapter 2

2.A Simple Derivations

Average Productivity at Home

$$
\begin{aligned}
\tilde{\varphi}(\varphi^*) &= \left[\frac{\varphi^{*k}}{(\varphi_m(t))^k}\int_{\varphi^*}^{\infty}\varphi^{\sigma-1}k\frac{(\varphi_m(t))^k}{\varphi^{k+1}}d\varphi\right]^{\frac{1}{\sigma-1}} \\
&= \left[\varphi^{*k}k\int_{\varphi^*}^{\infty}\frac{\varphi^{\sigma-1}}{\varphi^{k+1}}d\varphi\right]^{\frac{1}{\sigma-1}} \\
&= \left[\varphi^{*k}k\int_{\varphi^*}^{\infty}\varphi^{\sigma-k-2}d\varphi\right]^{\frac{1}{\sigma-1}} \\
&= \left[\varphi^{*k}k\left|\frac{1}{\sigma-k-1}\varphi^{\sigma-k-1}\right|_{\varphi^*}^{\infty}\right]^{\frac{1}{\sigma-1}} \\
&= \left[\varphi^{*k}\frac{k}{k-(\sigma-1)}\varphi^{*\sigma-1-k}\right]^{\frac{1}{\sigma-1}} \\
&= \left[\frac{k}{k-(\sigma-1)}\varphi^{*\sigma-1}\right]^{\frac{1}{\sigma-1}} \\
&= \left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}}\varphi^*
\end{aligned}
$$

Note that $\left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}} > 0$.

$$
\begin{aligned}
\tilde{\varphi}(\varphi_x^*) &= \tilde{\varphi}\left(\tau\left(\frac{f_x}{f}\right)^{\frac{1}{\sigma-1}}\varphi^*\right) \\
&= \left[\frac{k}{k-(\sigma-1)}\tau^{\sigma-1}\frac{f_x}{f}\varphi^{*\sigma-1}\right]^{\frac{1}{\sigma-1}} \\
&= \left[\frac{k}{k-(\sigma-1)}\frac{f_x}{f}\right]^{\frac{1}{\sigma-1}}\tau\varphi^*
\end{aligned}
$$

Probability of Exporting

$$
p_x = \frac{1-G(\varphi_x^*)}{1-G(\varphi^*)} = \frac{\left(\frac{(\varphi_m(t))}{\varphi_x^*}\right)^k}{\left(\frac{(\varphi_m(t))}{\varphi^*}\right)^k} = \frac{\varphi^{*k}}{\varphi_x^{*k}} = \frac{1}{(\tau f^*)^k}
$$

Average total productivity Inserting the definitions of N_{tot} and N_x into the definition of average total productivity (2.24) we can write

$$\tilde{\varphi}_{tot} = \left(\frac{1}{1+p_x} [\tilde{\varphi}^{\sigma-1} + p_x(\tau^{-1}\tilde{\varphi}_x)^{\sigma-1}] \right)^{\frac{1}{\sigma-1}} . \tag{2.50}$$

Substituting in the expressions from (2.20), (2.21) and (2.23) we obtain

$$\begin{aligned} \tilde{\varphi}_{tot} &= \left(\frac{1}{1+(\tau f^*)^{-k}} [(k^*\varphi^*)^{\sigma-1} + (\tau f^*)^{-k}(k^* f^* \varphi^*)^{\sigma-1}] \right)^{\frac{1}{\sigma-1}} \\ &= k^*\varphi^* \left(\frac{\tau^k f^{*k} + f^{*\sigma-1}}{\tau^k f^{*k} + 1} \right)^{\frac{1}{\sigma-1}} . \end{aligned}$$

The zero cutoff profit function (ZCP)

$$\begin{aligned} \bar{\pi} &= f \cdot \left(\left[\frac{\tilde{\varphi}(\varphi^*)}{\varphi^*} \right]^{\sigma-1} - 1 \right) + p_x f_x \cdot \left(\left[\frac{\tilde{\varphi}(\varphi_x^*)}{\varphi_x^*} \right]^{\sigma-1} - 1 \right) \\ &= f \left[\frac{k^*\varphi^*}{\varphi^*} \right]^{\sigma-1} - f + \frac{1}{(\tau f^*)^k} f_x \left[\frac{k^* f^* \tau \varphi^*}{f^* \tau \varphi^*} \right]^{\sigma-1} - \frac{1}{(\tau f^*)^k} f_x \\ &= f \left[\frac{k}{k-(\sigma-1)} \right] - f + \frac{1}{(\tau f^*)^k} f_x \left[\frac{k}{k-(\sigma-1)} \right] - \frac{1}{(\tau f^*)^k} f_x \\ &= \left(f + \frac{1}{(\tau f^*)^k} f_x \right) \left[\frac{k}{k-(\sigma-1)} \right] - \left(f + \frac{1}{(\tau f^*)^k} f_x \right) \\ &= \left(f + \frac{1}{(\tau f^*)^k} f_x \right) \left[\frac{k}{k-(\sigma-1)} - 1 \right] \\ &= \left(f + \frac{1}{\tau^k} \left(\frac{f_x}{f} \right)^{\frac{k}{\sigma-1}} f_x \right) \left[\frac{\sigma-1}{k-(\sigma-1)} \right] \\ &= \left(f + \frac{1}{\tau^k} f^{\frac{-k}{\sigma-1}} f_x^{1-\frac{-k}{\sigma-1}} \right) \frac{\sigma-1}{k-(\sigma-1)} \end{aligned}$$

2.B Graphical Appendix

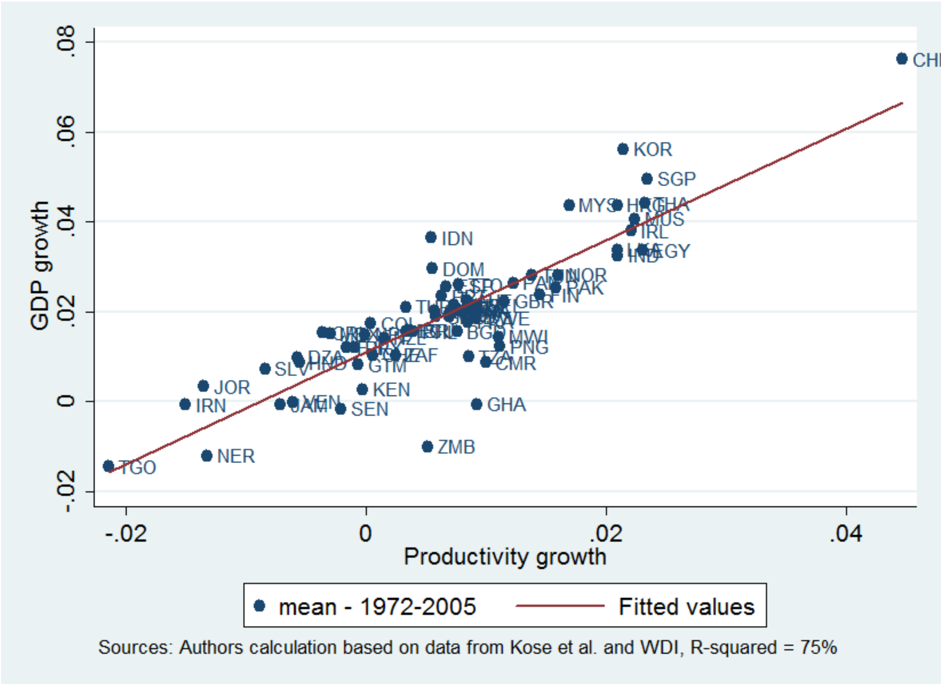

Figure 2.3: GDP Growth and Productivity Growth for 67 Countries.

Sources: WDI, Kose et al. (2009) and authors' calculation.

2.C Tables

	FE				GMM			
	OLS		OLS-Cluster		Diff GMM		System GMM	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Inflation inertia	0.6430***	0.5625***	0.6430***	0.5625***	0.6523***	0.5253***	0.6608***	0.5336***
	[52.9460]	[39.3526]	[20.1036]	[18.9087]	[17.6712]	[12.5015]	[17.7495]	[12.8658]
Δ ln Openness	-0.0492***	-0.0472***	-0.0492***	- 0.0472***	-0.0474***	-0.0362***	-0.0464***	-0.0362***
	[6.5049]	[5.8091]	[3.6929]	[3.5399]	[3.6251]	[2.7134]	[3.5415]	[2.7734]
Δ ln Productivity	-0.1029***	-0.1224***	-0.1029***	-0.1224***	-0.1139***	-0.1014***	-0.1070***	-0.1118***
	[6.5853]	[7.1297]	[3.4636]	[3.9534]	[3.6862]	[3.1726]	[3.4678]	[3.4080]
Δ ln Productivity * Δ ln Openness	-0.2976***	-0.5016***	-0.2976***	-0.5016***	-0.3247***	-0.4357***	-0.3088***	-0.4365***
	[4.2012]	[6.0995]	[2.6665]	[3.8088]	[3.0452]	[3.1772]	[2.7878]	[3.3807]
Δ ln Money supply		0.1040***		0.1040***		0.0826***		0.0814***
		[14.4981]		[4.8848]		[3.6762]		[3.8442]
Exchange-rate regimes		-0.0056***		-0.0056**		-0.0034		-0.0050
		[3.4461]		[2.4960]		[0.9000]		[1.4227]
Inflation targeting		-0.0178***		-0.0178**		-0.0654***		-0.0108**
		[3.1214]		[2.5460]		[2.9503]		[2.3226]
Constant	0.0654***	0.0841***	0.0654***	0.0841***			0.0182***	0.0250**
	[11.3280]	[10.7757]	[12.7182]	[8.5741]			[6.0392]	[2.4140]
Observations	3,960	3,106	3,960	3,106	3,833	2,868	3,960	3,106
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.5208	0.5670	0.5208	0.5670				
Number of countries	123	121	123	121	123	118	123	121

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.3: Main Regression Results

	FE				GMM			
	OLS		OLS-Cluster		Diff GMM		System GMM	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Inflation inertia	0.6184***	0.5436***	0.6184***	0.5436***	0.6227***	0.4846***	0.6400***	0.5403***
	[43.8728]	[32.9578]	[18.7303]	[17.5372]	[14.3297]	[10.2958]	[15.0228]	[13.0303]
Δ ln Openness	-0.0524***	-0.0491***	-0.0524***	-0.0491***	-0.0460***	-0.0337**	-0.0489***	-0.0398***
	[6.0975]	[5.3073]	[3.6410]	[3.3416]	[3.2601]	[2.2749]	[3.4626]	[2.8183]
Δ ln Productivity	-0.1005***	-0.1182***	-0.1005***	-0.1182***	-0.1122***	-0.0953***	-0.1033***	-0.1086***
	[5.5915]	[6.0241]	[3.0369]	[3.5834]	[3.2040]	[2.7717]	[2.9095]	[2.9829]
Δ ln Productivity * Δ ln Openness	-0.2984***	-0.5237***	-0.2984**	-0.5237***	-0.3291***	-0.4481***	-0.3277***	-0.4715***
	[3.7570]	[5.6893]	[2.5174]	[3.8775]	[2.8073]	[3.0509]	[2.7314]	[3.2326]
Δ ln Money supply		0.1074***		0.1074***		0.0823***		0.0870***
		[12.9516]		[4.4642]		[3.2064]		[3.6772]
Exchange-rate regimes		-0.0070***		-0.0070**		-0.0040		-0.0064
		[3.4527]		[2.5285]		[0.8140]		[1.3365]
Inflation targeting		-0.0193**		-0.0193*		-0.0666**		-0.0231***
		[2.2769]		[1.9786]		[2.4573]		[3.1342]
Quality of institutions	0.0128**	0.0129*	0.0128**	0.0129*	0.0039	-0.0102	0.0088	0.0252*
Freedom house index	[2.0132]	[1.7904]	[2.1560]	[1.7360]	[0.1710]	[-0.4579]	[0.5235]	[1.8097]
War dummy	0.0154***	0.0159***	0.0154**	0.0159**	0.0013	-0.0351	0.0128	0.0071
	[2.9779]	[2.7165]	[2.3653]	[2.2221]	[0.0716]	[-1.5029]	[1.0465]	[0.3994]
Constant	0.0755***	0.0812***	0.0755***	0.0812***			0.0104	0.0107
	[10.3725]	[8.2259]	[10.9706]	[6.5129]			[0.9489]	[0.6015]
Observations	3,141	2,431	3,141	2,431	3,016	2,214	3,141	2,431
R-squared	0.4700	0.5284	0.4700	0.5284				
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	121	118	121	118	121	115	121	118

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.4: Robustness Check: Including Institutional and Conflict Dummies as Controls

	FE				GMM			
	OLS		OLS-Cluster		Diff GMM		System GMM	
	(1) 1973-1989	(2) 1990-2009	(3) 1973-1989	(4) 1990-2009	(5) 1973-1989	(6) 1990-2009	(7) 1973-1989	(8) 1990-2009
Inflation inertia	0.4678***	0.5203***	0.4678***	0.5203***	0.4429***	0.4786***	0.6406***	0.4982***
	[18.3761]	[27.8058]	[10.3446]	[13.5300]	[5.6286]	[8.0827]	[12.8543]	[9.0285]
Δ ln Openness	-0.0050	-0.0795***	-0.0050	-0.0795***	-0.0103	-0.0643***	-0.0027	-0.0614***
	[0.3879]	[7.7341]	[0.2831]	[5.3894]	[-0.4797]	[3.6292]	[0.1319]	[3.8390]
Δ ln Productivity	-0.0998***	-0.1400***	-0.0998***	-0.1400***	-0.0773*	-0.1305***	-0.1095**	-0.1281***
	[3.8372]	[5.9018]	[2.7177]	[2.8924]	[1.8535]	[2.6781]	[2.3809]	[2.7768]
Δ ln Productivity * Δ ln Openness	-0.3447**	-0.5276***	-0.3447*	-0.5276***	-0.3069	-0.4305**	-0.4608*	-0.3741***
	[2.1239]	[5.6656]	[1.6743]	[3.5474]	[1.3241]	[2.2748]	[1.7498]	[2.6916]
Δ ln Money supply	0.0778***	0.1028***	0.0778***	0.1028***	0.0409	0.0861**	0.0856***	0.0809***
	[6.6163]	[11.1253]	[3.0128]	[3.3508]	[1.3103]	[2.5250]	[3.3402]	[2.6424]
Exchange-rate regimes	-0.0068**	0.0001	-0.0068*	0.0001	0.0045	-0.0062	-0.0065	-0.0075*
	[2.1456]	[0.0317]	[1.7327]	[0.0217]	[0.7520]	[1.3462]	[1.2016]	[1.7138]
Inflation targeting		-0.0082		-0.0082		-0.0573***		-0.0123**
		[1.1867]		[1.2168]		[2.7940]		[2.3312]
Constant	0.0627***	0.0143*	0.0627***	0.0143			0.0381**	0.0335**
	[5.7269]	[1.9577]	[4.5696]	[1.2610]			[2.5575]	[2.6031]
Observations	1,308	1,798	1,308	1,798	1,167	1,701	1,308	1,798
R-squared	0.3459	0.5414	0.3459	0.5414				
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	105	121	105	121	101	116	105	121

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

The division into periods follows Kose (2003). The second period coincides with the time of rapid globalization.

Table 2.5: Robustness Check: Sample Split into Time Intervals

	FE				GMM			
	OLS		OLS-Cluster		Diff GMM		System GMM	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	OECD	Non-OECD	OECD	Non-OECD	OECD	Non-OECD	OECD	Non-OECD
Inflation inertia	0.6351***	0.5341***	0.6351***	0.5341***	0.5925***	0.4727***	0.6037***	0.5017***
	[27.0993]	[31.6248]	[14.6151]	[15.2939]	[10.8707]	[10.4613]	[16.3752]	[10.8791]
Δ ln Openness	-0.0917***	-0.0446***	-0.0917**	-0.0446***	-0.0963**	-0.0311**	-0.0846*	-0.0344**
	[3.6025]	[4.9748]	[2.0846]	[3.1982]	[2.3517]	[2.3059]	[1.8650]	[2.5638]
Δ ln Productivity	-0.1484***	-0.1098***	-0.1484**	-0.1098***	-0.1688**	-0.0855***	-0.1678***	-0.1020***
	[2.8287]	[5.7760]	[2.5774]	[3.3521]	[2.7161]	[2.6937]	[3.0951]	[2.9873]
Δ ln Productivity* Δ ln Openness	-2.4745***	-0.4802***	-2.4745	-0.4802***	-2.3355	-0.4039***	-2.6468*	-0.4153***
	[4.8054]	[5.3964]	[1.6804]	[3.5843]	[1.5099]	[3.0391]	[1.7494]	[3.2741]
Δ lnMoney supply	0.1183***	0.0981***	0.1183***	0.0981***	0.1299***	0.0621***	0.1331***	0.0714***
	[10.9889]	[11.4150]	[4.2189]	[4.1581]	[4.2063]	[3.4656]	[4.5863]	[3.3747]
Exchange-rate regimes	-0.0018	-0.0045**	-0.0018	-0.0045	0.0029	-0.0050	-0.0008	-0.0052
	[0.7585]	[2.2201]	[0.6778]	[1.6072]	[0.7377]	[1.0903]	[0.2158]	[1.3383]
Inflation targeting	-0.0043	-0.0247**	-0.0043	-0.0247**	-0.0172*	-0.0423**	-0.0044	-0.0035
	[0.8575]	[2.4431]	[0.8188]	[2.2578]	[2.0224]	[2.0058]	[1.3704]	[0.4616]
Constant	0.0250**	0.0819***	0.0250***	0.0819***			0.0066	0.0284**
	[2.3005]	[8.1840]	[3.2305]	[6.1585]			[0.6312]	[2.5204]
Observations	672	2,434	672	2,434	623	2,245	672	2,434
R-squared	0.8541	0.5004	0.8541	0.5004				
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	26	95	26	95	26	92	26	95

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.6: Robustness Check: Sample Split into OECD *vs* Non-OECD Countries

	FE					GMM				
	OLS		OLS-Cluster			Diff GMM		System GMM		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Inflation inertia	0.6621***	0.5970***	0.6621***	0.5970***	0.5771***	0.6816***	0.6075***	0.6800***	0.5870***	0.5723***
	[40.4676]	[31.9771]	[13.2589]	[15.0265]	[14.4749]	[11.0967]	[9.4165]	[11.4973]	[9.3502]	[9.9459]
Δ ln Openness	-0.0755***	-0.0695***	-0.0755***	-0.0695***	-0.0715***	-0.0729***	-0.0737***	-0.0713***	-0.0666***	- 0.0649**
	[6.7430]	[5.8650]	[3.7218]	[2.9866]	[2.8185]	[3.5924]	[3.0788]	[3.5887]	[2.9982]	[2.5965]
Δ ln Productivity	-0.1577***	-0.1853***	-0.1577***	-0.1853***	-0.1771***	-0.1641***	-0.1804***	-0.1683***	-0.1921***	-0.1744***
Solow's residual	[5.9528]	[6.5251]	[3.3879]	[3.7102]	[3.7452]	[3.2604]	[3.0509]	[3.3589]	[3.3982]	[3.1760]
Δ ln Productivity * Δ ln Openness	-0.5142***	-0.7071***	-0.5142*	-0.7071**	-0.7667***	-0.5511**	-0.5501**	-0.5465**	-0.6202**	-0.7439***
	[3.0291]	[4.0108]	[1.8108]	[2.3054]	[2.6611]	[2.1125]	[2.1217]	[2.0609]	[2.3500]	[2.8707]
Δ ln Money supply		0.0973***		0.0973***	0.0982***		0.0904***		0.0876***	0.0960***
		[10.5221]		[3.8703]	[3.8683]		[3.9790]		[3.4661]	[4.2282]
Exchange-rate regimes		-0.0042**		-0.0042*	-0.0047*		0.0025		0.0013	0.0021
		[2.2343]		[1.6880]	[1.7189]		[0.5523]		[0.2960]	[0.4303]
Inflation targeting		-0.0105*		-0.0105	-0.0165*		-0.0028		-0.0108**	-0.0183**
		[1.7046]		[1.4071]	[1.6942]		[0.1043]		[2.1282]	[2.3823]
Quality of institutions					0.0197**					0.0208
Freedom house index					[2.0644]					[0.9770]
War dummy					0.0185**					0.0207
					[2.4978]					[1.2016]
Constant	0.0369***	0.0250***	0.0369***	0.0250***	0.0164			0.0161***	0.0094	-0.0123
	[5.5096]	[3.0515]	[3.1166]	[2.9639]	[1.1493]			[3.4385]	[0.8168]	[0.5135]
Observations	2,136	1,743	2,136	1,743	1,487	2,069	1,609	2,136	1,743	1,487
R-squared	0.5592	0.5999	0.5592	0.5999	0.5658					
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	67	66	67	66	65	67	66	67	66	65

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.7: Robustness Check: With Productivity Data from Kose (2009)

	FE					GMM				
	OLS		OLS-Cluster			Diff GMM		System GMM		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Inflation inertia	0.6313***	0.5114***	0.6313***	0.5114***	0.4996***	0.6435***	0.5004***	0.6504***	0.4930***	0.4903***
	[49.6312]	[30.0054]	[19.3218]	[13.3610]	[13.5807]	[17.0186]	[9.9319]	[17.0292]	[10.6883]	[10.9030]
Δ ln Openness	-0.0502***	-0.0480***	-0.0502***	-0.0480***	-0.0445**	-0.0480***	-0.0483***	-0.0470***	-0.0475***	-0.0426**
	[6.4180]	[4.5325]	[3.6864]	[2.7302]	[2.4502]	[3.5601]	[2.7192]	[3.4638]	[2.8201]	[2.5327]
Δ ln Productivity	-0.1061***	-0.1545***	-0.1061***	-0.1545***	-0.1462***	-0.1180***	-0.1502***	-0.1130***	-0.1532***	-0.1373***
	[6.5350]	[6.1973]	[3.5000]	[4.2924]	[4.1381]	[3.7627]	[3.2788]	[3.5575]	[3.6312]	[3.4677]
Δ ln Productivity * Δ ln Openness	-0.2937***	-0.5345***	-0.2937***	-0.5345***	-0.7190***	-0.3329***	-0.5101**	-0.3237***	-0.5629***	-0.6624***
	[4.0308]	[3.8761]	[2.6169]	[2.7238]	[3.6362]	[3.1164]	[2.5876]	[2.9389]	[2.8408]	[3.3876]
Δ ln Money supply		0.0910***		0.0910***	0.0904***		0.0758***		0.0767***	0.0806***
		[10.6189]		[4.5419]	[4.5084]		[4.3698]		[4.1241]	[5.0148]
Exchange rate regimes		0.0221***		0.0221***	0.0225***		0.0241***		0.0230***	0.0255***
ERR of Reinhart and Rogoff (2002)		[16.1316]		[7.4686]	[7.0083]		[5.9621]		[6.3679]	[6.8637]
Inflation targeting		-0.0303***		-0.0303***	-0.0344***		-0.0831**		-0.0381***	-0.0509***
		[5.3667]		[4.1244]	[4.0172]		[2.4990]		[5.9553]	[6.0430]
Quality of institutions					0.0079					0.0219
Freedom house index					[0.8001]					[1.6184]
War dummy					0.0124*					-0.0004
					[1.9572]					[0.0349]
Constant	0.0860***	0.0351***	0.0860***	0.0351***	0.0090			0.0235***	-0.0229***	-0.0442***
	[14.3529]	[5.1112]	[14.2070]	[3.3231]	[0.8207]			[6.7293]	[2.8204]	[3.5409]
Observations	3,715	2,000	3,715	2,000	1,736	3,588	1,919	3,715	2,000	1,736
R-squared	0.5021	0.6353	0.5021	0.6353	0.6038					
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	123	67	123	67	65	123	67	123	67	65

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.8: Robustness Check: Exchange-Rate Regime Classification Following Reinhart and Rogoff (2002)

	FE					GMM				
	OLS		OLS-Cluster			Diff GMM		System GMM		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Inflation inertia	0.6313***	0.5520***	0.6313***	0.5520***	0.5923***	0.6435***	0.5196***	0.6504***	0.5295***	0.5697***
	[49.6312]	[36.9592]	[19.3218]	[18.1574]	[14.4649]	[17.0186]	[12.0114]	[17.0292]	[12.7047]	[8.9523]
Δ ln Openness	-0.0502***	-0.0473***	-0.0502***	-0.0473***	-0.0696***	-0.0480***	-0.0379***	-0.0470***	-0.0372***	-0.0640**
	[6.4180]	[5.6105]	[3.6864]	[3.4271]	[2.7126]	[3.5601]	[2.6640]	[3.4638]	[2.6709]	[2.5448]
Δ ln Productivity	-0.1061***	-0.1272***	-0.1061***	-0.1272***	-0.1916***	-0.1180***	-0.1028***	-0.1130***	-0.1188***	-0.1932***
	[6.5350]	[7.1229]	[3.5000]	[4.0475]	[3.7293]	[3.7627]	[3.1923]	[3.5575]	[3.5883]	[3.3625]
Δ ln Productivity * Δ ln Openness	-0.2937***	-0.5028***	-0.2937***	-0.5028***	-0.7557***	-0.3329***	-0.4086***	-0.3237***	-0.4251***	-0.8356***
	[4.0308]	[5.9382]	[2.6169]	[3.7920]	[3.1244]	[3.1164]	[3.0027]	[2.9389]	[3.2406]	[3.8474]
Δ ln Money supply		0.1066***		0.1066***	0.0972***		0.0826***		0.0823***	0.0871***
		[14.2563]		[4.8134]	[3.9060]		[3.5950]		[3.7904]	[3.4720]
Exchange-rate regimes		-0.0061***		-0.0061**	-0.0051**		-0.0010		-0.0052	0.0010
		[3.4055]		[2.3799]	[2.0364]		[0.2255]		[1.2417]	[0.2288]
Inflation targeting		-0.0175***		-0.0175**	-0.0134*		-0.1071***		-0.0134***	-0.0070
		[2.7782]		[2.3424]	[1.8533]		[3.0454]		[2.6975]	[1.0126]
Quality of Institutions					-0.0021*					-0.0031*
ICRG Index					[1.9169]					[1.7772]
War dummy					0.0118*					0.0159
					[1.9318]					[0.9449]
Constant	0.0860***	0.0859***	0.0860***	0.0859***	0.0495***			0.0235***	0.0338***	0.0385**
	[14.3529]	[10.5105]	[14.2070]	[8.2353]	[3.3072]			[6.7293]	[2.8380]	[2.1459]
Observations	3,715	2,898	3,715	2,898	1,664	3,588	2,671	3,715	2,898	1,664
R-squared	0.5021	0.5513	0.5021	0.5513	0.6088					
Country Fixed Effects	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	123	119	123	119	62	123	118	123	119	62

t-statistics in brackets; *** p<0.01, ** p<0.05, * p<0.1

Table 2.9: Robustness Check: Institutional Quality Data from the International Country Risk Guide (ICRG)

Variables	Obs	Mean	Std. Dev.	Min	Max
Δln CPI	4403	.0869042	.0960851	-.276732	.8474171
Δln Openness	4322	.0132791	.1328754	-1.416514	2.233043
Δln Productivity	4322	.0183262	.0633431	-.4491743	.7804412
Δln Money supply	4306	.1492613	.1580446	-1.118959	2.229269
Exchange regime	3671	2.428494	.8095108	1	3
Inflation targeting	4788	.0484545	.214747	0	1
Freedom house	3578	.5480716	.3721498	0	1
War dummy	4551	.1551307	.3620691	0	1

Table 2.10: Summary Statistics

Algeria Australia Austria Bahamas, The Bahrain Bangladesh Barbados Belgium Belize Bhutan Botswana Brunei Darussalam Burkina Faso Burundi Cameroon Canada Cape Verde Central African Republic Chad China Colombia Congo, Rep. Costa Rica Cote d'Ivoire Cyprus Denmark Dominica Dominican Republic Ecuador Egypt, Arab Rep. El Salvador Equatorial Guinea Ethiopia Fiji Finland France Gabon Gambia, The Ghana Greece Grenada Guatemala Guinea-Bissau Haiti Honduras Hong Kong SAR, China Hungary Iceland India Indonesia Iran, Islamic Rep. Ireland Israel Italy Jamaica Japan Jordan Kenya Korea, Rep. Kuwait Lao PDR Lesotho Libya Luxembourg Madagascar Malawi Malaysia Mali Malta Mauritania Mauritius Mexico Morocco Myanmar Nepal Netherlands Netherlands Antilles New Zealand Niger Nigeria Norway Pakistan Panama Papua New Guinea Paraguay Philippines Poland Portugal Qatar Romania Rwanda Samoa Saudi Arabia Senegal Seychelles Singapore Solomon Islands South Africa Spain Sri Lanka St. Kitts and Nevis St. Lucia St. Vincent and the Grenadines Sudan Suriname Swaziland Sweden Switzerland Syrian Arab Republic Tanzania Thailand Togo Tonga Trinidad and Tobago Tunisia Turkey Uganda United Kingdom United States Uruguay Vanuatu Venezuela, RB Yemen, Rep. Zambia

Table 2.11: List of Countries – Full Sample

Australia 1993, Canada 1991, Colombia 1999, Ghana 2007, Hungary 2001,Iceland 2001, Israel 1992, Korea, Rep. 1998, Mexico 1999, New Zealand 1990, Norway 2001, Philippines 2002, Poland 1998, Romania 2005, South Africa 2000, Sweden 1993, Switzerland 2000, Thailand 2000, Turkey 2006, United Kingdom 1992.

Table 2.12: List of Inflation Targeting Countries

Chapter 3

Non-Renewable but Inexhaustible - Resources in an Endogenous Growth Model

3.1 Introduction

We contribute to resolve a contradiction between theoretical predictions and empirical evidence on non-renewable resources. According to growth theory, economic growth is not limited by non-renewable resources due to three forces: technical change in the use of non-renewable resources, substitution of non-renewable resources by capital, and returns to scale, see Stiglitz (1974), Suzuki (1976) and Groth (2007). Hence, these models predict growth in output, decreasing non-renewable resource extraction and an increasing resource price, see Barro and Sala-i-Martin (2004) and Aghion and Howitt (1998). However, it is a well established fact that these predictions are not in line with the empirical evidence from the historical evolution of prices and production of non-renewable resources. Prices for metals and hydrocarbons show different long term paths with mostly constant or even decreasing long term trends, whereas the extraction of non-renewable resources has strongly increased (Krautkraemer (1998), Livernois (2009) and Lee et al. (2006)).

In our model, we add innovation in the extraction technology to an endogenous growth model with an essential, non-renewable resource. The amount available of the non-renewable resource is a function of extraction costs and hence the investment in the extraction technology.

Exponential economic growth triggers exponentially growing investment in extraction technology. Innovation in the extraction technology offsets the cost-increasing effects of extracting the non-renewable resource from occurrences with lower ore grades, where "ore grade" is the concentration of a resource in the soil. Hence, the extraction and use of the non-renewable resource increase exponentially, whereas prices stay constant over the long run. We provide such evidence from data on prices and production of major non-renewable resources in the past 200 years. Our results suggest that the industrialisation of China and other emerging economies triggers investment in cost-reducing extraction technologies. If historical trends continue, innovation in the extraction technology will offset the depletion of easily accessible deposits. Even if non-renewable resource use and production increase exponentially, resource prices might stay constant in the long run.

Compared to the existing literature, our model combines technological progress in the extraction technology and the deterioration of the resource stock in an endogenous growth model that explicitely models the investment in the innovation of the extraction technology. Heal (1976) introduced a non-renewable resource, which is inexhaustible, but available at different grades and costs in a classical Hotelling (1931) optimal depletion model. Extraction costs increase with cumulative extraction, but then remain constant as a "backstop" supply is reached. Slade (1982) added exogenous technological progress in the extraction technology to the Hotelling (1931) model and predictes a U-shaped relative price curve. Cynthia-Lin and Wagner (2007) use a similar model with an inexhaustible non-renewable resource and obtain a constant relative price and increasing extraction. In comparison to our model, these models take the technological progress in the extraction technology as given and do not take output growth into account.

There are two papers to our knowledge that are similar to ours in that they include technological progress in the extraction of a non-renewable resource in an endogenous growth model. Fourgeaud et al. (1982) focus on explaining sudden fluctuations in the development of non-renewable resource prices. Tahvonen and Salo (2001) model the transition from a non-renewable energy resource to a renewable energy resource. Their model follows a learning-by-doing approach as technical progress is linearly related to the level of extraction and the level of productive capital. It explains decreasing prices and increasing consumption of non-renewable energy for a certain time period.

As opposed to these last two papers, our model aims to understand long run historic trends in a theoretical framework of economic growth. We argue that the continuation of these developments is a possible scenario for the foreseeable future.

This basic long-term perspective could be enriched with a number of aspects, from which we abstracted in order to highlight the main mechanism. This aspects include environmental externalities, uncertainty in research and recycling: Even though the extraction of non-renewable resource and their use is strongly linked to negative effects on the environment, we do not include such externalities.[1] Another limitation is the lack of market structure in the resource market. In the short run, these markets might be highly oligopolistic or even monopolistic. However, in the long run, these markets are rather competitive, thus coming close to our treatment. Furthermore, uncertainty in research and long investment horizons are likely to produce strong fluctuations in price and production, which we do not include. Finally, we do not explicitly deal with recycling. For metals, secondary resources are available in different scrap grades in deposits in the technosphere. Even in the case of recycling, the energy requirements and hence extraction costs rise exponentially to prohibitive levels for highly dispersed secondary metals in e.g. chemicals.[2] In so far, there are some similarities to the assumptions that we make on the extraction costs for primary resources.

In Section 2, we document geological evidence that supports the key assumptions of our model. In Section 3, we present an endogenous growth model which incorporates a resource extraction sector. Section 4 provides empirical evidence for the major results of the model. Section 5 concludes.

3.2 Stylized Facts on Innovation and Non-Renewable Resources

In our model we make two major assumptions based on stylized facts from geology. In this section we briefly present them. The first is the role of innovation in extraction technology for the availability of resources. The second describes the abundance and distribution of non-renewable resources in the earth's crust.

[1] This aspect has been treated by Acemoglu et al. (2009) among others.

[2] See Steinbach and Wellmer (2010). The authors argue that the metal supply will be obtained increasingly from secondary and less from primary resources in the future due to increasing energy requirements in extraction.

3.2.1 Innovation and Non-Renewable Resources

Minerals are available at different extraction costs in the earth's crust. Several reasons account for this phenomenon, including varying ore grades, thickness and depths of occurrences.

The definition of resources by the US-Geological Survey reflects this fact. It defines resources as "a concentration of naturally occurring solid, liquid, or gaseous material in or on the earth's crust in such form and amount that economic extraction (...) from the concentration is currently or potentially feasible.", see U.S. Geological Survey (2011), p. 193. The term "economic" implies that profitable extraction under defined investment assumptions has been established. All other occurrences of an element in the earth's crust that are not considered at least potentially economic are not classified as resources. The boundary between resources and other occurrences "is obviously uncertain, but limits may be specified in terms of grade, quality, thickness, depth, percent extractable, or other economic-feasibility variables.", see U.S. Geological Survey (2011), p. 194.

Throughout history, mineral resources have been extracted from ever decreasing grades or deeper depths. The example of copper in Figure 3.3 in the appendix illustrates that the ore grades of U.S. copper mines have constantly decreased over the long run. The same is true for hydrocarbons. Figure 3.4 shows that crude oil has been extracted from ever deeper sources in the Gulf of Mexico.

Innovation in the extraction technology has made it profitable to extract minerals from occurrences with lower ore grades, see Wellmer (2008). Case studies find that innovation in the extraction technology has offset cost increasing degradation of resources in the examples of the asbestos industry in Canada, see Lasserre and Ouellette (1988), and the offshore oil industry in the Gulf of Mexico, see Managi et al. (2004).

In his book on the history of copper Radetzki (2009) describes how technological innovation has made the extraction of copper from ever decreasing ore grades possible. 7000 years ago pure copper (100% ore grade) was used from nuggets. Small investments gradually decreased the extractable ore grade by developing processes. Today, ore grades of 0.2% can be extracted profitably. His account suggests that the cost of innovation might increase exponentially in making an additional ore grade accessible for human use. Decreasing the extractable ore grade from 50% to 49% has probably required only a small investment, but decreasing it from 1.2% to 0.2% required a lot of investment into technological progress.

As a consequence of technological progress, the amount of resources that is considered as economically feasible has stayed constant or even increased in the past decades. Figure 3.5 shows that the reserves of copper have increased by more than 600 percent over the last 60 years. Figure 3.6 presents similar data for reserves of conventional oil. Since the 1980s conventional oil reserves have doubled.

3.2.2 Geological Distribution of Non-Renewable Resources

Computing the total abundance of each of the elements in the earth's crust leads to enormous quantities for many non-renewable resources. This includes even those resources which are considered the most scarce. This is shown in Table 3.1, see also Nordhaus (1974). Hydrocarbons are quite common in the sediments of the earth's crust as well. Rogner (1997) assesses world hydrocarbon resources and comes to the conclusion that "fossil energy appears almost unlimited" (p. 249) given a continuation of historical technological trends.

	Reserves/ Annual production (Years)	**Resources/ Annual production** (Years)	**Crustal mass/ Annual production** (Years)
Aluminium	133	261,000	9,400,000,000
Iron	87	230	1,400,000,000
Copper	39	185	93,000,000
Gold	20	13	27,800,000
Rare earths	846	"Very large"	n.a.
Coal	144	2,900	
Oil	40	23	} 1,400,000
Unconventional oil	34	202	
Gas	2,100	2,700	

Table 3.1: Availability for selected non-renewable resources in years of production left in the reserve, resource and crustal mass at the current production rate.

Reserves include all material which can currently be extracted. The definition of resources can be found in Section 3.2.1. Sources: U.S. Geological Survey (2011), Perman et al. (2003), Nordhaus (1974), International Energy Agency (2010a), International Energy Agency (2010b), Federal Institute for Geosciences and Natural Resources (2010), Littke and Welte (1992). Note: Data for the crustal mass of conventional oil, gas and coal includes all organic carbon in the earth's crust.

However, the economic availability of these resources is, as explained above, a function of extraction costs and the development of extraction technologies. Hence, it would be unduly optimistic to consider all of these enormous quantities to be extractable in the near future.

The extraction costs are a function of the ore grades and other geological characteristics. The quantity of non-renewable resources is not uniformly distributed across the different ore grades in the earth's crust. Geochemical processes have decreased or increased the local abundance during history. Unfortunately, geologists do not agree on the distribution of the elements in the earth's crust. On the one hand, Ahrens (1953, 1954) suggests that all elements are lognormally distributed. On the other hand, Skinner (1979) proposes a bimodal distribution due to the so-called "mineralogical barrier".

Due to a lack of geological data, both parties acknowledge that an empirical proof is still outstanding. In a recent empirical study, Gerst (2008) concludes that he can neither confirm nor refute these two hypotheses. Based on worldwide data on copper deposits over the past 200 years, he finds evidence for a lognormal relationship between copper production and average ore grades. With respect to inference about future supply, we acknowledge that there is uncertainty about the extent of non-linearities in the development of ore grades in the earth's crust.

3.3 The Model

We set up a model of endogenous growth with a non-renewable resource where we assume that the stock of the resource is only limited at a given cost and for a given technology. By investing into extraction technology, the stock available at a given cost expands. This allows us to match the historical fact that consumption increased whereas prices of non-renewable resources exhibit constant or even decreasing long term trends.

Section 3.3.1 shows how the cost for innovation and the distribution of resources over ore grades can be combined to obtain the cost of research per unit of the resource. Section 3.3.2 uses this result to establish the resource dynamics. Section 3.3.3 integrates the resource dynamics into a Schumpeterian growth model. Section 3.3.4 presents how prices and resource consumption grow when resources are inexhaustible. Section 3.3.5 concludes the model section with a discussion on the limits to growth in this model.

3.3.1 The Extraction Technology

The General Technology Function

Let M_t be the cumulative amount of capital invested by the social planer into extraction technology up to time t (we drop the time index to simplify notation). We define the extraction technology as a function mapping ore grades into extraction costs depending on M:

$$\phi_M\colon [0,1] \times \mathbb{R}_+ \to \bar{\mathbb{R}}_+, (g, M) \mapsto \phi_M(g) \ . \tag{3.1}$$

This means, for a cumulative investment $M \in \mathbb{R}_+$ the social planer can extract ore grade $g \in [0,1]$ at cost $\phi_M(g) \in \bar{\mathbb{R}}_+ = \mathbb{R}_+ \cup \infty$. The lower the ore grade, the higher the cost. This implies that ϕ_M is non-increasing in g:

$$\forall M: \quad g > g' \quad \Rightarrow \quad \phi_M(g) \leq \phi_M(g') \ . \tag{3.2}$$

We assume that investing in M increases productivity for all ore grades Therefore, extracting the non-renewable resource becomes cheaper at any given ore grade:

$$\forall g: \quad \frac{\partial \phi_M(g)}{\partial M} \leq 0 \ . \tag{3.3}$$

At time t, the social planer invests an amount $\frac{\partial M_t}{\partial t}$ into the extractive technology to reduce extraction costs. The social planer determines the investment into the extraction technology as an optimization between extraction costs and investment in extraction technology. To simplify this optimization problem for the social planer, we will assume a very simple functional form for the technology function.

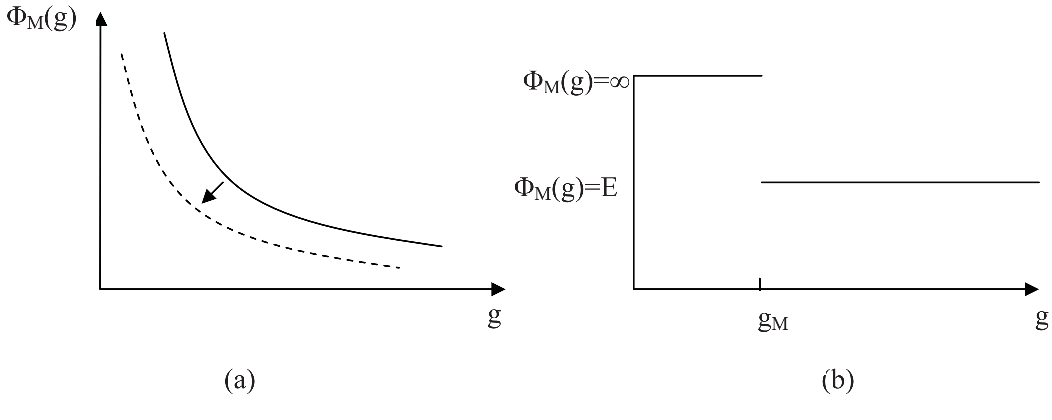

Figure 3.1: Extraction Costs as a Function of Ore Grades

A Simplified Extraction Technology Function

Figure 3.1, panel (a) shows the extraction technology function in its general form. The exploitation of lower ore grades generates higher costs, but with increasing investment into extraction technology the function moves downward. Panel (b) illustrates a very simple form of the extraction technology function, which we use in the following. In case (b), there is a certain ore grade associated with a unique level of investment into extraction technology g_M, above which the social planer can extract the resource at cost E. This function g_M maps the values of total past technology investments into a value for the ore grade which can be exploited at cost E:

$$g\colon \mathbb{R}_+ \to [0,1], M \mapsto g_M \ . \tag{3.4}$$

At lower ore grades than g_M extraction is impossible, because the cost is infinite. The technology function thus takes the degenerate form of

$$\phi_M(g) = \begin{cases} E, & \text{if} \quad g \geq g_M, \\ \infty, & \text{if} \quad g < g_M. \end{cases} \tag{3.5}$$

This simplifies the optimization: If unextracted deposits with an ore grade larger than g_M exist, the social planer can extract them without any investment into extraction technology. Otherwise, the social planner needs to invest into the extraction technology to produce the non-renewable resource needed in the next period.

The Per-Unit Cost of Innovation in the Extraction Technology

The social planer faces cost of E for extracting a unit of the non-renewable resource. However, to obtain the total production costs of the resource, we have to add the investment into extraction technology. To calculate the costs of investing into extraction technology per unit of the extracted resource, we need to combine two functions.

The first of these functions is g_M, the cost in terms of M of developing the technology to extract at a lower ore grade. Based on the evidence presented in Section 3.2.1, we consider a functional form of

$$g_M = \gamma_1 e^{-\gamma_2 M} \tag{3.6}$$

with parameters $\gamma_1, \gamma_2 \in \mathbb{R}_+$. Panel (a) of Figure 3.2 illustrates the shape of g_M. Hence additional gains in ore grade decrease with the amount of investment made.

The second function is the distribution of the non-renewable resources over ore grades. It maps a certain ore grade to the amount of resource available at that ore grade.

$$D\colon [0,1] \to \mathbb{R}_+, g \mapsto D(g) \tag{3.7}$$

The empirical evidence on this function has been discussed in Section 3.2.2. We formulate the relation in a general way with parameters $\delta_1, \delta_2 \in \mathbb{R}_+$ and $\delta_2 \leq 1$:

$$D(g) = -\delta_1 \ln(\delta_2 g) \tag{3.8}$$

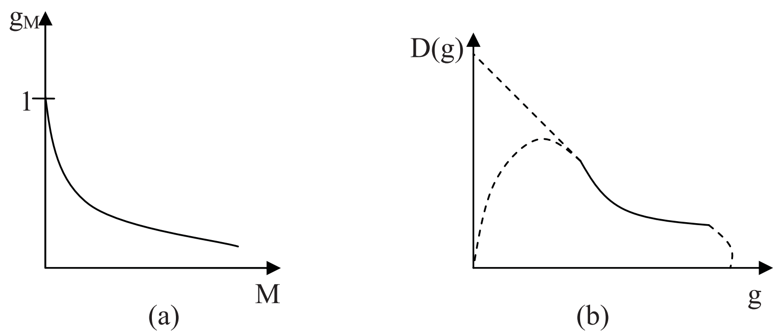

Figure 3.2: (a) Ore grade access as a function of accumulated technology investment
(b) Amount of metal available per ore grade

We are now ready to combine the technology and the density function:

Proposition 3.1 *The marginal cost for one unit of a resource in terms of investment in technology is constant and given by*

$$F = \frac{1}{\delta_1 \gamma_2}.$$

The proposition says that the innovation cost of the resource is constant and independent of the amount M invested in technology previously and of time. The exact amount of the innovation cost depends on parameters γ_2 and δ_1, which determine the curvature of the extraction technology as defined in equation (3.6) and the distribution of ore grades as in (3.8). The result depends on the functional forms. For functional forms that do not offset each other, the innovation cost would not be constant.

3.3.2 The Production Cost of the Resource

As we have seen in the previous section, two kinds of costs must be paid in order to produce a unit of the metal. The first is the extraction cost, labelled E above. The second is the cost for research in the extraction technology that allows the extraction at an ore grade marginally above the grade that has last been extracted in the period before. We assume this price to be denoted in units of capital.

The stock of the non-renewable resource at time t, for which the extraction technology is available, is noted $X_t \in \mathbb{R}_+$. X_t can refer to any non-renewable resource that is essential for production. This applies to the base metals for which we have data, but it might be possible to apply it to hydrocarbons as well.

The stock X_t is affected by an outflow as in traditional models based on Hotelling (1931) as well as by an inflow. The unit of the outflow is R_t, the amount of resources extracted. Its cost is noted E, the cost for extraction per unit. On the side of inflows we note units as S_t, the amount of resources added to the available stock. Its cost is F, the cost of research per unit as seen in the previous section. Noting time derivatives with a dot over the variable we can write the evolution of the stock as

$$\dot{X}_t = S_t - R_t \ . \tag{3.9}$$

Naturally, quantities of research and extraction as well as the stock of available resources are bound to be non-negative:

$$X \geq 0, S_t \geq 0, R_t \geq 0 \ . \tag{3.10}$$

Proposition 3.1 assures that the amount of the resource discovered for a given unit of investment is constant. Following the structure of the technology function, equation (3.5), the extraction cost is constant as well. The total expenditure for the production of the resource at time t is thus given by

$$R_t \cdot E + S_t \cdot F \ . \tag{3.11}$$

The success of research and development (R&D) is highly unpredictable which means that R&D investment produce results that arrive stochastically. To avoid running out of the resource, it is therefore desirable for the social planer to keep a positive amount of the resource X_t, from which the economy can draw in case of a sequence of bad luck in research.

Here, however, we abstract from stochastic R&D results. Intuitively, this implies that the social planer can extract from the original resource stock X_0 without investing into R&D. At the point where the stock is about to run out, investment starts at the optimal level. The mechanism in the case of stochastic R&D will be very similar with a positive stock used to buffer bad research draws.

In the next step we include equations (3.9) and (3.11) into a framework of Schumpeterian endogenous growth.

3.3.3 The Growth Framework

We include the extraction technology and the production cost into a growth framework in order to analyse their implications on a historical scale. For this we choose the Schumpeterian approach of Aghion and Howitt (1998), chapter 5. On the one hand, this model is a standard framework which allows to understand how our description of the mining sector fits into the literature. The general idea of this kind of model is consistently supported by empirical investigations, see Ha and Howitt (2007), Madsen (2008) and Ang and Madsen (2011). On the other hand, it is a tractable model that allows to keep the non-essential features of the model manageable and focus on what is new.

The lifetime utility function is

$$W = \int_0^\infty e^{-\rho t} u(c) dt \tag{3.12}$$

with $\rho > 0$ and the isoelastic utility function

$$u(c) = \frac{c^{1-\varepsilon} - 1}{1 - \varepsilon}, \quad \varepsilon > 0 \; . \tag{3.13}$$

The production function for final output is

$$Y = L^\beta \int_0^1 B(i) x(i)^\alpha di R^\nu$$

where L is labor, $B(i)$ is a quality parameter indicating the productivity of intermediate good i and R is the resource as before. Each intermediate good is produced according to the constant-returns production function $x(i) = K(i)/B(i)$ where $K(i)$ is the amount of capital used to produce i. It is optimal to produce the same quantity of each intermediate good

$x(i) = K/B$, see Section 5.1.2 in Aghion and Howitt (1998). This simplifies the production function to

$$Y = K^{\alpha} B^{1-\alpha} L^{\beta} R^{\nu}. \tag{3.14}$$

The coefficients α, β, ν are all positive with

$$\alpha + \beta + \nu = 1. \tag{3.15}$$

Thus, for a given state of research there are constant returns to scale in the three inputs capital, labor and natural resources.

Note that the model includes two types of technology. One type is the technology specific to resource extraction. The level of extraction technology is proportional to M, the aggregate amount of investment into this technology. The other type is the "general technology" B, the technological level of the intermediate good producers as in the standard Schumpeterian model.

There is a total supply of labor normalized to 1. This can be distributed to research, noted n, and manufacturing L, so that

$$L = 1 - n\ . \tag{3.16}$$

This allocation will be endogenously determined.

The evolution of the general technology is given as

$$\dot{B} = \sigma \eta n B. \tag{3.17}$$

σ is a parameter representing the size of each innovation. η is a parameter of the research technology indicating the Poisson arrival rate of innovations to a single research worker.

The details of the setup up to this point can be found in the description of the models in Section 5.1 and 5.3.2 in Aghion and Howitt (1998). We now include the cost for the resource (3.11) into the model.

The change in the capital stock is given as

$$\dot{K} = Y - C - ER - FS. \tag{3.18}$$

This means that total production has to be allocated to consumption C, investment $\dot{K}$, extraction cost ER and research in extraction technology FS.

So just as research into the general technology for intermediate goods is endogenous and depends on labor investments, equation (3.17), research into the input factor resources is also endogenous. For each investment into the resource stock an amount of F units of capital has to be used. Unlike the sector for intermediate goods which could keep producing with a fixed technology, the mining sector needs research for each unit it produces, because in a world without uncertainty the deposits available at the given level of technology are already exploited in optimum. Nevertheless, there is a trade-off between the different technology investments. The more is invested into the general technology, the less is available for mining and vice versa. In equilibrium, investments are allocated in such a way as to equalize productivity in terms of consumption.

3.3.4 Results

As a first step, we show that the intuition concerning the management of the stock can be verified. In an economy without uncertainty, no resources are lost on research, S, as long as a positive stock of the resource, X, remains. However, no resource can be extracted for which the technology hasn't been developed. Consequently, research has to keep up with extraction, R.

Proposition 3.2 *As long as a positive amount of the resource remains there is no investment into extraction technology:*

$$X > 0 \quad \Rightarrow \quad S = 0 \; .$$

As soon as the stock of the resource is zero, resources made available through technological investment equal extracted resources:

$$X = 0 \quad \Rightarrow \quad S = R \; .$$

This strong result of permanently zero resource stocks is due to the assumed absence of uncertainty. Inclusion of uncertainty would obtain $S \approx R$ for a positive X^*.

Just to illustrate that the model can be solved, we note

Proposition 3.3 *There is a steady state in which the common growth rate of consumption C, capital K and output Y is*

$$g_Y = \frac{1}{\varepsilon}\left(\eta\sigma\frac{1-\alpha}{1-\alpha-\nu} - \rho\right).$$

The growth rate of technology is

$$g_B = (1-\varepsilon)\left(1 - \frac{\nu}{1-\alpha}\right)g_Y + \eta\sigma - \rho + \frac{\nu\rho}{1-\alpha}\,.$$

We can now derive a prediction on the consumption of non-renewable resources:

Proposition 3.4 *The consumption of non-renewable resources grows at the same rate as output, and the output-resource ratio is given by*

$$\frac{R}{Y} = \frac{\nu}{E+F}. \tag{3.19}$$

Note that this result relies heavily on the assumption that costs per unit of resource are constant. This assumption may fail in the very long run, but as we have seen in the stylized facts, the point of exhaustion may be hundreds of thousand of years away for many essential resources.

We made an *assumption* on the distribution of resources across ore grades. This is the equation (3.8), which reflects the state of knowledge in *geology*. Our *results* concerns the *economic* use of resources in a growth framework. Summarizing, we assume that enormous resources are available on earth, and as a result we obtain that they are practically inexhaustible to an innovating economy.

Propositions 3.3 and 3.4 allow to understand which parameters affect the growth rate of the economy and which affect the level of resource use:

Proposition 3.5 *The resource/output ratio $\frac{R}{Y}$ is*
(i) positively affected by ν, the elasticity of output with respect to the resource,
(ii) negatively affected by E, the extraction cost of the resource and
(iii) positively affected by δ_1 and γ_2, the two curvature parameters.
The growth rate of the economy g_Y is positively affected by ν, the elasticity of output with respect to resources.

That the cost of extraction E decreases resource use is straightforward. As δ_1 and γ_2 increase it becomes cheaper to innovate and more resources are available for a given technological advance. Therefore, the cost of research per unit of the resource reduces and thus increases the amount of resource used. An increase in ν means that production relies more heavily on resource use. This has two implications. First, a higher share of capital is invested in the production of the resource, inducing a higher resource/output ratio. Second, it shifts more importance on resources (recall that $\alpha + \beta + \nu = 1$). If the increase in ν is offset by an decrease in α, it leaves the growth rate unaffected. If it is offset by an decrease in β however, it moves weight from a limited input, labor, to an input that grows exponentially, resources, and allows the economy to grow faster.

3.3.5 Discussion

Our model takes a stylized social planner approach, with constraints on the availability of the physical commodities, notably the non-renewable resource, equation (3.9), labor, equation (3.16), and capital, equation (3.18). There are no market prices. However, a more detailed model, including a decentralized resource sector would yield similar implications. Individual firms would sell the non-renewable resource at the extraction cost $E + F$ times a mark-up μ. The mark-up depends on the competition in the sector. The implications of our model would remain the same as long as the mark-up has no long-term trend.

Function g from equation (3.4) maps the cumulative amount of investment in development of the extraction technology into the ore grade that can be extracted. Geologists cannot give an exact functional form for g, so we used the form given in (3.6) as a plausible hypothesis. How would other functional forms affect the predictions of the model? First, the predictions are valid for all parameter values $\gamma_1, \gamma_2 \in \mathbb{R}_+$. Secondly, if g is discontinuous with a "jump" at M_0 at which parameters change to $\gamma_1', \gamma_2' \in \mathbb{R}_+$, there would be two balanced growth paths: one for the period before and one for the period after the jump. Both would behave as our model predicts. They would differ in the capital cost of resources and the amount of resources used in the economy. To see this, recall from Proposition 3.1 that F is a function of γ_2. A non-exponential form of g would affect the results.

How does this model compare to a model with finite resources? Unlike many models on resource use, we do not assume that resources are finite as their availability is a function of technological progress. As a consequence, resource availability does not limit growth.

Substitution of non-renewable resources by capital and increasing returns to scale are therefore not necessary for sustained growth. Growth depends on technical progress as much as it does in standard growth models without a non-renewable resource.

Our model suggests that resources can be thought of as a form of capital: The economy has to invest into it, but if it does, the input is available without limits. This feature marks a distinctive difference to models such as that of Bretschger and Smulders (2003). They investigate the effect of various assumptions on substitutability and a decentralized market on long-run growth, but keep the assumption of finite resources. Without this assumption, the elasticity of substitution between resources and other input factors is not central to the analysis of limits to growth.

The version of our model with finite resources is given in Aghion and Howitt (1998), chapter 5.3.2. In this model, the finite stock of the resource gradually declines. Over time, production and use of the non-renewable resource decline as well and prices increase. The growth rate of the model from Aghion and Howitt (1998) is given by

$$g_Y = \frac{1}{\varepsilon}\left(\eta\sigma - \rho\right).$$

This is similar to our model, but our model exhibits an additional ν, the elasticity of output with respect to the resource, entering negatively into the denominator. The growth rate in our chapter is higher, as growth is not constrained by a finite non-renewable resource and as two of the three inputs (capital and resource extraction) grow exponentially.

How robust are our results to changes in the production function? The Cobb-Douglas production function is the standard assumption in Schumpeterian models and endogenous growth models in general, see Aghion and Howitt (1998), chapter 3, Barro and Sala-i-Martin (2004), chapter 7, and Acemoglu (2009), chapter 14. It is a special case of an elasticity of substitution of 1. As Dasgupta and Heal (1979) point out in their Section 7.2, the question of limits to growth depends crucially on substitutability. Following this book chapter, we could generalize our production function to a CES production function:

$$Y = B\left[\alpha K^{\frac{\psi-1}{\psi}} + \beta L^{\frac{\psi-1}{\psi}} + \nu R^{\frac{\psi-1}{\sigma}}\right]^{\frac{\psi}{\psi-1}} \quad . \tag{3.20}$$

In the case $\psi > 1$ the resource is not necessary for production. $\psi = 1$ is the case of the Cobb-Douglas production function. In the remaining case, $\psi < 1$, total production is strictly less than total resources available multiplied by a constant. If resources are finite, the economy is doomed in this case, meaning that output has to decline to zero. In our model, resources are not finite, so that there is no upper bound for output.

3.4 Empirical Analysis: Long Run Prices, Production and GDP

Our model predicts constant prices, exponential growth in production and consumption of the non-renewable resource, and exponential growth in output in the long run. In the following, we examine to what extent our theoretical results are in line with the historical evidence on non-renewable resource markets. We use long run data on world GDP as well as prices and primary refined production of five major base metals and crude oil, for which long run data is available. We examine the long run trends following Cynthia-Lin and Wagner (2007).

As Figure 3.7 in the appendix indicates, real prices exhibit strong short term fluctuations. However, we find that the growth rates of all prices are not significantly different from zero and trendless in the long run, confirming one major component of our model, see Table 3.2.

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil
Range		1905-2009	1792-2009	1792-2009	1792-2009	1824-2009	1862-2009
Constant	Coeff.	-1.764	0.184	0.109	1.668	0.702	7.236
	t-stat.	-0.181	0.073	0.4	0.73	0.148	0.79
Lin.Trend	Coeff.	0.008	0.011	0.006	-0.001	0.013	-0.017
	t-stat.	0.138	0.533	0.259	-0.079	0.378	-0.276

Table 3.2: Tests of the stylized fact that the growth rates of prices equal zero and do not follow a statistically significant trend. The table presents coefficients and t-statistics for regressions of the growth rates on a constant and a linear trend.***, ** and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Sources: Schmitz (1979), British-Petroleum (2010) and Federal Institute for Geosciences and Natural Resources (2011a). Please see also the note of Figure 3.7 for further information on the deflation of prices and the exchange rates used.

As Figure 3.8 in the appendix shows, world primary production of the examined non-renewable resources and world GDP have grown exponentially since 1820. A closer statistical examination reveals that the production of the non-renewable resources exhibits significantly positive growth rates in the long run, see Table 3.3. This is in contrast to the model of

Hotelling (1931) and the majority of theoretical papers on non-renewable resources, which predict a declining production of resources, but completely in line with the prediction of our model.

Furthermore, we find evidence that the growth rates of the production of copper, lead, tin and zinc do not exhibit a statistically significant trend over the long run. Hence, the levels of production of these non-renewable resources grow exponentially over time, which confirms the basic prediction of our model.

The level of crude oil production follows this exponential pattern only until 1975. Including the time period from 1975 until today reveals a statistically significant negative trend, therefore diminishing growth rates over time and hence only cubical growth. In the case of aluminium, we also find diminishing growth rates over time and hence no exponential growth of production level. This might be due to the fact that recycling has become important in aluminium production. Recycling is neither included in our model nor in the data.

The growth rates of world GDP exhibit an increasing trend over the long run, hinting at an underlying explosive growth process, whereas our model predicts exponentially growing output. However, the explosive growth process might be due to the strong increase of the service sector in the world economy, which our model does not account for.

As our model does not include population growth, we run the same tests for the per capita data of the respective time series. We find some evidence that the growth rates of the production of copper and zinc are positive and mostly trendless over the long run. Hence, their levels of production grow exponentially over time. We find the same result for tin only for the the very long time period from 1792 to 2009 but not for subperiods. Growth rates of lead production exhibit a statistically significant negative trend for long time periods, and no statistically significant constant and trend for the shorter time periods. The results for per capita aluminium and crude oil production as well as per capita GDP do not significantly change compared to the absolute data.

Overall, our investigation provides empirical evidence for the theoretical results of the model. It is in line with broad trends in the long run data on world prices and world production for at least some major non-renewable resources. Our model under-predicts the development of world output, probably because the service sector is not included.

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil	World GDP
Range		1855-2009	1821-2009	1802-2009	1792-2009	1821-2009	1861-2009	1792-2009
Constant	Coeff.	48.464	4.86	16.045	4.552	30.801	35.734	0.128
	t-stat.	*** 3.810	*** 2.694	*** 3.275	* 2.231	** 2.58	*** 4.365	0.959
Lin.Trend	Coeff.	-0.221	-0.006	-0.087	-0.016	-0.174	-0.182	0.018
	t-stat.	** -2.568	-0.439	** -2.294	-0.999	* -1.975	*** -3.334	*** 16.583
Range		1855-2009	1850-2009	1850-2009	1850-2009	1850-2009	1861-2009	1850-2009
Constant	Coeff.	35.657	5.801	6.032	3.569	5.579	25.198	0.995
	t-stat.	*** 4.398	*** 3.461	***3.371	* 2.185	*** 3.774	*** 4.81	*** 5.49
Lin.Trend	Coeff.	-0.221	-0.018	-0.038	-0.015	-0.021	-0.182	0.019
	t-stat.	** -2.568	-1.007	-1.938	-0.833	-1.308	*** -3.334	*** 9.797
Range		1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009
Constant	Coeff.	19.703	5.965	2.980	2.844	4.44	9.883	2.004
	t-stat.	*** 5.498	*** 2.651	* 2.043	1.361	* 2.225	*** 6.912	*** 7.8
Trend	Coeff.	-0.178	0.035	-0.019	-0.015	-0.018	-0.083	0.018
	t-stat.	*** 3.174	-0.995	-0.853	-0.464	-0.592	***-3.711	***4.549
Range		1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009
Constant	Coeff.	10.781	5.043	13.205	0.051	5.675	9.897	4.729
	t-stat.	*** 7.169	*** 4.979	*** 2.936	0.028	*** 4.619	*** 9.574	*** 12.89
Lin.Trend	Coeff.	-0.171	-0.057	-0.48	0.04	-0.078	-0.196	-0.028
	t-stat.	*** -3.999	-1.978	-1.553	0.768	* -2.255	*** -6.64	*** -2.724
Range		1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975
Constant	Coeff.	50.75	6.307	3.851	3.762	4.384	12.272	1.244
	t-stat.	*** 4.846	** 2.543	1.938	1.664	* 2.032	*** 4.060	*** 5.509
Lin.Trend	Coeff.	-0.53	-0.024	-0.018	-0.026	-0.005	-0.072	0.027
	t-stat.	*** -2.974	-0.566	-0.536	-0.66	-1.26	-1.403	***7.045

Table 3.3: Tests for the stylized facts that growth rates of world primary production and world GDP are equal to zero and trendless. The table presents coefficients and t-statistics for regressions of the growth rates on a constant and a linear trend. ***, ** and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Sources: Schmitz (1979), Neumann (1904), Metallgesellschaft (1904), Federal Institute for Geosciences and Natural Resources (2011b) and Maddison (2010)

		Aluminum	Copper	Lead	Tin	Zinc	Crude Oil	World GDP
Range		1855-2009	1821-2009	1802-2009	1792-2009	1821-2009	1861-2009	1792-2009
Constant	Coeff.	48.301	5.474	20.57	4.427	30.7	35.689	0.032
	t-stat.	*** 3.824	*** 3.06	*** 3.845	* 2.181	** 2.584	*** 4.379	0.276
Lin.Trend	Coeff.	-0.229	-0.018	-0.125	-0.023	-0.182	-0.19	0.01
	t-stat.	*** -2.677	-1.367	*** -3.025	-1.457	* -2.071	*** -3.499	*** 11.066
Range		1855-2009	1850-2009	1850-2009	1850-2009	1850-2009	1861-2009	1850-2009
Constant	Coeff.	35.043	5.399	5.629	3.179	5.18	24.681	0.628
	t-stat.	*** 4.353	*** 3.254	***3.169	1.961	*** 3.541	*** 4.733	*** 4.052
Lin.Trend	Coeff.	-0.229	-0.027	-0.047	-0.024	-0.03	-0.19	0.01
	t-stat.	*** -2.677	-1.523	** -2.442	-1.348	-1.895	*** -3.499	*** 5.876
Range		1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009	1900-2009
Constant	Coeff.	18.595	4.985	2.028	1.903	3.473	8.869	1.071
	t-stat.	*** 5.242	* 2.241	1.41	0.918	1.763	*** 6.306	*** 4.862
Trend	Coeff.	-0.l84	-0.042	-0.027	-0.023	-0.026	-0.09	0.01
	t-stat.	*** -3.315	-1.214	-1.186	-0.694	-0.404	*** -4.084	*** 3.01
Range		1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009	1950-2009
Constant	Coeff.	8.583	2.952	1.141	-1.954	3.578	7.716	2.632
	t-stat.	*** 5.742	*** 2.892	1.04	1.086	*** 2.87	*** 7.493	*** 7.444
Lin.Trend	Coeff.	-0.156	-0.044	-0.35	0.051	-0.065	-0.18	-0.016
	t-stat.	*** -3.667	-1.515	-1.129	0.997	-1.819	*** -6.14	-1.551
Range		1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975	1875-1975
Constant	Coeff.	50.004	5.854	3.413	3.317	3.942	11.789	0.834
	t-stat.	*** 4.81	** 2.386	1.738	1.480	1.851	*** 3.933	*** 4.509
Lin.Trend	Coeff.	-0.542	-0.038	-0.032	-0.039	-0.019	-0.086	0.013
	t-stat.	*** -3.06	-0.908	-0.959	-1.028	-0.517	-1.691	***4.004

Table 3.4: Tests for the stylized fact that growth rates of world per capita primary production and world per capita GDP are equal to zero and trendless. The table presents coefficients and t-statistics for regressions of the growth rates on a constant and a linear trend. ***, ** and * indicate significance at the 1%, 2.5% and 5% level, respectively.

Sources: Schmitz (1979), Neumann (1904), Metallgesellschaft (1904), Federal Institute for Geosciences and Natural Resources (2011b) and Maddison (2010).

3.5 Conclusion

This chapter takes a combined empirical and theoretical look at a wide range of natural resources, classified into important industrial metals such as copper on the one hand and hydrocarbons, which are presently extracted in the form of oil for example, on the other hand. We claim that these resources are non-renewable but inexhaustible. They are non-renewable because they do not regenerate naturally in a time-frame relevant to humanity. But they are inexhaustible because they are available in a form that is accessible in such large quantities that they could be used at the current rate for at least hundreds of years to come.

This result is both empirical and theoretical. It is empirical because it is based on geological evidence on the quantity and the distribution of the investigated resources on earth. It is theoretical because it uses a endogenous growth model to understand the pattern of prices, resource consumption and the process of investing in extraction technology. The theoretical side explains how the economy can make use of the geological preconditions on earth.

Our results are a positive statement on past developments and future *possibilities*. They do not make a normative statement on how these possibilities should be used. Resource extraction and the use of non-renewable resources is associated to tremendous negative environmental externalities. Internalizing these externalities is a broad field of analysis in itself, see Acemoglu et al. (2009). We intend to complement the literature on sustainable growth by challenging the assumption of resource exhaustibility. It would be interesting to merge our model of innovation in extraction technology with the model by Acemoglu et al. (2009) and to analyse the policy implications.

The model is written in the simplest form that still conveys the key message. Numerous extensions could be made to explore related aspects in detail. Incorporating them into the model will not change the key result of resource inexhaustibility but may reveal additional and related insights. These extensions include a decentralised extraction sector, a stochastic process of R&D, a detailed model of process innovation in the extraction sector and the effect of recycling.

Appendix to Chapter 3

3.A Figures

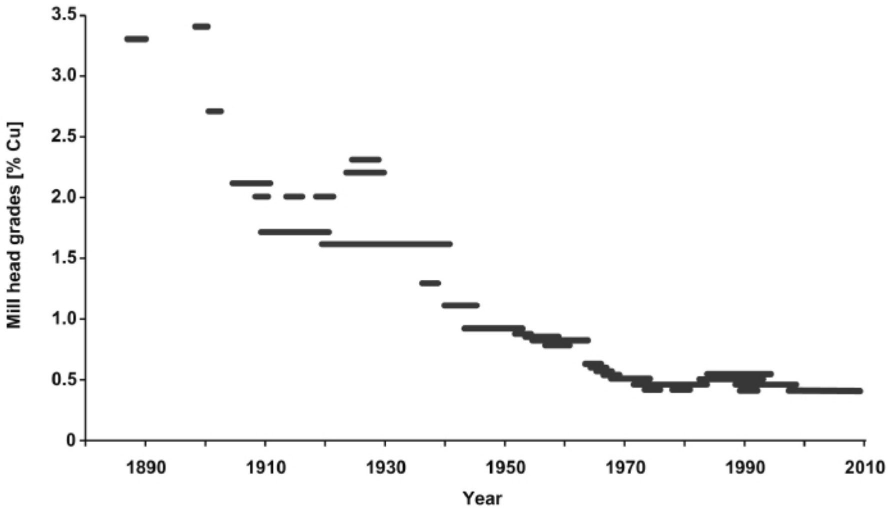

Figure 3.3: Historical Development of Mining of Various Grades of Copper in the U.S.

Source: Wagner and Wellmer (2009).

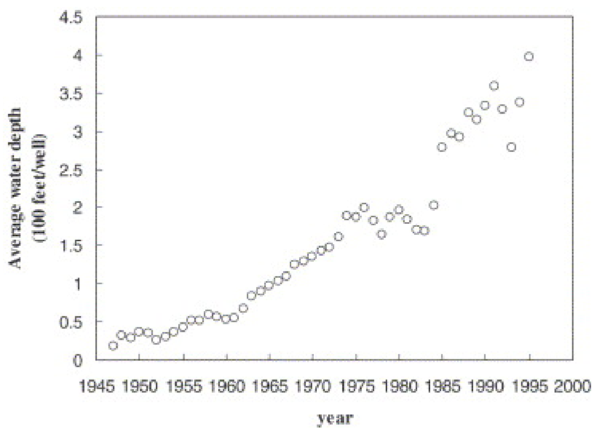

Figure 3.4: Average Water Depth of Wells Drilled in the Gulf of Mexico.

Source: Managi et al. (2004).

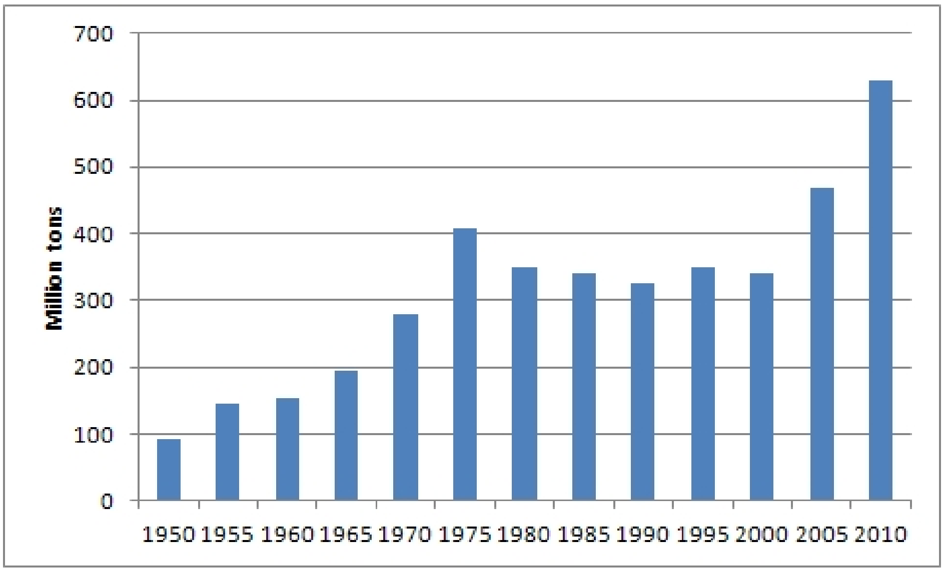

Figure 3.5: The Evolution of World Copper Reserves, 1950 - 2010.

Sources: Tilton and Lagos (2007), U.S. Geological Survey (2011).

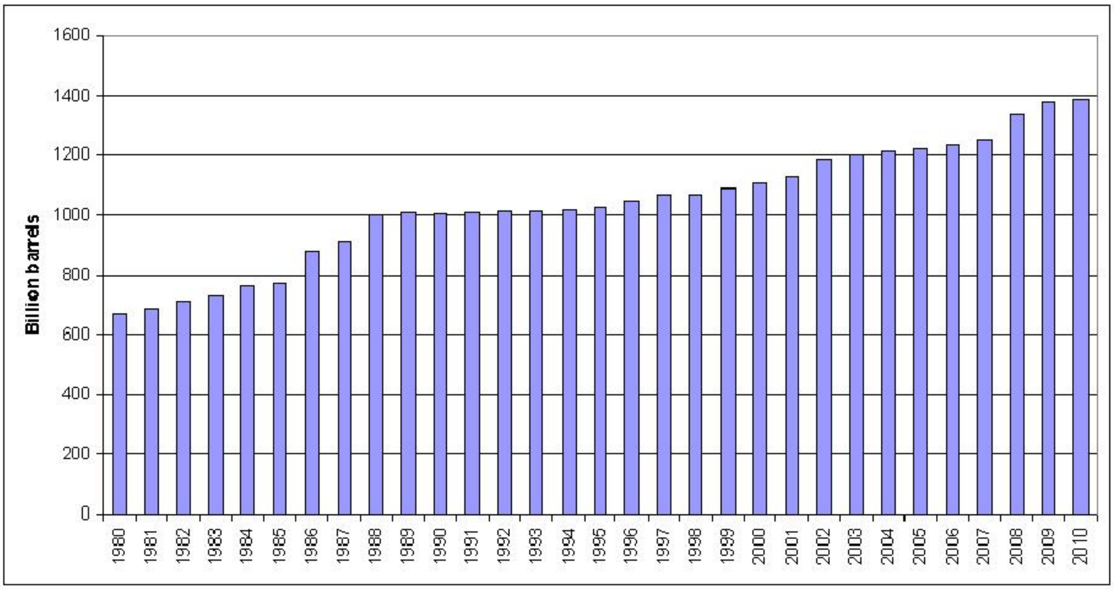

Figure 3.6: Historical Evolution of Conventional Oil Reserves, 1950 - 2010.

Source: British-Petroleum (2010).

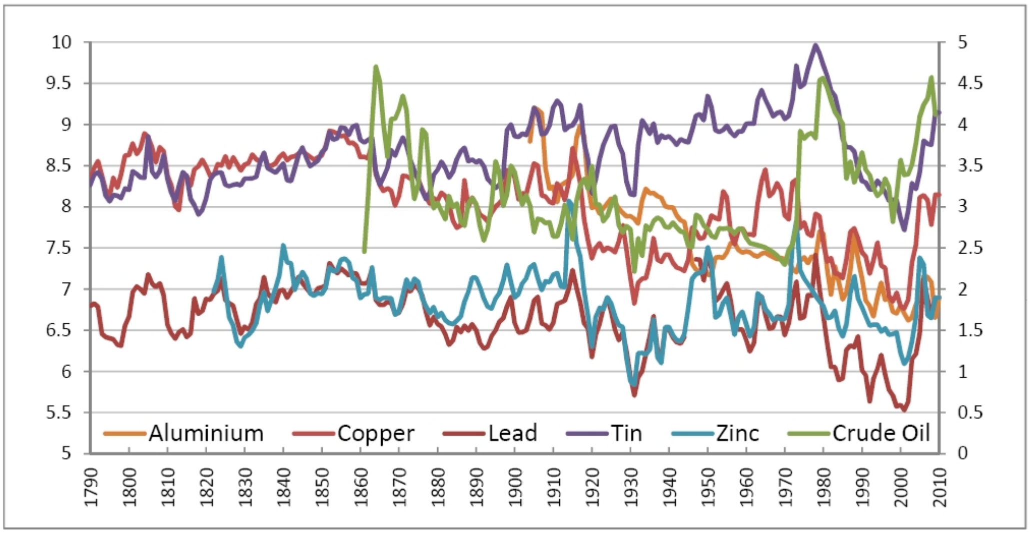

Figure 3.7: Prices of different non-renewable resources in constant 1980-82 US-Dollar in logs.

Sources: Schmitz (1979), British-Petroleum (2010) and Federal Institute for Geosciences and Natural Resources (2011a). Notes: All prices, except from the prize for crude oil, are prices of the London Metal Exchange and its predecessors. The oil price is the US-price, as assembled by British-Petroleum (2010). As the price of the London Metal Exchange used to be denominated in British Sterling in earlier times, we have converted these prices to US-Dollar by using historical exchange rates from Officer (2011b). We use the US-Consumer Price Index provided by Officer (2011a) and the US Bureau of Labor Statistics (2010) for deflating prices. The secondary y-axis relates to the price of crude oil.

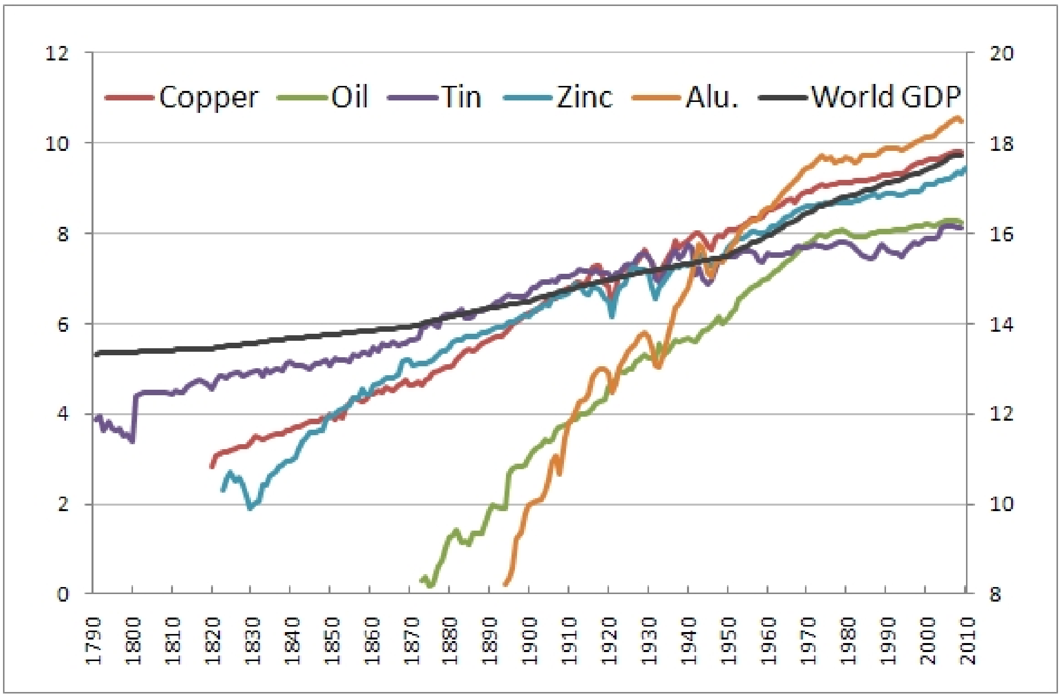

Figure 3.8: World primary production of non-renewable resources and world GDP in logs.

Sources: Schmitz (1979), Neumann (1904), Metallgesellschaft (1904), Federal Institute for Geosciences and Natural Resources (2011b) and Maddison (2010).

3.B Proofs

Proof of Proposition 3.1

The amount of the resource obtained per unit of technology investment $A(M)$ is given by

$$\begin{aligned} A(M) &= D(g_M) \\ &= -\delta_1 \ln(\delta_2 \gamma_1 e^{-gamma_2 M}) \\ &= -\delta_1 \ln(\delta_2 \gamma_1) + \delta_1 \gamma_2 M. \end{aligned}$$

Thus the marginal amount of the resource made available for one unit of technology investment M is

$$\frac{\partial A(M)}{\partial M} = \delta_1 \gamma_2$$

and thus a constant. The cost for a unit of the resource in terms of technology investment is constant as well and given by the amount invested per unit of the resource:

$$F = \frac{1}{\delta_1 \gamma_2}.$$

Proof of Proposition 3.2

The model contains the dynamics of the three state variables capital K, intermediate good quality B and the stock of the resources X:

$$\begin{aligned} \dot{K} &= K^{\alpha} B^{1-\alpha} (1-n)^{\beta} R^{\nu} - C - ER - FS, \\ \dot{B} &= \eta \sigma B n, \\ \dot{X} &= S - R \end{aligned}$$

as well as two non-negativity constraints (the resource input R is obviously positive since it is an essential input to production):

$$S \geq 0, \tag{3.21}$$

$$X \geq 0\,. \tag{3.22}$$

The Hamiltonian to be maximized is thus

$$H = u(C) + \lambda[K^{\alpha} B^{1-\alpha} (1-n)^{\beta} R^{\nu} - C - ER - FS] + \mu[\eta \sigma B n] + \varphi[S - R] + w_1 S + w_2 X\ .$$

The first order conditions for S, K and X are

$$\begin{aligned} -\lambda F + \varphi + w_1 &= 0, \\ \dot{\lambda} &= \delta \lambda - \lambda \alpha \frac{Y}{K}, \\ \dot{\mu} &= \delta \mu + w_2. \end{aligned}$$

Writing the last two of these in terms of growth rates yields

$$-\lambda F + \varphi + w_1 = 0, \tag{3.23}$$
$$g_\lambda = \delta - \alpha \frac{Y}{K}, \tag{3.24}$$
$$g_\mu = \delta + \frac{w_2}{\mu}. \tag{3.25}$$

The non-negativity conditions are

$$w_1 \geq 0, \quad w_1 S = 0, \tag{3.26}$$

$$w_2 \geq 0, \quad w_2 X = 0. \tag{3.27}$$

Let us first consider the case where there is a positive initial stock $X > 0$. Then by condition (3.27) we have $w_2 = 0$. In that case and if $w_1 = 0$, then by (3.23) we have $g_\lambda = g_\varphi$ so that conditions (3.24) and (3.25) imply $\frac{Y}{K} = 0$, which cannot be true in equilibrium. Therefore we have $w_1 > 0$ and it follows from equation (3.26) that $S = 0$.

Now let us assume that the stock of the resource is zero, $X = 0$. Then it is also constant over time, so that $\dot{X} = 0$. From this it follows by (3.9) that $S = R$.

Proof of Proposition 3.3

Using Proposition 3.2, the Hamiltonian to be maximized can be simplified to

$$H = u(C) + \lambda[K^\alpha B^{1-\alpha}(1-n)^\beta R^\nu - C - (E+F)R] + \mu\eta\sigma B n \; .$$

First order conditions are

$$\begin{aligned}
\frac{\partial H}{\partial C} = u'(C) - \lambda &= 0, \\
\frac{\partial H}{\partial n} = \lambda\beta(1-n)^{\beta-1}(-1)K^\alpha B^{1-\alpha} R^\nu + \mu\eta\sigma B &= 0, \\
\frac{\partial H}{\partial R} = \lambda(1-n)^\beta K^\alpha B^{1-\alpha} \nu R^{\nu-1} - \lambda(E+F) &= 0, \\
\frac{\partial H}{\partial K} = \lambda(1-n)^\beta \alpha K^{\alpha-1} B^{1-\alpha} R^\nu &= \lambda\rho - \dot{\lambda}, \\
\frac{\partial H}{\partial B} = \lambda(1-n)^\beta (1-\alpha) K^\alpha B^{-\alpha} R^\nu + \mu\eta\sigma n &= \mu\rho - \dot{\mu} \; .
\end{aligned}$$

The FOC with respect to C can be written $C^{-\varepsilon} = \lambda$ and thus

$$g_\lambda = -\varepsilon g_K. \tag{3.28}$$

The FOC with respect to n can be written as $\mu = \beta c^{-\varepsilon} V(1-n)^{-1}[\eta\sigma B]^{-1}$ and thus

$$g_\mu = (1-\varepsilon) g_K - g_B, \tag{3.29}$$

where we have used $g_K = g_Y = g_C$, see Barro and Sala-i-Martin (2004), chapter 2.5. The FOC with respect to R can be written $\nu\frac{Y}{R} = E + F$ and thus

$$g_R = g_Y = g_K. \tag{3.30}$$

The FOC with respect to K can be written as $\alpha c^{-\varepsilon}\frac{Y}{K} = c^{-\varepsilon}\rho + \varepsilon c^{-\varepsilon-1}\dot{c}$ and thus

$$g_K = \frac{1}{\varepsilon}\left(\alpha\frac{Y}{K} - \rho\right). \tag{3.31}$$

The FOC with respect to B can be written as $\frac{1}{\mu}c^{-\varepsilon}(1-\alpha)\frac{Y}{B} + \eta\sigma n = \rho - \frac{\dot{\mu}}{\mu}$ and thus

$$g_B = (1-\varepsilon)\left(1 - \frac{\nu}{1-\alpha}\right) g_K + \eta\sigma - \rho + \frac{\nu\rho}{1-\alpha}\ . \tag{3.32}$$

where we substituted in equation (3.29).

From the production function we get

$$g_B = \left(1 - \frac{\nu}{1-\alpha}\right) g_K \tag{3.33}$$

Substituting equation (3.31) into equation (3.33) we get

$$g_B = \left(1 - \frac{\nu}{1-\alpha}\right)\frac{1}{\varepsilon}\left(\alpha\frac{Y}{K} - \rho\right). \tag{3.34}$$

Substituting equation (3.31) into equation (3.32) we get

$$g_B = \frac{1-\varepsilon}{\varepsilon}\alpha\frac{Y}{K} - \frac{\rho}{\varepsilon} - \frac{1-\varepsilon}{\varepsilon}\alpha\frac{\nu}{1-\alpha}\frac{Y}{K} + \frac{\nu}{1-\alpha}\frac{1}{\varepsilon}\rho + \nu\sigma\ . \tag{3.35}$$

Equating equation (3.34) and equation (3.35) yields

$$\alpha \frac{Y}{K} = \eta\sigma \frac{1-\alpha}{1-\alpha-\nu}. \tag{3.36}$$

Substituting this into equation (3.31) yields

$$g_K = \frac{1}{\varepsilon}\left(\eta\sigma\frac{1-\alpha}{1-\alpha-\nu} - \rho\right). \tag{3.37}$$

Proof of Proposition 3.4

The FOC for the resource R in the proof of Proposition 3.3 can be written as

$$R = \frac{\nu Y}{E+F} .$$

Since output Y grows exponentially and the other terms on the right are constant, R grows exponentially as well.

Proof of Proposition 3.5

For the first statement use $F = \frac{1}{\delta_1 \gamma_2}$ and Proposition 3.4. The second statement follows from Proposition 3.3.

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