Essays on Fiscal Policy

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Contents

Zusammenfassung

Diese Dissertation entstand im Rahmen meines Studiums im Doktorandenprogramm *Decision Sciences* an der Graduate School of Decision Sciences sowie während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Makroökonomie der Universität Konstanz. Sie umfasst drei unabhängige Kapitel, die sich mit den Zielkonflikten befassen, mit denen die Fiskalpolitik im Kontext der Bevölkerungsalterung und Automatisierung konfrontiert ist.

Im ersten Kapitel, *Population aging, inequality and public policy*, untersuche ich die Auswirkungen und quantifiziere die Folgen der Bevölkerungsalterung für die politische Ökonomie, die der Verteilung öffentlicher Ressourcen zwischen Renten und Bildung zugrunde liegt – zweier Bereiche der öffentlichen Ausgaben, die sinnbildlich für den Kompromiss zwischen der Verteilung öffentlicher Ressourcen zwischen älteren und jüngeren Menschen in einer Volkswirtschaft stehen. Zu diesem Zweck entwickle ich ein quantitatives Modell überlappender Generationen mit heterogenen Haushalten, das auf die deutsche Volkswirtschaft im Jahr 2020 kalibriert ist. Das Modell umfasst den Staat als Akteur, der Renten und Bildungsinvestitionen finanziert. Die Entscheidungen der öffentlichen Politik werden einem probabilistischen Wahlmodell folgend getroffen, wodurch sichergestellt wird, dass Veränderungen in der Altersstruktur endogen und kontinuierlich die Verteilung der öffentlichen Ressourcen beeinflussen.

Die zentrale Erkenntnis ist, dass die Alterung der Bevölkerung die politische Macht älterer Wähler stärkt. Dies hat eine langfristige Umverteilung der öffentlichen Ausgaben zur Folge: Die Ausgaben für Renten steigen auf Kosten der Bildungsinvestitionen. Diese Verschiebung hat erhebliche makroökonomische Konsequenzen. So nimmt die Produktion deutlich ab, während die Einkommensungleichheit sinkt und die Vermögensungleichheit zunimmt. Die zunehmende politische Macht älterer Menschen sorgt dafür, dass die durchschnittliche Rentenersatzquote, die in einer kontrafaktischen Wirtschaft, in der die öffentliche Politik unabhängig von der Altersstruk-

tur wäre, deutlich sinken würde, im Laufe der Zeit nahezu konstant bleibt. Höhere individuelle Renten verringern die Anreize für Kapitalakkumulation im Laufe des Lebenszyklus, was zu einem geringeren Gesamtkapitalstock führt. Geringere Investitionen in Bildung senken das durchschnittliche Humankapitalniveau und somit die effektive gesamtwirtschaftliche Arbeitskraft. Darüber hinaus erfordert die Beibehaltung der durchschnittlichen Rentenersatzquote auf einem nahezu konstanten Niveau eine erhebliche Erhöhung des Sozialabgabensatzes, da die Alterung der Bevölkerung zu einem steigenden Anteil von Rentnern führt. Trotz gekürzter Investitionen in die öffentliche Bildung steigen die Gesamtsteuerverbindlichkeiten für Erwerbstätige. Dadurch wird das Arbeitsangebot verzerrt, was wiederum die effektive gesamtwirtschaftliche Arbeitskraft verringert. Sowohl der Rückgang des Gesamtkapitals als auch die Verringerung der effektiven gesamtwirtschaftlichen Arbeitskraft führen zu einem langfristigen Rückgang der Produktion. Insgesamt nimmt die Einkommensungleichheit ab, was in erster Linie auf den Umverteilungseffekt der Renten unter den Rentnern zurückzuführen ist. Gleichzeitig nimmt die Vermögensungleichheit zu, da höhere Renten insbesondere für Haushalte mit niedrigem Einkommen die Sparanreize mindern.

In meinem probabilistischen Wahlmodell maximiert der politische Entscheidungsträger eine gewichtete Wohlfahrtsfunktion aller lebenden Personen, wobei die Gewichte den alters- und bildungsspezifischen Wahlbeteiligungsquoten entsprechen. Diese Wahlbeteiligungsquoten, die aus Umfragedaten geschätzt werden, stehen in positivem Zusammenhang mit dem Bildungsniveau und weisen eine buckelförmige Beziehung zum Alter auf. In einem kontrafaktischen Szenario werden die deutschen Wahlbeteiligungsquoten durch die für Belgien geschätzten Quoten ersetzt, da dort Wahlpflicht besteht. Dadurch wird die politische Macht in Richtung jüngerer und weniger gebildeter Personen verlagert, was die Verzerrung zugunsten der Rentenausgaben verringert – wenn auch nicht vollständig. Die makroökonomischen Konsequenzen werden abgemildert.

Insgesamt verdeutlichen die Ergebnisse die schwerwiegenden wirtschaftlichen Folgen, die sich aus der politischen Ökonomie der Bevölkerungsalterung ergeben, zeigen aber auch, dass eine institutionelle Reform den damit verbundenen wirtschaftlichen Herausforderungen teilweise entgegenwirken kann.

Das zweite Kapitel, *Fiscal policy and human capital in the race against the machine*, ist eine gemeinschaftliche Arbeit mit Daniele Angelini (Universität Wien) und Stefan Niemann (Universität Konstanz). Darin untersuchen wir die Zielkonflikte der

Fiskalpolitik in einem dynamischen Wachstumsmodell, das Automatisierung, eine endogene Bildungsentscheidung sowie Humankapitalbildung beinhaltet. Wir kommen zu dem Ergebnis, dass die Fiskalpolitik die Wohlfahrt durch eine koordinierte Erhöhung der Steuern auf Arbeitseinkommen und Robotersteuern erhöhen kann, wenn die Humankapitalbildung durch staatliche Ausgaben beeinflussbar ist. Entscheidend für die Auswirkungen auf Wachstum und Ungleichheit ist die Zusammensetzung der Steuern, die zur Finanzierung von Transferleistungen und Bildungsausgaben verwendet werden, da die Robotersteuer eine stärkere Umverteilungswirkung hat als die lineare Steuer auf Arbeitseinkommen. Wir kalibrieren unser Modell auf die US-Wirtschaft und ermitteln die wohlfahrtsmaximierende Steuerpolitik. Dabei stellen wir fest, dass die Regierung in den kommenden Jahren zunächst die Robotersteuer erheblich senken sollte, um das automatisierungsgetriebene Wachstum zu fördern. Die Einnahmeausfälle sollten durch eine höhere Steuer auf Arbeitseinkommen ausgeglichen werden. In späteren Perioden sollte die Regierung die Robotersteuer schrittweise erhöhen und gleichzeitig die Steuer auf Arbeitseinkommen senken. Dieses dynamische Steuermuster bietet zunächst Anreize für mehr Forschung und Entwicklung sowie Automatisierung. Da die Produktivität der Maschinen zunimmt und sich die Qualifikationsprämie im Laufe der Zeit vergrößert, ist es für die Regierung optimal, die Robotersteuer zu erhöhen und die Steuer auf Arbeitseinkommen zu senken, um die Ungleichheit einzudämmen.

Wir analysieren auch die Rolle von Bildungszuschüssen. Wohlfahrtsgewinne entstehen, wenn die Pro-Kopf-Ausgaben für die Grundbildung als Reaktion auf die Politik angepasst werden und die Steuer auf Arbeitseinkommen die Zuschüsse finanziert, ohne die Ausgaben für die Hochschulbildung negativ zu beeinflussen.

Schließlich erweitern wir das Modell um die Möglichkeit, privat in die Hochschulbildung zu investieren. In diesem Szenario verdrängen Änderungen der öffentlichen Bildungsausgaben private Investitionen und schwächen somit den Humankapitalkanal. Die Bedeutung dieses Mechanismus hängt stark von der zugrunde liegenden Finanzierungsstruktur der Hochschulbildung ab. In einem europäischen Umfeld, in dem die Hochschulbildung hauptsächlich öffentlich finanziert wird, beinhaltet eine optimale Finanzierung der Umverteilungs- und Bildungspolitik der Regierung eine positive Robotersteuer. Personen mit Hochschulbildung, die in der Regel die Kapitaleigner sind, tragen nicht die direkten Kosten ihrer Hochschulbildung, sondern leisten einen indirekten Beitrag durch die Robotersteuer. In den USA, wo Personen mit Hochschulbildung die Kosten ihrer Hochschulbildung bereits selbst tragen, beträgt die optimale Robotersteuer null. In diesem Fall sollten die öffentlichen Ausgaben für

Umverteilung und Bildung ausschließlich über eine Steuer auf Arbeitseinkommen finanziert werden.

Das dritte Kapitel, *Population aging and fiscal multipliers*, untersucht, wie sich die Bevölkerungsalterung auf die Wirksamkeit der Fiskalpolitik auswirkt – gemessen am Umfang des Fiskalmultiplikators. Der Fiskalmultiplikator ist ein zentrales Konzept, um zu verstehen, wie staatliche Ausgaben die Wirtschaftsleistung beeinflussen. In der Literatur wird zunehmend anerkannt, dass seine Größe je nach Land und Zeitpunkt variiert und von strukturellen sowie konjunkturellen Bedingungen abhängt. Ein entscheidender, bislang jedoch wenig untersuchter struktureller Faktor in diesem Zusammenhang ist die Altersstruktur der Bevölkerung.

Meine empirische Analyse basiert auf einem strukturellen vektorautoregressiven Modell (SVAR), das auf Quartalsdaten von 35 Ländern im Zeitraum 1995–2019 angewendet wird. Ich schätze Impulsantwortfunktionen auf einen positiven Schock der Staatsausgaben und leite daraus die entsprechenden Fiskalmultiplikatoren ab. Die empirischen Ergebnisse lassen sich in drei stilisierten Fakten zusammenfassen: (i) Staatsausgabenschocks führen in der Regel zu positiven und signifikanten Reaktionen der Produktion, was mit einem Großteil der bestehenden Literatur übereinstimmt; (ii) diese positiven Produktionsreaktionen fallen in Ländern mit einer relativ jungen Bevölkerung wesentlich stärker aus; und (iii) über die Länder hinweg zeigt sich ein signifikanter negativer Zusammenhang zwischen der Höhe des Fiskalmultiplikators und dem Altenquotienten – einem zentralen Indikator für die Altersstruktur der Bevölkerung.

Um die stilisierten Fakten zu erklären, die Auswirkungen des demografischen Wandels auf die Fiskalmultiplikatoren zu quantifizieren und abzuschätzen, wie sich die künftige Bevölkerungsalterung auf die Wirksamkeit der Fiskalpolitik auswirken könnte, entwickle ich ein Modell mit überlappenden Generationen, heterogenen Haushalten und endogenem Arbeitskräfteangebot. Das Modell berücksichtigt idiosynkratische Einkommensrisiken und – besonders wichtig – länderspezifische demografische Strukturen. Fiskalische Expansionen in Form zusätzlicher Staatsausgaben werden über eine nicht verzerrende Pauschalbesteuerung refinanziert.

Mein Modell, das die empirisch beobachteten stilisierten Fakten erfolgreich reproduziert, wird für die Vereinigten Staaten im Jahr 2020 kalibriert und anschließend auf siebzehn weitere Länder ausgeweitet, was einen umfassenden internationalen Vergleich ermöglicht. Die fiskalischen Multiplikatoren im Modell werden maßgeblich durch die Reaktion des Arbeitskräfteangebots auf positive Staatsausgabenschocks bestimmt. Diese Reaktion hängt wiederum vom Sparverhalten der Haushalte und ihrer Sensitivität gegenüber Besteuerung ab. In alternden Gesellschaften rechnen Haushalte mit längeren Rentenphasen und sparen daher über ihren Lebenszyklus hinweg relativ mehr. Dadurch sinkt ihre Sensibilität gegenüber vorübergehenden Vermögensschocks – wie etwa in Form pauschaler Steuererhöhungen – was die Arbeitsangebotsreaktion abschwächt und folglich zu geringeren Produktionseffekten als Konsequenz einer fiskalischen Expansion führt.

Quantitativ ergibt sich aus meiner Analyse: Eine Zunahme des Altenquotienten um eine Standardabweichung – was einem Anstieg um 6,3 Prozentpunkte entspricht – verringert den Fiskalmultiplikator im Durchschnitt um 17,7 Prozent. Um demografische Effekte von anderen strukturellen Unterschieden abzugrenzen, simuliere ich kontrafaktische Szenarien, in denen die Altersstruktur eines Landes durch jene anderer Länder ersetzt wird, während alle übrigen Modellparameter unverändert bleiben. Diese kontrafaktischen Simulationen zeigen, dass selbst nach Kontrolle für nicht demografische Faktoren der isolierte Effekt der Bevölkerungsalterung den Fiskalmultiplikator bei einem Anstieg des Altenquotienten um eine Standardabweichung im Durchschnitt um 3,6 Prozent über alle Länder hinweg reduziert.

Um die zukunftsgerichteten Auswirkungen der Bevölkerungsalterung zu analysieren, prognostiziere ich deren Einfluss auf die Fiskalmultiplikatoren bis zum Jahr 2070. Die Ergebnisse dieser Analyse zeigen, dass die Alterung der Bevölkerung die durchschnittlichen Fiskalmultiplikatoren über alle Länder hinweg um 11,3 Prozent verringern wird – ausschließlich bedingt durch die erwarteten demografischen Veränderungen.

Meine Ergebnisse legen nahe, dass politische Entscheidungsträger, die über zusätzliche Staatsausgaben konjunkturelle Impulse setzen möchten, die demografische Struktur eines Landes künftig stärker in die Gestaltung und das Timing fiskalischer Maßnahmen einbeziehen sollten.

Summary

This dissertation arises from my studies in the doctoral program *Decision Sciences* at the Graduate School of Decision Sciences and my position as a research assistant at the Chair of Macroeconomics at the University of Konstanz. It comprises three independent chapters with a focus on trade-offs facing fiscal policy in the context of population aging and automation.

In the first chapter, *Population aging, inequality and public policy*, I examine the implications and quantify the consequences of population aging for the political economy underlying the allocation of public resources between pensions and education, two emblematic government items for the trade-off in the public resource allocation between elderly and young individuals in an economy. I develop a quantitative overlapping generations model with heterogeneous households, calibrated to the German economy in 2020. The model features a government that finances pensions and education investments. Public policy choices are determined through probabilistic voting, ensuring that shifts in the age structure endogenously and gradually affect the allocation of public resources.

The central finding is that population aging increases the political power of older voters, leading to a long-run reallocation of public spending: pension expenditures rise at the expense of education investment. This shift has significant macroeconomic consequences. Production drops markedly, total income inequality declines, and wealth inequality increases. The increasing voting power of the elderly keeps the average pension replacement rate – which falls significantly in a counterfactual economy where public policy is independent of the age structure – almost constant over time. Higher individual pensions for retirees reduce incentives for capital accumulation throughout the life cycle, resulting in a smaller aggregate capital stock. Reduced investment in education reduces the average level of human capital and, consequently, the effectiveness of labor. In addition, maintaining the average pension replacement rate at a constant level requires a significant increase in the social

security tax rate, as population aging leads to a rising share of retirees. Although the government cuts public education investment, overall tax liabilities for working individuals increase, distorting labor supply, and further reducing effective labor. Both the decline in capital and the reduction in effective labor lead to a long-run drop in production. Total income inequality declines, primarily due to the redistributive effect of pensions among retirees, while wealth inequality rises as higher pensions particularly disincentivize saving for low-income households.

In my probabilistic voting setup, the policymaker maximizes a weighted average welfare function of all living individuals, where the weights reflect age- and education-type-specific voter turnout rates. These turnout rates, estimated from survey data for Germany, are positively associated with educational attainment and exhibit a hump-shaped relationship with age. In a counterfactual scenario, I replace German turnout rates with those estimated for Belgium, where compulsory voting is in place. It shifts political power toward younger and less educated individuals, reducing, though not eliminating, the bias toward pension spending and mitigating the macroeconomic consequences.

Overall, the results highlight the severe economic consequences posed by the political economy underlying population aging, but also illustrate that an institutional reform can partially counteract the imposed economic challenges.

The second chapter, *Fiscal policy and human capital in the race against the machine*, is joint work with Daniele Angelini (University of Vienna) and Stefan Niemann (University of Konstanz). We study the trade-offs facing fiscal policy in a dynamic growth model that incorporates automation, educational choice, and human capital formation. We find that when human capital formation can be affected by government spending, fiscal policy can enhance welfare through a coordinated increase in labor and robot taxes. The composition of taxes used to finance transfers and education spending is key in determining their effects on growth and inequality, as the robot tax is more redistributive than the linear labor income tax. We calibrate our model to the US economy and determine the welfare-maximizing tax policy. We find that in future years, the government should initially reduce the robot tax substantially to foster automation-driven growth and compensate for the revenue loss with a higher labor tax. In later periods, the government should progressively raise the robot tax while reducing the labor tax. This dynamic tax pattern initially provides incentives for increased R&D and automation. As machine productivity increases and the skill premium widens over time, the government finds it optimal to increase the robot tax and reduce the labor tax to contain inequality.

We also analyse the role of education subsidies. Welfare gains arise when per capita spending on basic education adjusts in response to the policy, and the labor tax finances the subsidies without negatively affecting spending on higher education.

Finally, we extend the model to incorporate private investment in higher education. In this setting, changes in public education spending crowd out private contributions, thereby weakening the human capital channel. The importance of this mechanism depends strongly on the underlying funding mix for higher education. In a European setting, with mainly publicly financed tertiary education, optimal financing for the government's redistribution and education policy involves a positive robot tax. Tertiary-educated individuals, who are typically the owners of capital, do not bear the direct cost of their higher education but contribute indirectly through the robot tax. For the US setting, where tertiary-educated individuals already bear the cost of their higher education, the optimal robot tax is zero, with public spending on redistribution and education financed solely by the labor tax.

The third chapter, *Population aging and fiscal multipliers*, studies the consequences of population aging for the effectiveness of fiscal policy, as measured by the size of the fiscal multiplier. The fiscal multiplier is a central concept for understanding how government spending translates into economic output, and the literature increasingly recognizes that its magnitude varies across countries and over time, depending on both structural and cyclical conditions. A critical but underexplored structural factor in this context is the age composition of the population.

My empirical analysis is based on a structural vector autoregression (SVAR) framework applied to quarterly data for 35 countries over the period 1995–2019. I estimate impulse response functions to a positive government spending shock and derive corresponding fiscal multipliers. My empirical findings are summarized in three stylized facts: (i) government spending shocks generally lead to positive and significant output responses, consistent with much of the existing literature; (ii) these output responses are substantially larger in countries with relatively younger populations; and (iii) there is a significant negative relationship across countries between the size of the fiscal multiplier and the old-age dependency ratio – a key indicator of a population's age structure.

To explain the stylized facts, quantify the impact of demographic change on fiscal multipliers, and assess how future population aging may affect the effectiveness of fiscal policy, I develop a medium-scale overlapping generations model with

heterogeneous households and endogenous labor supply. The model incorporates idiosyncratic income risk and, importantly, country-specific demographic structures. Fiscal expansions in the form of additional government expenditures are financed via non-distortionary lump-sum taxation.

The model, which successfully replicates the stylized facts, is calibrated for the United States in 2020 and extended to seventeen additional countries, allowing for a rich cross-country comparison. Fiscal multipliers in the model are driven primarily by the labor supply response to positive government spending shocks, which in turn depends on savings behaviour and tax sensitivity of the households. In aging societies, households anticipate longer retirement periods and save relatively more over the life cycle, which reduces their sensitivity to transitory wealth shocks such as temporary lump-sum tax increases. This, in turn, weakens the labor supply response and leads to smaller output effects from fiscal expansions.

Quantitatively, I find that a one standard deviation increase in the old-age dependency ratio – equivalent to a 6.3 percentage point rise – reduces the fiscal multiplier by 17.7 percent on average. To disentangle demographic effects from other structural differences, I simulate counterfactual scenarios in which each country's age structure is varied while holding other model parameters constant. These within-country exercises show that even after accounting for non-demographic factors, the pure effect of population aging reduces the multiplier for a one standard deviation increase in the old-age dependency ratio by an average of 3.6 percent across countries.

To explore the forward-looking implications of these findings, I project the effects of population aging on impact multipliers through 2070. This analysis predicts that population aging will reduce fiscal multipliers by an average of 11.3 percent across the model sample.

The results highlight that policymakers aiming to stimulate output through additional government spending need to account more explicitly for the country-specific demographic structure in the design and timing of fiscal interventions.

Chapter 1

Population aging, inequality and public policy*

Abstract

This paper examines the implications of population aging for the political economy of allocating resources between pensions and education in a medium-scale overlapping generations model with heterogeneous households calibrated to the German economy. As a consequence of population aging, the increasing political power of the elderly shifts public policy toward higher pension spending at the expense of investment in education relative to an economy in which public policy is independent of the age structure. Aggregate output and total income inequality fall significantly while wealth inequality rises. Higher pensions discourage capital accumulation, while reduced public investment in education leads to a decline in the economy's human capital level. Rising tax liabilities to finance relatively higher pension spending distort individual labor supply, further depressing aggregate effective labor. Substantially higher redistributive pensions mitigate total income inequality but discourage capital accumulation, especially at the lower end of the wealth distribution, and increase wealth inequality. The magnitude of the effects decreases strongly with the size of future population growth rates. In a counterfactual experiment, a compulsory voting policy increases political participation, especially among younger individuals, and leads to less severe effects on aggregate output, higher total income inequality, and lower wealth inequality.

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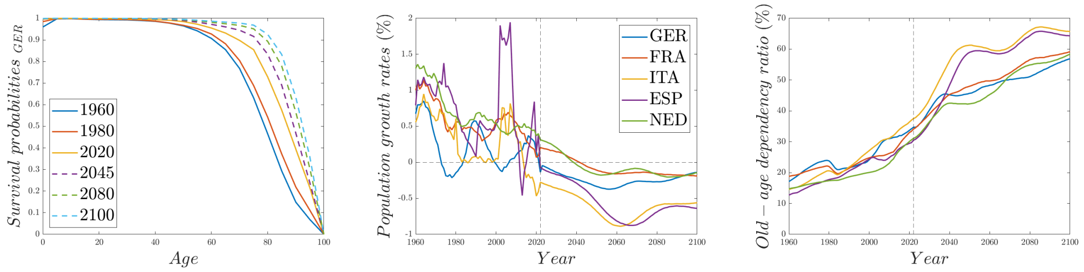
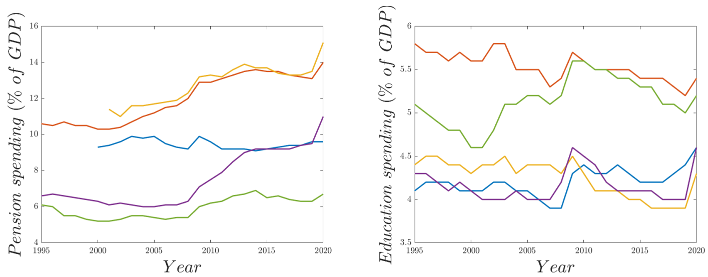
1.1 Introduction

Population aging represents one of the most significant demographic transformations in modern societies, with far-reaching implications for economic structures, public policy, and social equity. Advancements in healthcare, nutrition, and living standards have extended life expectancy, and fertility rates have declined. This has led to a significantly increased proportion of the elderly relative to the working-age population, particularly in European countries. A key indicator of this demographic shift is the old-age dependency ratio, which measures the number of individuals aged 65 and over in relation to the working-age population (15-64). This ratio has risen considerably in recent decades and is projected to continue rising in the future, as illustrated in Figure 1.1. For instance, in Germany, the old-age dependency ratio increased from 17.1 percent in 1960 to 34.7 percent in 2020, and it is estimated to reach 56.9 percent by 2100, according to data from United Nations (2022a). Similarly, Italy and Spain are expected to see their old-age dependency ratios reach 65.7 percent and 64.4 percent, respectively. Based on this significant demographic shift toward an aging population in European countries, one fundamental trade-off in the allocation of public resources between different population groups and generations has become particularly prominent - the trade-off between the needs and interests of the elderly and the young. This trade-off is most evident in two key policy areas where government intervention plays a central role in European countries: public pensions and public education spending. In Germany, for instance, public pensions accounted for 9.6 percent of GDP in 2020, while public education expenditures represented 4.6 percent of GDP, according to data from Eurostat (2023b,c). Public pensions are understood as predominantly benefiting the elderly, while public education spending primarily serves the younger generations. When the population ages, in democratic systems in which policymakers depend on electoral support, there is a natural tendency to cater to the elderly. Their political influence grows due to their increasing population share, and they have a strong interest in preserving or expanding pension benefits. The increasing fiscal burden of pensions requires governments to allocate a larger share of public resources to social security, as increasing the retirement age or reducing the pension replacement rate will find no political majority in an aging society. Public spending on education is generally seen as an investment in future generations, equipping the young with the skills and knowledge to participate productively in the labor market. In the context of an aging society, however, public education spending may come under

Figure 1.1: Population aging and public policy in Europe.



(a) Survival prob. in Germany. (b) Population growth rates. (c) Old-age dependency ratios.



(d) Public pension spending. (e) Public education spending.

Note: This figure shows survival probabilities for Germany (broken lines represent projections), and (annual) population growth rates and the old-age dependency ratios for the five largest European economies, Germany, France, Italy, Spain, and the Netherlands, from 1960 to 2100, and public education spending and pension spending relative to GDP from 1995 to 2020. Survival probabilities for the other countries can be found in Appendix 1.A, Figure 1.9. The vertical broken lines represent the latest measured data points for the population growth rates and the old-age dependency ratios in 2022. Further values are based on projections. Data for the survival probabilities are based on United Nations (2022a,b), for the population growth rates on United Nations (2024), for the old-age dependency ratios on Eurostat (2023a), for the public education spending to GDP ratio on Eurostat (2023b), and for the pension to GDP ratio on Eurostat (2023c).

pressure. As the electorate ages, political priorities tend to shift toward policies that directly benefit the elderly, crowding out investment in education and leading to long-term consequences. Crowded-out investment in education weakens the future labor force and diminishes an economy's productive capacity. In addition to the consequences for production and other economic aggregates, a shift in the use of public resources toward the elderly also has implications for inequality. While public pensions are generally understood as redistributive government expenditures, the impact of public education spending on inequality is more ambiguous (Artige and Cavenaile, 2023).

Taking the trade-off between public pensions and education spending and their ambiguous impact on inequality as the point of departure, this paper analyzes and quantifies the impact of population aging on the design of public policy, more specifically, the allocation of public resources towards public pensions and public education spending, and its consequences for economic aggregates and inequality. The demand for public spending varies across age groups and education types, the latter formalized as differences in deterministic labor productivity of households. It is affected by the exogenous but time-varying age structure of the population, specifically increasing survival probabilities and decreasing population growth rates. The demographic shift is translated into actual public policy via probabilistic voting in a medium-scale overlapping generations model in the spirit of Auerbach and Kotlikoff (1987) with heterogeneous agents and incomplete markets, a life-cycle extension of Aiyagari (1994), similar to Krueger and Ludwig (2007) and Conesa et al. (2009), calibrated to the German economy. Germany is the largest European economy, its population is rapidly aging, and both pensions and education spending are mainly publicly financed. In a perfectly competitive environment, firms operate with a constant returns to scale production function. Heterogeneity on the household side is rooted in differences in an individual's labor productivity. Households decide on consumption, individual labor supply (as long as they are workers), and their savings. They are taxed in proportion to their labor income. The government runs a balanced budget, and a share of the resources is allocated between the pension system and the public education system. Pensions are paid to retirees and are purely consumptive government expenditures. Public education spending is productive. It positively affects the human capital level of the newborn cohort, similar to Boldrin and Montes (2005) and Gonzalez-Eiras and Niepelt (2012), and therefore raises the average human capital level in the economy. Households vote on the tax rates financing public policy. The share of resources that is spent on public education and public pensions is implicitly determined by the budget-clearing condition of the government. The political process follows a probabilistic voting set-up inspired by Lindbeck and Weibull (1987) and Persson and Tabellini (2002), which finally breaks down to maximizing a political objective function that is a weighted average welfare function of all individuals that are currently alive. Age- and education types are naturally weighted according to their respective population shares and receive an additional type-specific weight, which is interpreted as a type-specific voter turnout rate and estimated from public survey data from European Social Survey (2023).

We start the analysis in a simplified version of the model economy, from which we identify several key margins that influence the demand for public policy. For the social security tax, older individuals benefit from a higher tax rate as it increases their pension payments directly. Especially low-productivity retirees benefit, as they gain relatively more due to their lower wealth holdings. Younger individuals also favor higher social security taxes. Their future pensions increase. The increase in the social security tax includes a positive interest rate effect driven by capital scarcity due to lower incentives to accumulate wealth over the life cycle. This positive effect is even stronger for low-productivity individuals, as they own less wealth and benefit more than proportionally from the increasing interest rate. For education taxes, younger individuals prefer a higher tax rate because it leads to higher public investment in education, which boosts the future tax base and their pensions in old age. Both tax rate increases come at the cost of lower current disposable income and savings. Additionally, an increase in the social security tax leads to a negative wage rate effect due to capital scarcity. A comparative static exercise for a stylized parametrized German economy in the stationary political equilibrium highlights the differential effects of either of the two demographic variables, the survival probability to old age or the population growth rate, on the political outcomes and inequality. Overall, population aging leads to a significant increase in the social security tax and, consequently, to increasing pension payments to retirees in the economy. Depending on the demographic variable, population aging either leads to an increase (when the survival probability increases) or a decline in the education tax rate (when the population growth rate declines) and, consequently, a respective adjustment in public spending on education. Inequality increases with population aging as a consequence of reduced incentives to accumulate wealth over the life cycle due to increasing pension payments, especially among low-productivity individuals. Independent of population aging, an increase in ex-ante inequality, formalized as the ratio of deterministic high- to low-type productivity, creates more demand for redistributive pensions and, therefore, an increase in the social security tax. The education tax declines. Ex-post inequality is amplified as the increase in the social security tax disincentivizes capital accumulation for low-productivity individuals more than proportionally.

The quantitative version of the model is calibrated to the German economy of 2020 as the initial stationary political equilibrium. It replicates salient features, most importantly, the observed ratios of pensions to GDP and public education spending to GDP from the data. To quantify the long-run effect of population aging on the allocation of public resources, economic aggregates, and inequality, we compare two different long-run scenarios. The first scenario is the long-run stationary political equilibrium after the exogenous demographic transition. The second scenario is a long-run stationary equilibrium for constant tax rates, but the demographic variables adjust over time. When tax rates adjust to population aging, we observe a relative reduction in the education tax and a significant relative increase in the social security tax. While a constant social security tax rate creates a substantial drop in the average replacement rate in the economy, the relative increase keeps the average replacement rate approximately constant in the long run. Individual pensions are substantially higher, disincentivize capital accumulation over the life cycle, and create a relative fall in aggregate capital. Public spending on education declines, negatively affecting the economy's human capital level. Tax liabilities for working households increase due to the significantly higher social security tax, distorting individual labor supply. Consequently, aggregate effective labor declines. Overall, the reduction in aggregate capital and aggregate effective labor creates a long-run fall in output by 6.90 percent relative to the constant tax rate case. The Gini coefficient for wealth inequality increases by 1.75 percent due to reduced incentives to accumulate wealth over the life cycle, especially among wealth poorer individuals. In contrast, the Gini coefficient for total income inequality declines significantly by 10.91 percent as redistributive pension payments to retirees in the economy increase. The magnitude of the effects decreases strongly with the size of projected population growth rates.

In a counterfactual experiment, we propose the introduction of a compulsory voting policy (CVP) as a potential policy to counteract the detrimental effects of population aging on aggregate output. The type-specific weights in the political objective function, interpreted as voter turnout rates, are adjusted to observable values in Belgium, leading to increasing political participation at the upper and especially at the lower end of the age distribution and generally for less educated individuals.[1] This shift in voter turnout rates creates mitigation. Aggregate output is 4.51 percentage points higher compared to the long-run situation without the CVP. The Gini coefficient for wealth inequality reduces by 0.94 percentage points, and the Gini coefficient for total income inequality increases by 6.21 percentage points. Higher future population growth rates, in combination with the shift of voter turnout rates more into the direction of less educated and especially younger individuals, create a more growth-orientated allocation of public resources and boost aggregate output even relative to the constant tax rate case. Wealth inequality reduces slightly, but total income inequality increases.

[1]We chose Belgian values for the counterfactual experiment because Belgium is one of the few countries worldwide where a CVP is in place at the national level, although not strictly enforced by the authorities. Non-European countries such as Australia, Argentina, Peru, and Brazil also use CVPs to enforce voting at the national level.

Related literature Our paper contributes to several strands of the literature. It relates to work that analyzes the macroeconomic implications of population aging and possible adjustment mechanisms. In closed economy set-ups Imrohoroglu et al. (1995), Huang et al. (1997), De Nardi et al. (1999) and Fuster et al. (2007) have focused on social security adjustments, and Domeij and Floden (2006), Börsch-Supan et al. (2006), Attanasio et al. (2007) and Krueger and Ludwig (2007) have analyzed the role of international capital flows during the demographic transition in open economies. Storesletten (2000) examines the effect of migration to industrialized countries during the demographic transition as an option to take pressure from the social security systems. The effects of adjustments in the human capital accumulation are analyzed by Fougère and Mérette (1999), Sadahiro and Shimasawa (2003), Buyse et al. (2012), and Ludwig et al. (2012). Vogel et al. (2017) show that human capital adjustments, in combination with an increasing retirement age, significantly mitigate the adverse consequences of population aging. More recent work shows that population aging slows down economic growth due to a reduced ability to innovate, a shrinking population, and slowed down employment and labor productivity growth (Aksoy et al., 2019; Jones, 2022b; Maestas et al., 2023). Work by Acemoglu and Restrepo (2017) argues that an intensified adoption of automated technologies induced by population aging can offset negative growth effects and even foster economic growth. Our paper relates specifically to the work on social security and human capital adjustments. Although potentially beneficial for economic growth or specific population groups, proposed reforms in this part of the literature are politically hard to implement or even infeasible. In our paper, political feasibility is directly ensured due to the political economy setup.

In terms of conceptual approach, our paper builds generally on the strand of the literature that uses probabilistic voting as a vehicle to transform individuals' preferences on different government instruments into actual public policy (Lindbeck and Weibull, 1987; Persson and Tabellini, 2002). When variations in the survival probabilities and population growth rates induce adjustments in the age structure of the population, the advantage of the probabilistic voting set-up relative to the canonical median voter set-up (Downs, 1957) lies in the ability of the former to capture changes in the support for public policy gradually, while the latter only captures changes if the demographic shift is strong enough such that it alters the identity of the median voter. Adjustments of the population structure in a median voter set-up induce only policy changes to the extent that general equilibrium effects induced by population aging alter the median voter's preferred policy. Additionally, as soon as the median voter changes, it often implies a drastic policy reversal, which is at odds with gradual policy adjustments that are observable in reality.

More specifically, with respect to the public policy items that are the subject of our paper, a first part of related work focuses on the effect of population aging on the social security system in a representative agent economy (Gonzalez-Eiras and Niepelt, 2008) or the effect of population aging on the social security system and its interaction with inequality in a small-scale heterogeneous agent economy (Song, 2011). A second part draws special attention to the effects of population aging on public education spending in a representative agent economy (Lancia and Russo, 2016), and a third part analyzes the interaction of the social security system and public education spending in a representative agent economy in a graying society (Gonzalez-Eiras and Niepelt, 2012; Ono and Uchida, 2016). None of this work focuses on the effect of population aging on the allocation of public resources between social security and public education spending in a heterogeneous agent set-up and quantifies the effect on economic aggregates and inequality in a larger-scale overlapping generations model. Only the work by Rauh (2017) uses a more than two-period overlapping-generations model with an embedded probabilistic voting set-up as the driver of the allocation of public resources in a partial equilibrium heterogeneous agent economy. This paper quantifies the effects of rising inequality on intergenerational earnings mobility across countries unrelated to population aging and social security.

Our paper also complements the work by Glomm and Kaganovich (2008) in terms of results. The authors study the relationship between economic growth and inequality, contingent on the funding levels of social security and public education for an exogenous variation in public policy unrelated to population aging. An exogenous increase in the social security tax typically reduces income inequality and has a non-monotonic effect on economic growth, contingent on the initial size of the social security tax. For high funding levels, which is the case in European countries, a further increase in the social security tax has a negative effect on economic growth, further amplified if the increase is financed by cutting the public education budget. In our paper, population aging through its impact on the allocation of public resources creates exactly this trade-off between increasing funding of the social security system and declining public education investment, leading to a long-run reduction in aggregate output, a decline in (total) income inequality, and an increase in wealth inequality.

Our paper also relates to the strand of the literature analyzing the characteristics of voter turnout empirically (Verba et al., 1978; Powell, 1986; Verba and Nie, 1987; Leighley and Nagler, 1992). According to Smets and van Ham (2013), age, education, and income are the most significant predictors of voter turnout, followed by home ownership, residential mobility, race, citizenship, and marital status as more modest predictors. Gender, occupational status, and urbanization appear to have little to no predictive power. We make use of these findings and estimate predicted probabilities of voting based on a probit model for two of the strongest predictors, age and education. These predicted probabilities of voting are then employed as proxies for the type-specific weights in the political objective function.

The rest of the paper is structured as follows. Section 3.3 outlines the quantitative model in detail. Section 1.3 presents analytical insights into the probabilistic voting outcomes on the design of public policy in a simplified version of the quantitative model. Section 1.4 discusses the calibration to the German economy of the year 2020 and evaluates the model fit of the initial stationary political equilibrium. Section 3.5 presents the quantitative results on the long-run effects of population aging on the allocation of public resources and its consequences for economic aggregates and inequality. It also discusses the transition to the final stationary political equilibrium in a situation in which both tax rates converge linearly to their final stationary political equilibrium values. Furthermore, Section 3.5 presents the results of the counterfactual experiment with a compulsory voting policy in place. Section 3.6 concludes.

1.2 Model

This section describes the quantitative model. The set-up is a medium-scale overlapping generations model in the spirit of Auerbach and Kotlikoff (1987) with heterogeneous agents and incomplete markets, a life-cycle extension of Aiyagari (1994), similar to Krueger and Ludwig (2007) and Conesa et al. (2009). The allocation of public resources is determined by probabilistic voting, in line with Lindbeck and Weibull (1987) and Persson and Tabellini (2002). The solution approach for the political equilibrium follows Rauh (2017).

1.2.1 Demographics and timing

A model period, t, corresponds to five years.[2] In each period, a continuum of new households is born. Newborns start at the real age of 20, denoted by $j = 1$. All generations retire at the age of 65, $j = J_r = 10$, and live up to a maximum age of 100, $j = J = 17$. In period t, all agents of age j survive to age $j+1$ with probability $\psi_{j+1,t+j-1}$, with $\psi_{1,t} = 1$ and $\psi_{J+1,t+J-1} = 0$. The size of a cohort of age j in period $s = t + j - 1$ is therefore given by

$$N_{j,s} = \psi_{j,s} \cdot N_{j-1,s-1}. \tag{1.1}$$

The size of a new generation in period t follows

$$N_{1,t} = (1 + n_t) \cdot N_{1,t-1}, \tag{1.2}$$

with $n_t > -1$ as the population growth rate. The total population size is given by $N_t = \sum_{j=1}^{J} N_{j,t}$. There exist no annuity markets. A fraction of households leave unintended bequests, which are lump-sum and uniformly distributed to all currently alive households, denoted by beq_t. Age-specific cohort weights are given by

$$m_{j,t} = \begin{cases} 1, & if\ j = 1, \\ \left(\frac{\psi_{j,t}}{1+n_t}\right) \cdot m_{j-1,t-1}, & else, \end{cases} \tag{1.3}$$

and the old age dependency ratio implied by the model has the following form

$$OADR_t = \frac{N_{r,t}}{N_{w,t}} = \frac{\sum_{j=J_r}^{J} m_{j,t}}{\sum_{j=1}^{J_r-1} m_{j,t}}, \tag{1.4}$$

with $N_{r,t}$ as the size of the retired population and with $N_{w,t}$ as the size of the working population.

1.2.2 Households

All households are endowed with one unit of time in each period and enter the economy with zero wealth, $a_{1,t} = 0$, except for accidental bequests. They spend their time supplying labor to a competitive market or consuming leisure. Individual

[2] The choice of this conversion is motivated by the idea of repeated voting on public policy. Voting on the national level takes place every four to five years in European countries.

preferences are given by

$$\mathbb{E}\left[\sum_{j=1}^{J}\beta^{j-1}\cdot\left(\Pi_{q=1}^{j}\psi_{q,o}\right)\cdot u(c_{j,s},\ell_{j,s})\right], \tag{1.5}$$

with $o = t + q - 1$, $\beta \in (0, 1)$ as the discount factor and per-period utility

$$u(c_{j,s},\ell_{j,s}) = \frac{\left((c_{j,s})^{\nu}\cdot(1-\ell_{j,s})^{1-\nu}\right)^{1-\frac{1}{\gamma}}}{1-\frac{1}{\gamma}}, \tag{1.6}$$

as a function of age j consumption, $c_{j,s}$, and labor supply, $\ell_{j,s}$, with $\gamma > 0$ as the intertemporal elasticity of substitution and $\nu \in [0, 1]$ as the taste parameter for consumption. The expectation is formed from an ex-ante perspective before any information about individual labor productivity, $\varepsilon\big(p_j, \theta, \eta\big)$, has been revealed to the household. Individual labor productivity depends on an age-dependent productivity component, p_j, a deterministic productivity component, $\theta \in \mathcal{I} \equiv \{\theta^1, ..., \theta^I\}$, which is drawn at the beginning of the life cycle, and an idiosyncratic shock component that follows a time-invariant AR(1) process given by

$$\log(\eta') = \rho\cdot\log(\eta) + \epsilon, \quad \epsilon \sim \mathcal{N}(0, \sigma_\epsilon^2) \tag{1.7}$$

with the discrete approximation given by a Markov chain with states $\eta \in \mathcal{M} \equiv \{\eta^1, ..., \eta^M\}$ and transition probabilities $\pi(\eta'|\eta) > 0$.[3] The unique invariant distribution associated with π is denoted by Π. Given these shocks, a household's individual labor productivity is given by

$$\varepsilon\big(p_j,\theta,\eta\big) = \begin{cases} p_j\cdot\theta\cdot\eta, & if\ j \leqslant J_r - 1, \\ 0, & if\ j \geqslant J_r. \end{cases} \tag{1.8}$$

At the mandatory retirement age, individual labor productivity drops to zero, and households stop working and start receiving pension payments, pen_t, provided by the government. Individual public pension payments to households are not type- or earnings history dependent in this setting and, therefore, have strong redistributive properties. Households maximize the expected lifetime utility of (3.10), subject to

[3] The deterministic productivity component is included to capture differences in the education level and drives heterogeneity in the simplified version of the model economy.

the periodic budget constraints

$$c_{j,t}+a_{j+1,t+1} = (1+r_t)\cdot a_{j,t}+beq_t+\begin{cases}(1-\tau_t^e-\tau_t^p)\cdot\varepsilon\big(p_j,\theta,\eta\big)\cdot h_{j,t}\cdot\ell_{j,t}\cdot w_t, & if\ j\leqslant J_r-1\\ pen_t, & if\ j\geqslant J_r\end{cases} \tag{1.9}$$

and a borrowing constraint, $a_{j,t}\geqslant 0$. Individual variables also satisfy $c_{j,t}>0$ and $\ell_{j,t}\in[0,1]$. In addition, the labor income of a working-age individual depends on the age-specific individual human capital level, $h_{j,t}$. The age-1 human capital level, $h_{1,t}$, reflects (per capita) public education spending during the previous period, $\hat{E}_{t-1}$, and depends on the age-1 human capital level of the previous generation, $h_{1,t-1}$. Specifically, it takes the following form

$$h_{1,t}=\Omega_H\cdot(h_{1,t-1})^{1-\iota}\cdot(\hat{E}_{t-1})^{\iota}, \tag{1.10}$$

where $\Omega_H>0$ is the (age-1) human capital productivity parameter and $\iota\in(0,1)$ is the elasticity of age-1 human capital with respect to per capita public education spending.[4] The individual human capital levels of all other working-age individuals are constant throughout their lives and depend only on their age-1 human capital levels, such that

$$h_{j,t}=h_{1,t+1-j},\quad if\ 2\leqslant j\leqslant J_r-1 \tag{1.11}$$

holds.

1.2.3 Firms

A continuum of competitive firms converts capital, K_t, and effective labor, L_t^{eff}, formally defined in (1.23), into output, Y_t, by means of a Cobb-Douglas technology,

$$Y_t=\Omega_Y\cdot(K_t)^{\alpha}\cdot(L_t^{eff})^{1-\alpha}, \tag{1.12}$$

with $\Omega_Y>0$ as the productivity parameter and $\alpha\in(0,1)$ as the capital share. Capital depreciates at the rate $\delta\in[0,1]$. The representative firm maximizes profits by choosing the amount of capital and effective labor used in the production process. The maximization problem is standard and has the following form

$$\max_{\{K_t,L_t^{eff}\}} Y_t-w_t\cdot L_t^{eff}-(r_t+\delta)\cdot K_t, \tag{1.13}$$

[4] Boldrin and Montes (2005) and Gonzalez-Eiras and Niepelt (2012) use a similar specification.

subject to (3.16). Solving the maximization problem yields

$$r_t = \Omega_Y \cdot \alpha \cdot \left(\frac{K_t}{L_t^{eff}}\right)^{\alpha-1} - \delta \tag{1.14}$$

for the interest rate and

$$w_t = \Omega_Y \cdot (1-\alpha) \cdot \left(\frac{K_t}{L_t^{eff}}\right)^{\alpha} \tag{1.15}$$

for the wage rate.

1.2.4 Government

The government runs two separate systems: the public education system and the public pension system, both operating on a balanced budget basis.[5] Public education spending, E_t, is financed through taxing labor income linearly at the education tax rate, $\tau_t^e \in (0,1)$, so that

$$E_t = \tau_t^e \cdot w_t \cdot L_t^s \tag{1.16}$$

holds. The pension system operates on a pay-as-you-go basis, i.e. the government collects contributions from working-age generations by taxing their labor income linearly at the social security tax rate, $\tau_t^p \in [0,1)$, and redistributes them directly to current retirees. The budget balance equation for the pension system is then

$$Pen_t = N_{r,t} \cdot pen_t = \tau_t^p \cdot w_t \cdot L_t^s. \tag{1.17}$$

Individual pension payments follow from (3.21) as

$$pen_t = \frac{\tau_t^p \cdot w_t \cdot L_t^s}{N_{r,t}}. \tag{1.18}$$

It is also true that $\tau_t^p \in [0,1)$, $\tau_t^e \in (0,1)$ and $\tau_t^p + \tau_t^e \in (0,1)$ holds. In addition, the government collects the wealth of households who die before the age of $j = J$ and redistributes it to all households currently alive as a lump sum accidental bequest, beq_t.

[5] Alternatively, we could also use one consolidated government budget operating on a balanced budget basis, with only one proportional tax rate, $\tau_t = \tau_t^e + \tau_t^p$, and a share variable, $\phi_t \in (0,1]$, which allocates total tax revenue to the education and the public pension system, such that $E_t = \phi_t \cdot \tau_t \cdot w_t \cdot L_t^s$, $Pen_t = (1-\phi_t) \cdot \tau_t \cdot w_t \cdot L_t^s$ and $\phi_t = \frac{\tau_t^e}{\tau_t}$ hold. This yields the same results but complicates the stationary political equilibrium expressions for the simplified version of the model economy in Section 1.3.

1.2.5 Competitive equilibrium

At the beginning of period t, as long as they are workers ($j = \{1, ..., J_r - 1\}$), households are indexed by their age, j, their deterministic productivity type, θ, their idiosyncratic productivity shock, η, and their wealth holdings, a. Thus their maximization problem (in recursive form) is

$$V_t(j, \theta, \eta, a) = \max_{c, a', \ell} \left\{ u(c, \ell) + \beta \cdot \psi_{j,t} \cdot \sum_{\eta'} \pi(\eta'|\eta) \cdot V_{t+1}(j + 1, \theta, \eta', a') \right\} \tag{1.19}$$

$$\text{s.t} \quad (1.8), \quad (1.9), \quad a' \geqslant 0, \quad c > 0, \quad \ell \in [0, 1].$$

The maximization problem of retired households ($j = \{J_r, ..., J\}$) is simplified since they do not supply labor, and their deterministic productivity type, as well as the realization of the idiosyncratic shock, become irrelevant,

$$V_t(j, a) = \max_{c, a'} \{u(c, \ell) + \beta \cdot \psi_{j,t} \cdot V_{t+1}(j + 1, a')\} \tag{1.20}$$

$$\text{s.t} \quad (1.9), \quad a' \geqslant 0, \quad c > 0, \quad \ell = 0.$$

Additionally, I define the cross-sectional measure of households at time t by Φ_t.

Definition 1.2.1 (Competitive equilibrium)**.** *Given initial age-dependent human capital levels, $\{h_{j,0}\}_{j=1}^{J_r-1}$, an initial stock of physical capital, K_0, an initial population size, $N_{1,0}$, an initial cross-sectional measure of households, Φ_0, a sequence of population growth rates, $\{n_t\}_{t=0}^{\infty}$, and a sequence of survival probabilities, $\{\{\psi_{j,t}\}_{j=1}^{J+1}\}_{t=0}^{\infty}$, a competitive equilibrium are sequences of individual functions for the households, $\{V_t(j, \theta, \eta, a), c_t(j, \theta, \eta, a), \ell_t(j, \theta, \eta, a), a'_t(j, \theta, \eta, a)\}_{t=0}^{\infty}$, sequences of age-dependent individual human capital levels, $\{\{h_{j,t}\}_{j=1}^{J_r-1}\}_{t=0}^{\infty}$, sequences of production plans, $\{L_t^{eff}, K_t\}_{t=0}^{\infty}$, prices, $\{w_t, r_t\}_{t=0}^{\infty}$, accidental bequests, $\{beq_t\}_{t=0}^{\infty}$, government policies, $\{\tau_t^p, \tau_t^e, pen_t, E_t\}_{t=0}^{\infty}$, and the cross-sectional measure of households, $\{\Phi_t\}_{t=0}^{\infty}$, such that*

1. *Given prices, policies, accidental bequests, and initial conditions, $V_t(j, \theta, \eta, a)$ solves (1.19), and $c_t(j, \theta, \eta, a), \ell_t(j, \theta, \eta, a)$ and $a'_t(j, \theta, \eta, a)$ are the associated policy functions.*

2. *The age-dependent human capital levels evolve according to (1.10) and (1.11).*

3. *The population size of the newborn generation evolves according to (3.7).*

4. *The interest rate and the wage rate satisfy (3.19) and (3.20).*

5. *The total accidental bequests are given by*

$$Beq_{t+1} = \int beq_{t+1} \cdot \Phi_{t+1}(dj \times d\theta \times d\eta \times da) \tag{1.21}$$

$$= \int (1 - \psi_{j,t}) \cdot (1 + r_{t+1}) \cdot a'_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da). \tag{1.22}$$

6. *The government policy satisfies (1.16) and (3.21) in each period.*

7. *Markets clear in all periods t,*

   - *the labor market,*

$$L_t^{eff} = L_t^s = \int h_{j,t} \cdot \varepsilon\big(p_j, \theta, \eta\big) \cdot \ell_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{1.23}$$

   - *the capital market,*

$$K_{t+1} = A_{t+1} = \int a'_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{1.24}$$

   - *and the goods market,*

$$Y_t = C_t + I_t + E_t, \tag{1.25}$$

   with aggregate consumption given by

$$C_t = \int c_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{1.26}$$

   and aggregate investment given by

$$I_t = K_{t+1} - (1 - \delta) \cdot K_t. \tag{1.27}$$

8. *The cross-sectional measure of households evolves as follows*

$$\Phi_{t+1}(\mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) = \int P_t((j, \theta, \eta, a), \mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{1.28}$$

for all sets, $\mathcal{J}, \mathcal{I}, \mathcal{M}, \mathcal{A}$, where the Markov transition function, P_t, is given by

$$P_t((j,\theta,\eta,a), \mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) \\ = \begin{cases} \psi_{j,t} \cdot \pi(\eta'|\eta), & if \;\; a'_t(j,\theta,\eta,a) \in \mathcal{A}, for \;\; \theta \in \mathcal{I}, j+1 \in \mathcal{J}, \eta' \in \mathcal{M}, \\ 0, & else. \end{cases} \tag{1.29}$$

and for newborns as

$$\Phi_{t+1}(\{1\} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) = N_{1,t+1} \cdot \begin{cases} \Pi_1(\theta,\eta), & if \;\; 0 \in \mathcal{A}, \\ 0, & else, \end{cases} \tag{1.30}$$

The initial distribution, $\Pi_1(\theta,\eta)$ of $\theta \in \mathcal{I} = \{\theta^1, ..., \theta^I\}$ and $\eta \in \mathcal{M} = \{\eta^1, ..., \eta^M\}$ among one-year-old households is chosen to be uniform.[6]

Definition 1.2.2 (Stationary competitive equilibrium). *A stationary competitive equilibrium is a competitive equilibrium in which individual variables grow at the growth rate of age-1 human capital and aggregate variables grow at the growth rate of age-1 human capital and the population growth rate. The population growth rate and the survival probabilities are constant over time, i.e. $n_t = n$ and $\{\psi_{j,t} = \psi_j\}_{j=1}^{J+1}$.*

1.2.6 Political equilibrium

The social security tax and the education tax are determined via probabilistic voting.[7] The idea of this voting setup is that political parties commit to policies before elections take place. The policy platform is chosen by opportunistic candidates who care only about winning the election. Political parties are assumed to differ along an ideological dimension observable to voters. Political candidates know the distribution of voters' ideological preferences. Therefore, they choose policies that appeal to those voters who are less driven by the ideological component. Political candidates have an average popularity that is common to all voters. Since the policy platform is chosen when the outcome is uncertain, parties maximize the expected vote share and, thus, the probability of winning the election. There exists a unique political equilibrium in which all political parties propose the same policies by maximizing a weighted average welfare function - the political objective function - in which

[6] In detail, $\Pi_1(\theta^1,\eta^1) = \Pi_1(\theta^1,\eta^2) = \Pi_1(\theta^2,\eta^1) = ... = \Pi_1(\theta^I,\eta^M) = \frac{1}{I \cdot M}$.

[7] The basic idea of the probabilistic voting setup goes back to Lindbeck and Weibull (1987) and Persson and Tabellini (2002).

we interpret the weights on different age groups, $j = \{1, ..., J\}$, and deterministic productivity types, $\theta \in \mathcal{I}$, as age- and education-type-specific voter turnout rates, $\omega(j, \theta) \in [0, 1]$.

The decisions that voters make today depend not only on tax rates in t but also on future tax rates that will be decided in future periods. To solve the problem numerically, I make the following assumption, similar to Rauh (2017). When voting on the preferred policy in period t, voters take the anticipated future values to be the same as those chosen in t and ignore the impact that their choice will have on future policy choices. This implies that the individuals assume that the chosen policy will be in place in all future periods. Since individuals are atomistic, this is a plausible assumption since they do not affect aggregate outcomes by themselves.[8] The political objective function under this assumption is then given by

$$\max_{\{\tau_t^e = \{\tau_{t+q}^e\}_{q=1}^{J-1} \in (0,1),\ \{\tau_t^p = \{\tau_{t+q}^p\}_{q=1}^{J-1} \in [0,1)\}} \mathcal{W}_t = \int \omega(j, \theta) \cdot \mathcal{U}_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{1.31}$$

where $\mathcal{U}_t(j, \theta, \eta, a)$ represents the indirect utility function of an individual of age j, deterministic productivity type θ, idiosyncratic shock realization η, and wealth a, at time t.

1.3 Simplified model

This section uses a simplified version of the quantitative model to gain analytical insights into the probabilistic voting outcomes on public policies, in particular, the margins that determine the social security and the education tax rates, before turning to quantitative results in the next sections.

It requires several restrictive assumptions about the household block in the model structure. We assume that agents live only for two periods ($J = 2$): in their first lifetime period as workers (denoted by y) and in their second lifetime period as retirees (denoted by o). Workers supply inelastically one unit of labor, and per-period utility is logarithmic in consumption. Agents face no idiosyncratic risk to their productivity but still differ in terms of their deterministic productivity type, θ^i, $i = \{H, L\}$.[9] Half of each generation ($p^H = \frac{1}{2}$) is born as a deterministic high

[8] A big advantage of this assumption is the implied reduction of computational complexity.

[9] The structure of the simplified model is similar to Song (2011). We add the feature of public spending on education and its productive effect on human capital.

productivity type, θ^H, interpreted as tertiary educated, the other half ($p^L = \frac{1}{2}$) is born as a deterministic low productivity type, θ^L, interpreted as non-tertiary educated. Average labor productivity is normalized to unity, $\sum_{i=\{H,L\}} p^i \cdot \theta^i = 1$. It holds $\theta^H \geqslant \theta^L$. This means that in the special case of $\theta^H = \theta^L$, there exists no within-cohort heterogeneity. Thus, differences in deterministic productivity are the only source of heterogeneity across workers in this simplified setting. Furthermore, capital fully depreciates within one model period. If a young individual dies at the end of the first lifetime period, the annuitized wealth is transferred to individuals who live throughout old age via annuity markets.[10]

1.3.1 Demographics

The size of the young generation in period t, $N_{y,t}$, follows (3.7), and the probability of a young agent surviving to old age is denoted by $\psi_{o,t+1}$. The model-implied old-age dependency ratio is then given by

$$OADR_t = \frac{N_{o,t}}{N_{y,t}} = \frac{\psi_{o,t}}{1+n_t}, \tag{1.32}$$

similar to (1.4), where $N_{o,t} = \psi_{o,t} \cdot N_{y,t-1}$ holds, similar to (1.1).

1.3.2 Households

Under the above-mentioned restrictive assumptions on the household block of the model structure, the maximization problem for a household with deterministic productivity $\theta^i, i = \{H, L\}$, becomes

$$\max_{\{c^i_{y,t}, c^i_{o,t+1}\}} \log(c^i_{y,t}) + \beta \cdot \psi_{o,t+1} \cdot \log(c^i_{o,t+1}) \tag{1.33}$$

$$\text{s.t.} \quad c^i_{y,t} + a^i_{o,t+1} = (1 - \tau^e_t - \tau^p_t) \cdot \theta^i \cdot h_{y,t} \cdot w_t, \tag{1.34}$$

$$c^i_{o,t+1} = \bar{R}_{t+1} \cdot a^i_{o,t+1} + pen_{t+1}, \tag{1.35}$$

where $\bar{R}_{t+1} = \frac{R_{t+1}}{\psi_{o,t+1}}$ holds and represents the return from savings under the perfect annuity market assumption. Individual public pension payments, pen_{t+1}, follow from the budget clearing condition of the public social security budget. Individual human capital at young age, $h_{y,t}$, follows (1.10). Household optimality requires for

[10] Thus, there is no need to redistribute accidental bequests to currently living households.

young age consumption

$$c^i_{y,t} = \left(\frac{1}{1+\beta\psi_{o,t+1}}\right) \cdot \left((1-\tau^e_t-\tau^p_t)\cdot\theta^i\cdot h_{y,t}\cdot w_t + \frac{pen_{t+1}}{\bar{R}_{t+1}}\right), \tag{1.36}$$

for old age consumption

$$c^i_{o,t+1} = \beta \cdot R_{t+1} \cdot c^i_{y,t}, \tag{1.37}$$

and for savings

$$a^i_{o,t+1} = \left(\frac{\psi_{o,t+1}}{1+\beta\psi_{o,t+1}}\right) \cdot \left(\beta\cdot(1-\tau^e_t-\tau^p_t)\cdot\theta^i\cdot h_{y,t}\cdot w_t - \frac{pen_{t+1}}{R_{t+1}}\right). \tag{1.38}$$

1.3.3 Firms

The assumption of inelastic labor supply by households ensures, by normalizing average labor productivity to unity, that the labor market clearing condition has the following form

$$L^{eff}_t = L^s_t = \underbrace{\left(\sum_{i=\{H,L\}} p^i\cdot\theta^i\right)}_{=1} \cdot h_{y,t}\cdot N_{y,t} = h_{y,t}\cdot N_{y,t}. \tag{1.39}$$

Thus, using (1.39), the production function from (3.16) can be rewritten as

$$\hat{Y}_t = \Omega_Y \cdot (\hat{K}_t)^\alpha \cdot (h_{y,t})^{1-\alpha}, \tag{1.40}$$

where $\hat{X}_t \equiv \frac{X_t}{N_{y,t}}$ holds. The wage rate follows from (3.20) in combination with (1.39) as

$$w_t = \Omega_Y \cdot (1-\alpha) \cdot \left(\frac{\hat{K}_t}{h_{y,t}}\right)^\alpha, \tag{1.41}$$

and assuming full capital depreciation ($\delta = 1$), using (3.19) in combination with (1.39), yields for the interest rate

$$R_t \equiv 1 + r_t = \Omega_Y \cdot \alpha \cdot \left(\frac{\hat{K}_t}{h_{y,t}}\right)^{\alpha-1} = \left(\frac{\alpha}{1-\alpha}\right)\cdot w_t \cdot \left(\frac{h_{y,t}}{\hat{K}_t}\right). \tag{1.42}$$

The capital market clearing is given by

$$K_{t+1} = N_{y,t} \cdot \sum_{i=\{H,L\}} p^i \cdot a^i_{o,t+1}, \tag{1.43}$$

and can be rewritten as

$$\hat{K}_{t+1} = \left(\frac{1}{2\cdot(1+n_{t+1})}\right)\cdot\left(a^{H}_{o,t+1}+a^{L}_{o,t+1}\right), \tag{1.44}$$

by using $p^i = \frac{1}{2}, i = \{H, L\}$, and (3.7).

1.3.4 Government

Public spending on education follows (1.16) and can be rewritten as per capita public education spending,

$$\hat{E}_t = \tau^e_t \cdot \underbrace{\left(\sum_{i=\{H,L\}} p^i\cdot\theta^i\right)}_{=1}\cdot h_{y,t}\cdot w_t = \tau^e_t\cdot h_{y,t}\cdot w_t. \tag{1.45}$$

Public spending on pensions follows (3.21) and can be rewritten as per capita public pension spending,

$$\hat{Pen}_t = \tau^p_t \cdot \underbrace{\left(\sum_{i=\{H,L\}} p^i\cdot\theta^i\right)}_{=1}\cdot h_{y,t}\cdot w_t = \left(\frac{\psi_{o,t}}{1+n_t}\right)\cdot pen_t, \tag{1.46}$$

using (1.32). Individual public pension payments to retired households are then calculated as

$$pen_t = \left(\frac{1+n_t}{\psi_{o,t}}\right)\cdot\tau^p_t\cdot h_{y,t}\cdot w_t. \tag{1.47}$$

1.3.5 Political equilibrium

The social security tax and the education tax are also determined via probabilistic voting. We impose the same assumption as in the quantitative model version. When individuals vote on the tax rates today, they assume that today's tax rate will also be in place tomorrow. Specifically, this means that $\tau^g_t = \tau^g_{t+1},\ g = \{e, p\}$ holds. The political objective function is then given by

$$\begin{aligned}\max_{\{\tau^e_t=\tau^e_{t+1}\in(0,1),\ \tau^p_t=\tau^p_{t+1}\in[0,1)\}} \mathcal{W}_t = \psi_{o,t}\cdot\left(\sum_{i=\{H,L\}}\omega(o,\theta^i)\cdot\mathcal{U}^i_{o,t}\right)\\ +(1+n_t)\cdot\left(\sum_{i=\{H,L\}}\omega(y,\theta^i)\cdot\mathcal{U}^i_{y,t}\right),\end{aligned} \tag{1.48}$$

with $\omega(j,\theta^i) \in [0,1]$, $j = \{y,o\}$, $i = \{H,L\}$, as the age and deterministic productivity type specific voter turnout rate and $\mathcal{U}^i_{j,t}$ as the corresponding indirect utility function. The indirect utility function for a currently living old and deterministic L-type individual is given by

$$\mathcal{U}^L_{o,t}\Big|_{t.i.p.} = \log\Big((\frac{2\alpha}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\Big), \tag{1.49}$$

where "$t.i.p$" indicates that the respective expression includes only terms that are affected by contemporaneous policy choices due to the logarithmic preference assumption. The variable $\lambda_{o,t} \equiv \frac{a^H_{o,t}}{a^L_{o,t}} \geqslant 1$ defines the wealth ratio of the currently living old individuals.[11] The indirect utility function for a currently living old and deterministic H-type individual follows

$$\mathcal{U}^H_{o,t}\Big|_{t.i.p.} = \log\Big((\frac{2\alpha\lambda_{o,t}}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\Big). \tag{1.50}$$

The indirect utility function for a currently living young individual of deterministic productivity type $i = \{H,L\}$, is given as

$$\begin{aligned}\mathcal{U}^i_{y,t}\Big|_{t.i.p.} &= (1+\beta\psi_{o,t+1}\alpha)\log\Big(1-\tau^e_t-\tau^p_t\Big) + \beta\psi_{o,t+1}(1-\alpha)\iota\log\Big(\tau^e_t\Big)\\ &+ (1+\beta\psi_{o,t+1})\log\Big(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_t\Big)\\ &- (1+\beta\psi_{o,t+1}\alpha)\log\Big((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\tau^p_t\Big).\end{aligned} \tag{1.51}$$

Plugging (1.49), (1.50) and (1.51) into (1.48) yields for the political objective function

$$\begin{aligned}\max_{\{\tau^e_t\in[0,1),\ \tau^p_t\in(0,1)\}} \mathcal{W}_t\Big|_{t.i.p.} &= \psi_{o,t}\cdot\Big(\omega(o,\theta^L)\cdot\log\Big((\frac{2\alpha}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\Big)\\ &+ \omega(o,\theta^H)\cdot\log\Big((\frac{2\alpha\lambda_{o,t}}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\Big)\Big)\\ + (1+n_t)\cdot\Big(\sum_{i=\{H,L\}}\omega(y,\theta^i)\cdot&\Big((1+\beta\psi_{o,t+1}\alpha)\log\Big(1-\tau^e_t-\tau^p_t\Big) + \beta\psi_{o,t+1}(1-\alpha)\iota\log\Big(\tau^e_t\Big)\\ &+ (1+\beta\psi_{o,t+1})\log\Big(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_t\Big)\\ &- (1+\beta\psi_{o,t+1}\alpha)\log\Big((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\tau^p_t\Big)\Big)\Big).\end{aligned} \tag{1.52}$$

[11]The detailed derivation of all indirect utility functions and their respective "t.i.p." terms can be found in Appendix 1.B.

1.3.6 Stationary political equilibrium

We now assume that the demographic variables - the survival probability to old age and the population growth rate - are constant. Specifically, this means that $\psi_{o,t} = \psi_o$ and $n_t = n$, $\forall t$, and implies that we can abstract from time subscripts in the first-order conditions with respect to the public policy instruments.[12]

In the first step, we decompose the relevant margins that drive public policy choices in the stationary political equilibrium. These margins can be identified from the stationary first-order conditions in (1.53) for the social security tax,

$$\begin{aligned}
&\psi_o \cdot \Big(\omega(o,\theta^L) \cdot \underbrace{\frac{(1-\alpha)}{(\frac{2\alpha}{1+\lambda_o}) + (1-\alpha)\tau^p}}_{(+)\ AIE^L_{o|o}} + \omega(o,\theta^H) \cdot \underbrace{\frac{(1-\alpha)}{(\frac{2\alpha\lambda_o}{1+\lambda_o}) + (1-\alpha)\tau^p}}_{(+)\ AIE^H_{o|o}}\Big) \\
&+ (1+n) \cdot \Big(\sum_{i=\{H,L\}} \omega(y,\theta^i) \cdot \Big(\underbrace{\frac{(1+\beta\psi_o)(1-\alpha)(\theta^i + \beta\psi_o)}{\theta^i(1+\beta\psi_o)\alpha + (\theta^i+\beta\psi_o)(1-\alpha)\tau^p}}_{(+)\ AIE^i_{y|o},\ (+)\ IRE^i_{y|o}} \Big)\Big) \\
&\stackrel{!}{=} (1+n) \cdot \Big(\sum_{i=\{H,L\}} \omega(y,\theta^i) \cdot \Big(\underbrace{\frac{(1+\beta\psi_o\alpha)}{1-\tau^e-\tau^p}}_{(-)\ AIE_{y|y},\ (-)\ SE_{y|o}} + \underbrace{\frac{(1+\beta\psi_o\alpha)(1-\alpha)}{(1+\beta\psi_o)\alpha + (1-\alpha)\tau^p}}_{(-)\ WRE_{y|o}} \Big)\Big),
\end{aligned} \tag{1.53}$$

and in (1.54) for the education tax,

$$\underbrace{\frac{\beta\psi_o(1-\alpha)\iota}{\tau^e}}_{(+)\ TBE_{y|o}} \stackrel{!}{=} \underbrace{\frac{1+\beta\psi_o\alpha}{1-\tau^e-\tau^p}}_{(-)\ AIE_{y|y},\ (-)\ SE_{y|o}}, \tag{1.54}$$

respectively.

There exist several positive margins that are traded off with negative margins to determine the size of the social security tax in the stationary political equilibrium as observable from (1.53). Current old individuals, regardless of their deterministic productivity type, benefit from an increase in the social security tax. A higher tax rate directly increases their pension payments and, thus, their disposable income. This positive *Available Income Effect*, $AIE^i_{o|o}$, for old individuals realizing in their second lifetime period is even stronger for L-type individuals. They own less wealth and an increase in their consumption generates stronger welfare gains due to the concavity of the utility function. Furthermore, young individuals know that a higher

[12] The time-dependent first-order conditions with respect to the public policy instruments can be found in Appendix 1.B.

social security tax tomorrow will increase their future pension payments, which is highlighted by the positive *Available Income Effect*, $AIE^i_{y|o}$. This effect materializes for young individuals when they are old. In addition, young individuals benefit from a positive *Interest Rate Effect*, $IRE^i_{y|o}$. The marginal product of capital increases due to reduced savings today, which leads to capital scarcity tomorrow. Consequently, the interest rate in the second lifetime period increases. These effects also vary across deterministic productivity types and are again stronger for L-type individuals because they hold less wealth. Their consumption increase generates stronger welfare gains due to the concavity of the utility function.

The positive margins are mitigated by negative margins resulting from an increase in the social security tax. First, and observable from the negative *Available Income Effect*, $AIE_{y|y}$, realized for young individuals already in their first lifetime period, their available income decreases. A higher social security tax rate today reduces their current after-tax labor income. Second, and observable from the negative *Savings Effect*, $SE_{y|o}$, that materializes for young individuals when they are old, the reduction in the after-tax income of young individuals reduces the amount of wealth that can be saved in the first lifetime period. Reduced savings today, and therefore depressed wealth holdings tomorrow, reduce the consumption options when individuals are old. In addition, young individuals suffer from a negative *Wage Rate Effect*, $WRE_{y|o}$, which materializes in their second lifetime period. A reduction in the marginal product of labor and, consequently, declining wage rates are induced by capital scarcity. This leads to a reduction in the future tax base and, thus, in an individual's future pension payments.

The margins that are traded off to determine the size of the education tax in the stationary political equilibrium are observable from (1.54). The positive *Tax Base Effect*, $TBE_{y|o}$, is the main margin that rationalizes the positive education tax rate in the stationary political equilibrium. This effect is realized for currently young individuals in their second lifetime period. Young individuals know that today's government investment into tomorrow's human capital increases the future tax base and, thus, their pensions in old age. This margin depends strongly on the elasticity of young-age human capital with respect to per capita public spending on education, ι. The higher the elasticity, the more efficient the per capita public education spending in boosting young-age human capital tomorrow, the stronger the margin, and the higher the education tax rate in the stationary political equilibrium.

This positive margin is mitigated, first, by a negative *Available Income Effect*, $AIE_{y|y}$, that is realized for young individuals already in their first lifetime period.

Today's higher education tax reduces their current available income. Second, by a negative *Savings Effect*, $SE_{y|o}$, that is realized for young individuals when they are old. Today's reduced disposable income dampens individuals' savings and reduces tomorrow's wealth holdings.[13]

In the second step, we now quantify the public policy preferences that depend on the age and the deterministic productivity type of a household. In the third step, we perform comparative statics on how population aging and variations in ex-ante inequality affect the political outcomes and ex-post inequality, formalized as the old age wealth ratio. These steps require the parameterization of several model parameters. We set the capital share, α, to a standard value of 0.33, the survival probability to old age, ψ_o, to 0.45, and the population growth rate, n, to 0.05. Furthermore, we set all voter turnout rates to unity.[14] The discount factor, β, the elasticity of young age human capital with respect to per capita public education spending, ι, and the deterministic productivity level of the H-type individuals, θ^H, are adjusted so that the ratio of public pension spending to production is 9.6 percent, the ratio of public education spending to production is 4.6 percent, and the ratio of labor income of the deterministic H- to L-type individuals, interpreted as the skill premium, is at a value of 1.49.[15] The parameterization strategy requires values of $\beta = 0.72$, $\iota = 0.44$, and $\theta^H = 1.12$. As a result of the stationary political equilibrium choice, public policy consists of a social-security tax of 14.30 percent and an education tax of 6.85 percent.

Figure 1.2 shows the percentage point differences for both tax rates that fund public policy relative to the initial parameterization when a particular deterministic productivity type, θ^i, $i = \{H, L\}$, in a particular age group, $j = \{y, o\}$, is not included in the political objective function. In particular, $\omega(j, \theta^i) = 0$ holds, meaning that the preferences of that specific type play no role in determining public policy.

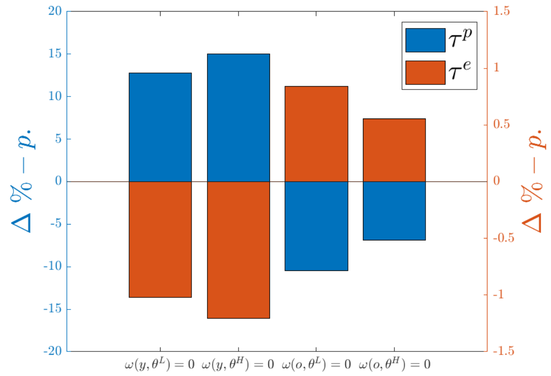
Excluding old individuals from the political objective function, regardless of their deterministic productivity type, leads to a significant decrease in the social security

[13] $AIE^i_{y|o}$, $IRE^i_{y|o}$ and $WRE_{y|o}$ in (1.53) are a consequence of the assumption that today's and tomorrow's tax rates coincide, $\tau^g_t = \tau^g_{t+1}$, $g = \{e, p\}$. As currently alive individuals are not affected by tomorrow's education tax, τ^e_{t+1}, these second-period effects do not materialize in (1.54). These effects do play a role in the quantitative version of the model.

[14] At this stage, we abstract from the impact of differential voter turnout rates on the allocation of public resources.

[15] These three calibration targets represent the German economy in the year 2020. They are also used to calibrate the quantitative version of the model. The ratio of public pension spending to production is calculated directly using (1.40) and (1.46) so that $\frac{Pen}{Y} = (1-\alpha)\tau^p$ holds and similarly, by using (1.40) and (1.45), for the ratio of public education spending to production, so that $\frac{E}{Y} = (1-\alpha)\tau^e$ holds.

Figure 1.2: Preferences on public policy items.

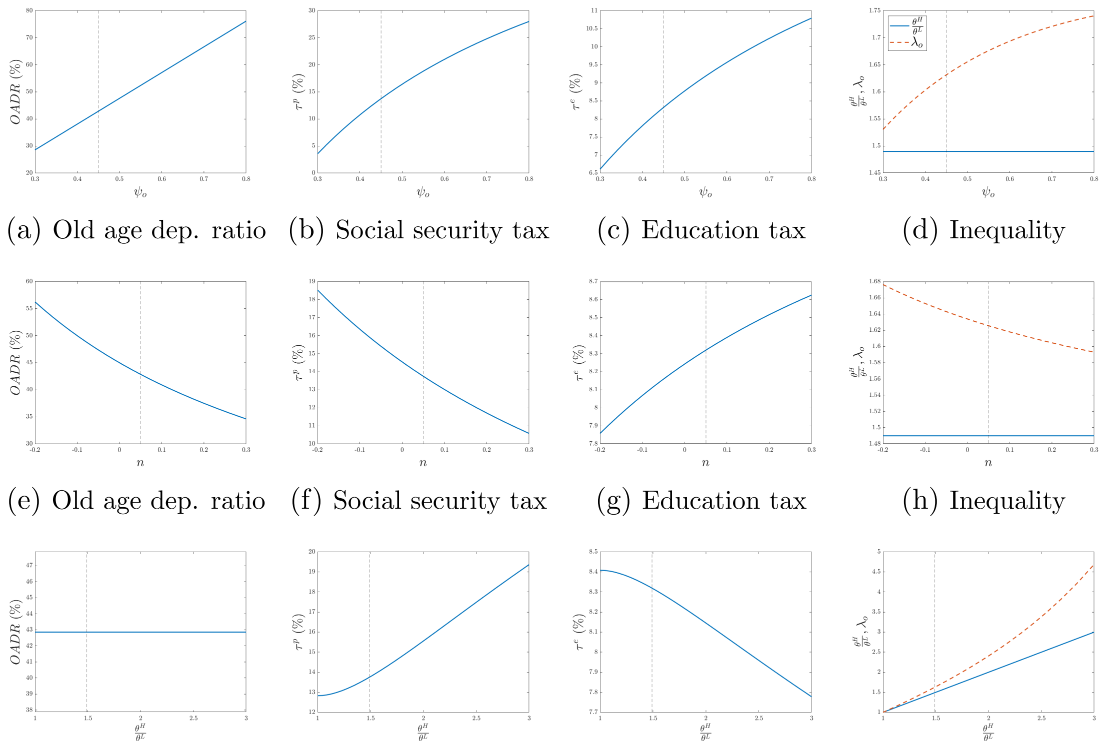


Note: This figure shows the percentage point deviations in the social security (blue, left y-axis) and education (orange, right y-axis) taxes relative to the stationary political equilibrium for the baseline parameterization in the simplified model when an individual of a given age, $j = \{y, o\}$, and deterministic productivity type, $\theta^i, i = \{H, L\}$, is by assumption excluded from the political objective function by setting the corresponding voter turnout rate to zero, $\omega(j, \theta^i) = 0$. For details, see text.

tax and an increase in the education tax. The effect is more pronounced for old L-type individuals ($\omega(o, \theta^L) = 0$) due to the redistributive nature of the public pension payments. Excluding old L-type individuals from voting reduces the social security tax from its initial value of 14.30 percent by 10.44 percentage points to 3.86 percent. The education tax increases by 0.86 percentage points from its initial value of 6.85 percent to 7.71 percent. The exclusion of young individuals from the political process, regardless of their deterministic productivity type, leads to a significant increase in the social security tax and a decrease in the education tax. The effect is more pronounced for young H-type individuals ($\omega(y, \theta^H) = 0$). They benefit more strongly from a significant tax reduction in the first lifetime period than L-type individuals. They save more and are therefore less dependent on (redistributive) pension payments in their second lifetime period. The exclusion of young H-type individuals from the political process increases the social security tax by 15.04 percentage points to 29.34 percent. The education tax decreases by 1.18 percentage points to 5.67 percent. Young individuals have a stronger preference for public spending on education, while old individuals have a stronger preference for public spending on pensions. Preferences for public spending on pensions are generally stronger for L-type individuals due to the redistributive nature of pensions in the model.

Figure 1.3 displays comparative static exercises for a variation in the survival probability to old age, ψ_o, in the first row, the population growth rate, n, in the second row, and ex-ante inequality (measured as the ratio of deterministic H-type

Figure 1.3: Comparative statics.



(a) Old age dep. ratio (b) Social security tax (c) Education tax (d) Inequality

(e) Old age dep. ratio (f) Social security tax (g) Education tax (h) Inequality

(i) Old age dep. ratio (j) Social security tax (k) Education tax (l) Inequality

Note: This figure shows comparative static exercises for the baseline parameterization of the simplified model; in the first row, variations in the survival probability to old age, ψ_o; in the second row, variations in the population growth rate, n; and in the third row, variations in ex-ante inequality, measured as the ratio of deterministic H- to L-type productivity, $\frac{\theta^H}{\theta^L}$. The vertical broken line in all panels displays the initial parameterized value of the respective variable. For details, see text.

and L-type productivity), $\frac{\theta^H}{\theta^L}$, in the third row. The variables of interest are the old-age dependency ratio, $OADR$, the social security tax, the education tax, and ex-post inequality (measured as the old-age wealth ratio), λ_o. Vertical dashed lines show the initial parameterized value of the respective variable.

An increase in the survival probability to old age, ψ_o, leads to a significant increase in the old age dependency ratio and, thus, to population aging. The social security tax significantly increases in the survival probability to old age. First, the importance of elderly individuals in the political objective function increases, thereby exerting pressure on the public policy instrument that benefits them most. Second, young individuals also benefit from higher social security taxes, given that they will retire in the next lifetime period. Their future pensions increase. An increase in the survival probability to old age implicitly increases the weight of second-period effects for current young individuals. We also observe an increase in the education tax in the survival probability to old age. Individuals already know today that they must plan for a longer life and that the future tax base will increase if the government invests more in education. Specifically, it leads to an increase in the future human capital level of the economy. An increase in the survival probability thus increases the demand for public policy and tax liabilities for current young individuals. Ex-ante inequality is constant (by assumption), but ex-post inequality increases with the survival probability to old age. This is due to a reduction in the incentive to save in the first lifetime period, as individuals will receive significantly higher pensions with an increasing social security tax. Savings decrease more than linearly for L-type individuals, leading to a growing wealth ratio and higher ex-post inequality.

A decline in the population growth rate, n, leads to an increase in the old-age dependency ratio and, thus, to population aging. The social security tax increases significantly with a declining population growth rate as the relative importance of old individuals in the political objective function increases. The education tax declines with a reduction in the population growth rate. This is due to the lower relative importance of young individuals in the political objective function. A decline in the population growth rate has ambiguous implications for the demand for public policy. Furthermore, the effects of population aging on the education tax, induced by an increase in the survival probability or a reduction in the population growth rate, work in opposite directions. Again, ex-ante inequality is constant (by assumption), but ex-post inequality increases with a decreasing population growth rate. Young individuals today understand that due to the increasing social security tax, their future pensions will increase and they accumulate less wealth today. This reduction in the incentives to save is stronger for L-type individuals and leads to an increase in the wealth ratio of H- to L-type individuals tomorrow and, therefore, to rising ex-post inequality.

A change in ex-ante inequality, measured as the ratio of deterministic H-type to L-type productivity, $\frac{\theta^H}{\theta^L}$, has no effect on the age structure of the population, but still affects political outcomes. For the special case of a unitary deterministic productivity ratio, we are in the canonical representative agent setting and there exists neither ex-ante nor ex-post inequality in the economy. The tax rates are at the lowest value for the social security tax and the highest value for the education tax. There exists no redistributive effect of the social security tax across old individuals, reducing the demand for the redistributive public policy instrument. Any increase in ex-ante inequality leads to an increase in the social security tax as the redistributive properties of the tax become increasingly important. The opposite is true for the

Table 1.1: Exogenously chosen parameters.

Parameter	Description	Value	Source
n	Population growth rate (%)	0.92	United Nations (2024)
α	Capital share	0.33	Standard
γ	Intertemp. elasticity of substitution	0.5	Standard
Ω_H	Human capital productivity	1	Normalization
h_{J_r-1}	Oldest-worker human capital	1	Normalization
ρ	Persistence of idiosyncratic shock	0.335	Brinca et al. (2021)
$\{\psi_j\}_{j=1}^{J+1}$	Survival probabilities	Figure 1.4a	United Nations (2022a,b)
$\{p_j\}_{j=1}^{J_r-1}$	Age-dependent productivity	Figure 1.4b	Heer (2019)
$\{\{\omega(j,\theta^i)\}_{j=1}^{J}\}_{i=\{H,L\}}$	Voter turnout rates	Figure 1.5	European Social Survey (2023)
I	No. of determ. productivity types	2	Tertiary vs. Non-Tertiary, $i = \{H, L\}$
M	No. of idiosync. productivity types	7	Standard

Note: This table reports the exogenously chosen parameters for the stationary political equilibrium in 2020. For details, see text.

education tax, which decreases with ex-ante inequality, driven by the increasing demand for the social security tax. The size of redistributive pensions increases. This leads to a more than proportional reduction in the incentives to accumulate wealth for young L-type individuals and creates higher ex-post inequality.[16]

1.4 Calibration and characteristics of the stationary political equilibrium

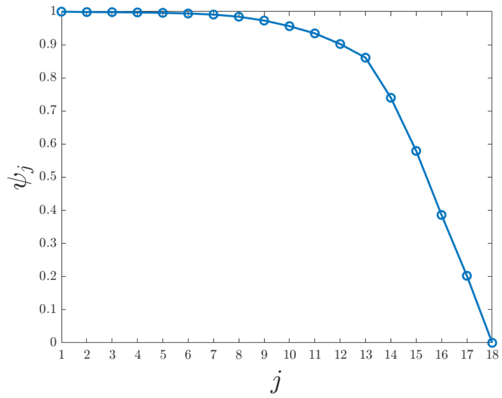
This section describes the calibration strategy for the quantitative model and discusses the characteristics of the stationary political equilibrium.

1.4.1 Calibration

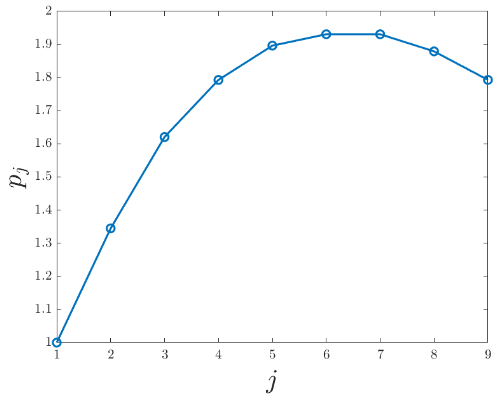
The quantitative version of the model is calibrated to the German economy of the year 2020 as the initial stationary political equilibrium, in which both, the survival probabilities and the population growth rate are assumed to be constant. Germany is the largest economy in Europe, its population is rapidly aging, and its pension and education systems are largely publicly funded. Table 1.1 and Table 1.3 summarize the choice of the exogenously chosen parameters as well as those endogenously calibrated within the model. We choose seven model parameters endogenously to match seven different targets. Table 1.4 summarizes the model fit with respect to the targeted moments and Table 1.5 reports various distributional measures for labor income, total income, and wealth.

[16]Further comparative static exercises for variations in the discount factor, β, the elasticity of human capital with respect to per capita public spending on education, ι, and the capital share, α, can be found in Appendix 1.B.

Figure 1.4: Exogenously chosen and age-dependent parameters.



(a) Survival probabilities.



(b) Age-dependent productivity.

Note: This figure depicts the survival probabilities and the age-dependent productivities for the stationary equilibrium in 2020. Survival probabilities are based on data from United Nations (2022a,b). Age-dependent productivities are based on data from Heer (2019). For details, see text.

Exogenously chosen parameters

The population growth rate, n, is taken from United Nations (2024) and set to 0.92 percent. Annual growth rates are converted to five-year values. The capital share, α, is set to 0.33, and the parameter governing the intertemporal elasticity of substitution, γ, is set to 0.5, both standard values in the literature. The human capital productivity parameter, Ω_H, is normalized to unity. The same applies to the oldest worker's human capital level, h_{J_r-1}. The persistence of the idiosyncratic shock process, ρ, is set to 0.335, in line with Brinca et al. (2021). The age-dependent survival probabilities, $\{\psi_j\}_{j=1}^{J+1}$, shown in Figure 1.4a, are taken from United Nations (2022a,b) and (if necessary) converted to five-year values.[17] We then take the average values of the respective five consecutive years to fit the data into the quantitative model. The deterministic and age-dependent productivity component, $\{p_j\}_{j=1}^{J_r-1}$, depicted in Figure 1.4b, is taken from Heer (2019).[18] We normalize the age-1 component, p_1, to unity. By assumption, age-dependent productivity falls to zero for retired individuals.

Deterministic productivity- and age-dependent voter turnout rates, $\{\{\omega(j,\theta^i)\}_{j=1}^{J}\}_{i=\{H,L\}}$

[17] Conversion is required for the years 2020 and 2021 because the dataset reports survival probabilities on an annual basis for these two years. The annual survival probabilities are multiplied in five-year increments to correspond to the age-group intervals in line with the quantitative model. Detailed numbers can be found in Appendix 1.C, Table 1.8.

[18] Heer (2019) computes the age-dependent productivity component for Germany using the average hourly wages of j-year old individuals during the period 1990-1997 following the method of Hansen (1993).

are constructed by the use of survey data from the European Social Survey (2023) based on ESS round 8 in the year 2016.[19] The German sample includes 2,466 observations with a weighted average voter turnout rate of 84.47 percent.[20]

To estimate the deterministic productivity- and age-dependent voter turnout rates, we first use the probit model in (1.55) to quantify the effects of a tertiary education degree and an individual's age on the probability of voting,

$$Pr(Voted = 1) = \Psi(\mu_1 \cdot Tertiary + \mu_2 \cdot Age + \mu_3 \cdot Age^2 + \mu_0). \tag{1.55}$$

The dependent variable, $Voted$, indicates whether the respondent in the survey sample voted in the last national election ($Voted = 1$) or not ($Voted = 0$).[21] The independent variable, $Tertiary$, is a dummy variable indicating whether the individual has a tertiary education ($Tertiary = 1$) or not ($Tertiary = 0$). The independent variable, Age, includes information on the individual's age, harmonized with the age groups in the quantitative model. Specifically, the variable $Age \in \{1, 2, .., 13\}$ corresponds to the real-world age groups of $\{20-24, 25-29, ..., 80+\}$.[22] Due to the small sample size of the age groups $\{85-89, 90-94, 95-99, 100+\}$ in the ESS sample, which correspond to the age groups $\{14, 15, 16, 17\}$ in the quantitative model, we assign individuals from these age groups into the age group $Age = 13$ for the estimation of the probability of voting. We also include the independent variable, Age^2, to capture the fact that political participation is (potentially) hump-shaped with an individual's age.

The coefficients of the probit model for the ESS round 8 in the year 2016 with robust standard errors are reported in Table 1.2. Columns (1) and (2) report the results considering education or age separately, while column (3) reports the results

[19] The European Social Survey (ESS) measures the attitudes, beliefs, and behavior patterns of diverse populations in more than thirty European nations, among other things, individual voting behavior. The ESS round 8 in the year 2016 is the last ESS round in which Germany is completely included in the ESS sample. Although Germany is also included in ESS round 11 in the year 2023, the relevant weighting measure is missing in the data set.

[20] The observed average voter turnout rate for the German national election in 2013 was at a value of 71.5 percent. The ESS sample overstates the average voter turnout by about 18.2 percent relative to the data. As long as the bias is the same across age groups and productivity types, this is a minor problem since the differences in the weight of the specific individuals in the political objective function arise from differences in relative, not absolute, voter turnout rates. A reduction of all type-specific voter turnout rates in the calibration by 18.2 percent would yield the same results.

[21] The variable $Voted$ is based on the following question: "Some people don't vote nowadays for one reason or another. Did you vote in the last [country] national election in [month/year]?".

[22] Individuals in the age group 20-24 fall in the category of $Tertiary = 1$ as long as they are students at the time of the survey.

Table 1.2: Probit model results.

	Dependent variable: Voted		
	(1)	(2)	(3)
Tertiary	0.599***		0.634***
	(0.092)		(0.093)
Age		0.153***	0.144***
		(0.041)	(0.041)
Age^2		−0.007**	−0.006**
		(0.003)	(0.003)
Constant	0.932***	0.398***	0.313***
	(0.040)	(0.118)	(0.119)
Observations	2,466	2,466	2,466
Avg. Turnout (%)	84.47	84.47	84.47

Note: This table reports probit model results for (1.55), based on data from the ESS round 8 in the year 2016. Robust standard errors are given in brackets. Results on all other ESS rounds and years can be found in Table 1.10. It holds: $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. For details, see text.

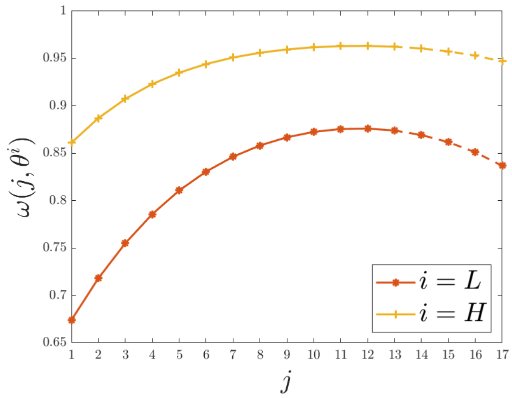
for the full specification. We observe that the probability of voting increases significantly with the level of education and in a hump-shaped manner with the age (group) of the individual. Having completed tertiary education leads to an increase in the probability of voting by 0.634 units, while moving from a younger age group to the next older age group leads to an increase in the probability of voting by 0.138 units.[23] In terms of average marginal effects with respect to the education level, the probit model predicts that switching from a non-tertiary to a tertiary education degree increases the probability of voting on average by 12 percent. With respect to the age of an individual, a switch from one age group to the next older age group increases the probability of voting on average by 3.5 percent.[24] Second, given the estimated coefficients, $\mu = \{\mu_0, ..., \mu_3\}$, we compute the predicted probabilities of voting, $\Psi(j, \theta^i, \mu)$, of an individual with age, $j \in \{1, ..., 13\}$, and deterministic productivity type, $\theta^i, i \in \{H, L\}$. The predicted probabilities based on the estimated coefficients in Table 1.2, column (3), are shown in Figure 1.13b in Appendix 1.C. We observe the lowest probability of voting of 67.4 percent for 20-24-year-old individuals without a tertiary education degree and the highest probability of voting of 96.3 percent for 70-74-year-old individuals with a tertiary degree.

As a final step, we interpret the deterministic type- and age-dependent probabilities of voting as the respective voter turnout rates in the political objective

[23] Estimation results for other ESS rounds can be found in Table 1.10 in Appendix 1.C.

[24] Average marginal effects for other ESS rounds and years can be found in Figure 1.15 in Appendix 1.C.

Figure 1.5: Exogenously chosen deterministic productivity- and age-dependent voter turnout rates.



Note: This figure shows the exogenously chosen deterministic productivity- and age-dependent voter turnout rates. Voter turnout rates for age groups up to $j = 13$ (solid parts of the lines) are taken directly from the probit model estimates. Voter turnout rates for older age groups ($j = \{14, 15, 16, 17\}$, dashed parts of the lines) are based on out-of-sample predictions. For details, see text.

function in (1.31), such that $\omega(j, \theta^i) \equiv \Psi(j, \theta^i, \mu)$ holds. Since we are only estimating predicted probabilities for age groups 1 through 13, we are missing values for age groups 14 through 17, which are required for the political objective function specified above. To specify voter turnout rates for these age groups, we use out-of-sample predictions. Figure 1.5 depicts the final exogenously chosen deterministic type- and age-dependent voter turnout rates.[25]

Endogenously chosen parameters

The production productivity parameter, Ω_Y, is set to a value of 1.545 so that we observe a unitary wage rate in the stationary political equilibrium. The depreciation rate, δ, is calibrated to a value of 0.368 so that the model-implied capital-output ratio is equivalent to 301 percent, which is close to the value reported in Brinca et al. (2021) for Germany.[26] The taste parameter for consumption, ν, is set to 0.352 and chosen so that the average individual labor supply of all workers is 33 percent of the total time endowment, a standard target in the literature. The variance of the permanent productivity effect, σ_θ, is chosen so that the tertiary education premium corresponds to a value of 1.49 (OECD, 2023a) and is set to a value of 0.034. The tertiary education premium in the quantitative model, $\frac{\bar{y}(\theta^H)}{\bar{y}(\theta^L)}$, is calculated as the average (pre-tax) labor income ratio of permanent high- to low productivity

[25] Detailed numerical results are presented in Table 1.12 in Appendix 1.C.
[26] The chosen depreciation rate is equivalent to an annual rate of 8.76 percent.

Table 1.3: Endogenously calibrated parameters.

Parameter	Description	Value
Ω_Y	Production productivity	1.545
δ	Depreciation rate	0.368
ν	Taste parameter for consumption	0.352
σ_θ	Variance of permanent productivity	0.034
σ_ϵ	Variance of idiosyncratic productivity	0.128
ι	Human capital elasticity	0.025
β	Discount rate	0.881

Note: This table reports the seven endogenously calibrated parameters for the stationary political equilibrium in 2020. For details, see text.

individuals.[27] The variance of the idiosyncratic productivity effect, σ_ϵ, is set to 0.128 and chosen to match a Gini coefficient for individual (pre-tax) labor income, $Gini_y$, of 0.40, in line with Drechsel-Grau et al. (2022).[28] The human capital elasticity parameter, ι, and the discount rate, β, are chosen so that the political outcome regarding the two tax rates leads to a ratio of public education spending to GDP of 4.6 percent (Eurostat, 2023b) and a ratio of public pension to GDP of 9.6 percent (Eurostat, 2023c). This requires a value of 0.025 for the human capital elasticity parameter and a value of 0.881 for the discount rate. The latter corresponds to an annual discount rate of 0.975.

1.4.2 Characteristics

Before analyzing the effects of population aging and differential voter turnout on the political outcome regarding public policy, economic aggregate, and inequality, we briefly discuss the characteristics of the stationary political equilibrium. As observable from Table 1.4, the model perfectly fits the targeted moments. The political process pins down an education tax rate of 6.85 percent and a social-security tax rate of 14.30 percent in the stationary political equilibrium. The latter lies at a value of 18.30 percent in the data. The implied average pension replacement rate, $\bar{\kappa}_t$, measured as the individual pension payments relative to the average income of the previous period, lies at a value of 33.54 percent.[29] In addition, the annualized interest rate is 3.4 percent, and the model-implied investment-to-GDP ratio is 22.9

[27] The tertiary education premium in the data is calculated as the ratio of the earnings of workers with a tertiary education (specifically, a bachelor's degree or equivalent) to those of workers with an upper secondary education.

[28] Individual (pre-tax) labor income is defined as: $y_{j,t} = \varepsilon(p_j, \theta, \eta) \cdot h_{j,t} \cdot \ell_{j,t} \cdot w_t$.

[29] In detail, the average replacement rate is defined as: $\bar{\kappa}_t = \frac{pen_t}{w_{t-1} L^s_{t-1} / N_{w,t-1}}$

Table 1.4: Targeted moments.

Target	Description	Model	Data	Source
w	Wage rate	1	1	Normalization
$\frac{K}{Y}$	Capital-output ratio (%)	301	301	Brinca et al. (2021)
ℓ	Average labor supply (%)	33	33	Standard
$\frac{\bar{y}(\theta^H)}{\bar{y}(\theta^L)}$	Tertiary education premium	1.49	1.49	OECD (2023a)
$Gini_y$	Labor income Gini coefficient	0.40	0.40	Drechsel-Grau et al. (2022)
$\frac{E}{Y}$	Education-to-GDP ratio (%)	4.6	4.6	Eurostat (2023b)
$\frac{Pen}{Y}$	Pension-to-GDP ratio (%)	9.6	9.6	Eurostat (2023c)

Note: This table reports the seven targeted moments for the endogenous calibration for the stationary political equilibrium in 2020. For details, see text.

percent, close to its (non-targeted) real-world counterpart of 22.0 percent (World Bank, 2024b).

The model and data moments for the labor income, total income, and wealth distributions are reported in Table 1.5. The data counterparts for labor income are taken from Drechsel-Grau et al. (2022), and those for the total income and the wealth distribution from World Inequality Database (2025).[30] All distributional variables related to individual income are calculated before taxes.[31]

The highlighted distributional measures are the Gini coefficients, the quintile shares (Q1-Q5), the Bottom50, the Top10, the Top5, and the Top1 percent shares of the respective variable. The Gini coefficient on labor income as a targeted moment is perfectly matched. All other non-targeted distributional measures of labor income are close to their data counterparts, with small differences at the bottom and top of the labor income distribution. The model predicts an insufficiently high labor income share for the first quintile, and consequently for the Bottom50 percent share, and for the Top1 percent share.

The Gini coefficient for wealth is 0.63, 0.11 points lower than its real-world counterpart of 0.74. This is driven at the lower end of the wealth distribution by the assumption of non-negative wealth holdings due to the zero borrowing limit. The first quintile (Q1) has a negative wealth share in the data, while in the model, they simply own no wealth at all. At the top of the wealth distribution, wealth is not sufficiently concentrated. This is a general feature of standard Aiyagari (1994)-

[30] The distributional measures in Drechsel-Grau et al. (2022) are based on administrative data from personal income tax records from the Taxpayer Panel (TPP) and the social-security data from the Institute for Employment Research (IAB).

[31] (Pre-tax) total income consists of labor (if $j \leqslant J_r - 1$) and interest income, accidental bequests, and pension payments (if $j \geqslant J_r$), such that: $y^{tot}_{j,t} = \begin{cases} y_{j,t} + r_t \cdot a_{j,t} + beq_t, & if\ j \leqslant J_r - 1, \\ r_t \cdot a_{j,t} + beq_t + pen_t, & if\ j \geqslant J_r. \end{cases}$

Table 1.5: Distributional measures.

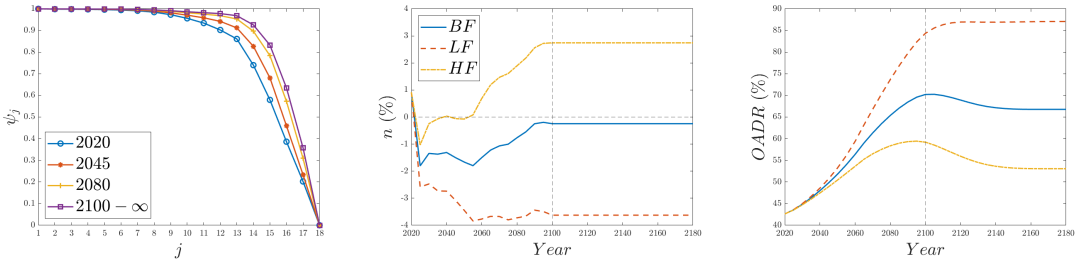
	Gini	Q1	Q2	Q3	Q4	Q5	Bottom50	Top10	Top5	Top1
					Labor income, y					
Model	0.40*	4.1	11.4	15.8	23.4	45.3	22.6	28.0	16.0	4.2
Data	0.40	4.8	11.6	17.0	23.7	42.9	24.2	27.0	16.9	5.9
					Wealth, a					
Model	0.63	0.0	1.3	10.7	26.3	61.7	5.1	39.0	23.3	11.2
Data	0.74	−0.3	1.3	7.1	17.9	74.0	3.5	57.6	44.7	26.4
					Total income, y^{tot}					
Model	0.41	6.8	9.7	13.0	22.5	48.0	22.5	30.3	18.2	4.8
Data	0.51	2.6	9.1	13.7	19.9	54.7	17.9	40.0	29.0	13.7

Note: This table reports Gini coefficients, the quintile shares (Q1-Q5), the Bottom50, the Top10, the Top5, and the Top1 percent shares for the stationary political equilibrium in 2020. All values, except the Gini coefficients, are calculated before taxes and expressed in percent. Data for distributional measures of the labor income are based on Drechsel-Grau et al. (2022) and for distributional measures of the total income and wealth on World Inequality Database (2025). *The labor income Gini coefficient is a targeted moment. For details, see text.

models. While the fifth quintile owns 74 percent of all wealth in the data, its share in the model is only 62 percent, 12 percentage points too small. The differences are even larger for the Top5 percent (21.3 percentage points) and the Top1 percent (15.1 percentage points) of the wealth distribution. A better fit of the overall model-implied wealth distribution relative to the empirical moments can be achieved by incorporating heterogeneity in subjective discount factors, in line with Krusell and Smith (1999). Recent empirical findings from Epper et al. (2020) support this idea, highlighting the significance of patience, alongside education, in predicting an individual's position in the wealth distribution. Furthermore, the introduction of a bequest motive and a negative borrowing limit can also help to bring the model-implied wealth distribution closer to the empirical observations (Brinca et al., 2021).

The Gini coefficient for total income is 0.10 points lower than its real-world counterpart. On the one hand, this is due to the strong redistributive effect of pensions in the model economy and implies that the share of the first quintile (Q1) in total income is significantly overstated by 3.6 percentage points relative to empirical observations. On the other hand, it is driven by the underestimated wealth inequality at the top of the wealth distribution, which does not generate enough interest income for wealthy individuals and thus does not generate enough total income differences for the fifth quintile (Q5), the Top10, the Top5 and the Top1 percent shares of total income.

Figure 1.6: Exogenous demographic transition.



(a) Survival probabilities. (b) Population growth rate. (c) Old-age dep. ratio.

Note: This figure shows the survival probabilities for different age groups for different years. The population growth rates and the old-age dependency ratio are reported in percent along the demographic transition until 2180 for the three fertility scenarios, $\{BF, LF, HF\}$. By assumption, both demographic variables stabilize by 2100. For details, see text.

1.5 Quantitative results

This section reports the quantitative results. First, we describe the underlying aging process. Then, we analyze the long-run effects of population aging on the allocation of public resources, economic aggregates, and inequality. We compare the final stationary political equilibrium after the demographic convergence with an equilibrium in which the current public policies are in place in the long run. We then analyze the transition of the economy for a situation in which the social security and education taxes converge linearly to their long-run values in the final stationary political equilibrium. In addition, we highlight the long-run and transitional effects of the counterfactual experiment in which a compulsory voting policy increases political participation, especially among younger and less-educated individuals.

Demographic transition Population aging in the model economy is generally driven by exogenous adjustments to the demographic variables, the survival probabilities, and the population growth rates, along with the projected data from United Nations (2022a) and United Nations (2024) to the year 2100. Figure 1.6 shows their respective adjustments over time and the old-age dependency ratio. From Figure 1.6a, we see that the survival probabilities are projected to increase substantially in future years, especially for retirees aged 65 and older ($j = \{10, ..., 17\}$). For the population growth rates, we generally distinguish between three fertility scenarios (see Figure 1.6b). A *Baseline Fertility (BF)* scenario, based on the predicted median population growth rates from United Nations (2024), a *Low Fertility (LF)* scenario with lower population growth rates, and a *High Fertility (HF)* scenario with higher population growth rates relative to the *BF* scenario. Common to all fertility scenarios is that population growth rates decrease in the near future relative to the 2020 value, and significant differences emerge in the long run. While in the *BF* scenario, the population growth rate stabilizes at a value of -0.25 percent in 2100 (-1.17 percentage points relative to 2020), it converges to a value of -3.63 percent in the *LF* scenario (-4.55 percentage points relative to 2020) and to a value of 2.74 percent in the *HF* scenario by 2100 (+ 1.82 percentage points relative to 2020). Both demographic variables are assumed to be constant from the year 2100 onwards so that the old-age dependency ratio converges by 2180 (see Figure 1.6c). It lies 24.16 percentage points above its 2020 value in the *BF* scenario, 44.46 percentage points above in the *LF* scenario and only 10.45 percentage points above in the *HF* scenario.

Long-run To analyze the long-run effect of population aging on the allocation of public resources, economic aggregates, and inequality, we compare the long-run stationary political equilibrium after the exogenous demographic transition in 2180 with the long-run equilibrium that would prevail if the tax rates stayed constant at their 2020 political equilibrium levels, but the demographic variables adjusted over time. In this sense, we compare the "pure aging effect" with constant taxes to the situation in which the age structure also affects policy choices. The results are reported in Table 1.6.

In the *BF* scenario, population aging leads to a 0.45 percentage point decrease in the education tax and an 8.00 percentage point increase in the social security tax relative to the constant tax rate case. The significantly higher social security tax keeps the average pension replacement rate at 33.38 percent and, therefore, more or less constant compared to its value of 33.54 percent in 2020. In the long run, compared to the constant tax rate case, the average replacement rate is 11.98 percentage points higher, as the replacement rate falls to 21.40 percent without a tax adjustment. This drop is implied by the substantial increase in the number of retired individuals in the economy. The old-age dependency ratio increases by 24.16 percentage points. The adjustment in the allocation of public resources relative to the constant tax rate case leads to a 6.90 percent reduction in long-run output and a 2.86 percent reduction in long-run consumption. The negative aggregate output effects are driven by a significant reduction in aggregate capital (-15.54 percent) and a reduction in aggregate effective labor (-2.33 percent). The substantial 45.19 percent increase in individual pension payments to the retirees in the economy, induced by the relatively higher social security tax, discourages individual capital accumu-

Table 1.6: Long-run effects of population aging for different fertility scenarios.

	Δ Constant taxes (%)		
Variable	(1) *BF*	(2) *LF*	(3) *HF*
τ^e	-0.45*	-0.86*	-0.09*
τ^p	+8.00*	+10.46*	+6.10*
$\bar{\kappa}$	+11.98*	+12.01*	+11.49*
E	-13.04	-19.71	-7.12
pen	+45.19	+58.92	+34.33
$\frac{E}{Y}$	-0.30*	-0.57*	-0.06*
$\frac{Pen}{Y}$	+5.36*	+7.01*	+4.08*
Y	-6.90	-8.21	-5.83
C	-2.86	-2.84	-2.59
K	-15.54	-19.11	-12.63
L^{eff}	-2.33	-2.32	-1.29
I	-16.34	-20.37	-13.05
Beq	-11.79	-14.13	-9.92
w	-4.68	-6.04	-3.62
r	+0.87*	+1.09*	+0.69*
$Gini_a$	+1.75	+2.28	+1.19
$Gini_{y^{tot}}$	-10.91	-14.35	-7.77

Note: This table reports the deviations of the stationary political equilibrium after the exogenous demographic transition in 2180 relative to the long-run equilibrium that would prevail if the tax rates stayed constant at their 2020 levels. Deviations are reported in percent and if marked with * as percentage point deviations. For details, see text.

lation over the life cycle and dampens aggregate investment (-16.34 percent). On the one hand, the reduction in aggregate effective labor is induced by a reduction in the average human capital level in the economy, as public spending on education falls significantly (-13.04 percent). On the other hand, the relatively higher social security tax increases the tax liabilities for workers distorting individual labor supply. This effect is even amplified by a long-run decrease in the wage rate (-4.68 percent), driven by the disproportionate decline in aggregate capital relative to aggregate effective labor, leading to a reduction in the marginal product of effective labor. The long-run interest rate rises by 0.87 percentage points, induced by capital scarcity and, therefore, an increase in the marginal product of capital due to reduced savings and investment. Aggregate accidental bequests fall by 11.79 percent in the long run, induced by reduced wealth holdings of individuals. The Gini coefficient for wealth inequality increases by 1.75 percent, while the Gini coefficient for total income decreases substantially by 10.91 percent. Total income inequality declines because pensions are highly redistributive and, therefore, reduce total income inequality, especially among retirees. The Gini coefficient for wealth inequality rises because higher pensions disproportionately discourage savings by younger low-income individuals.

We observe amplified effects in the *LF* scenario with significantly lower population growth rates compared to the *BF* scenario. The education tax rate decreases by 0.86 percentage points relative to the constant tax rate case, while the social security tax rate increases by 10.46 percentage points. The average pension replacement rate lies 12.01 percentage points above its constant tax rate value. An even lower population growth rate implicitly reduces the relevance of younger individuals for the allocation of public resources. In the long run, aggregate output falls by 8.21 percent and aggregate consumption by 2.84 percent relative to the constant tax rate situation. Incentives to accumulate wealth over the life cycle are reduced even more as individual pensions increase more strongly (+ 58.92 percent), leading to a significant decline in aggregate investment (-20.37 percent) and, consequently, in aggregate capital (-19.11 percent) and aggregate bequests (-14.13 percent). The total tax liabilities of working households increase relatively more compared to the *BF* scenario, distorting individual labor supply more strongly. The average human capital level in the economy decreases more strongly due to reduced public spending on education (-19.71 percent). In the long run, these changes lead to a 2.32 percent decline in aggregate effective labor. The wage rate falls by 6.04 percent due to the disproportionate decline in aggregate capital relative to aggregate effective labor, and the interest rate rises by 1.09 percentage points due to capital scarcity. The Gini coefficient for total income inequality decreases by 14.35 percent, while the Gini coefficient for wealth inequality increases by 2.28 percent. The amplified reduction in the Gini coefficient for total income is due to even higher pension payments to retirees, relative to the *BF* scenario, and the amplified increase in the Gini coefficient for wealth is due to the stronger declining incentives to accumulate wealth over the life cycle, especially for low-skilled young individuals.

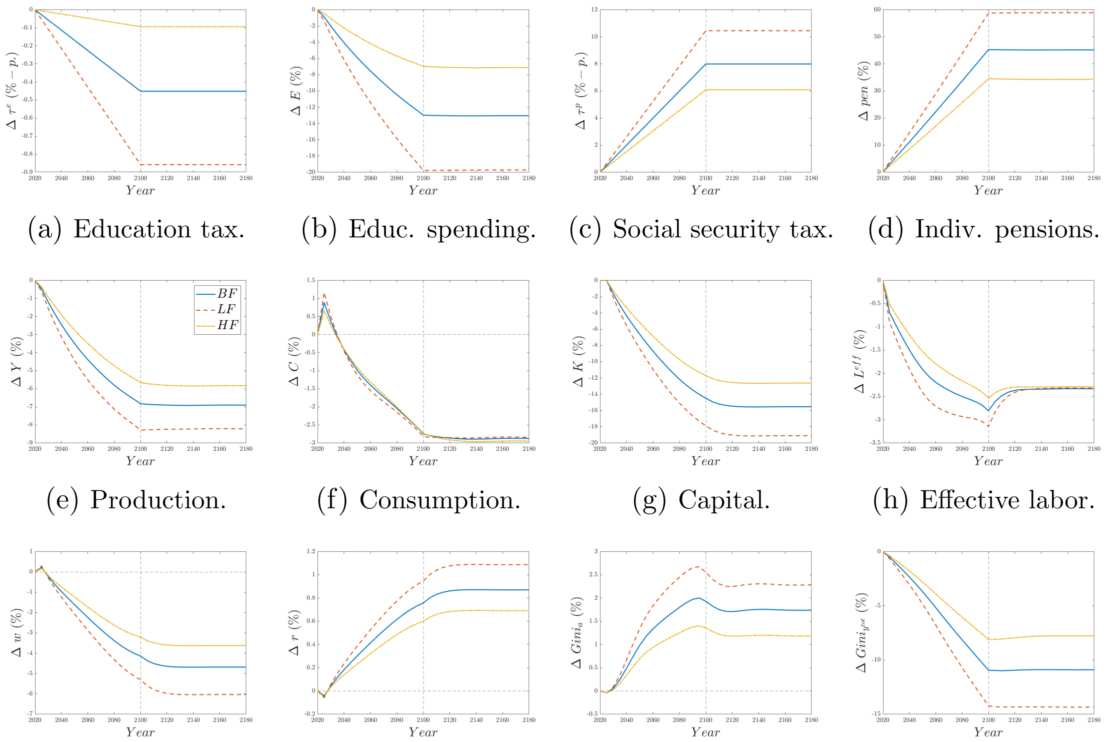
In the *HF* scenario, the long-run effects for the allocation of public resources, economic aggregates, and inequality are mitigated compared to the *BF* scenario. This is due to a relatively higher relevance of younger individuals and their different demands for public policy in the political process. The education tax rate barely changes (-0.09 percentage points), while the social security tax still increases by 6.10 percentage points, but almost 2 percentage points less compared to the *BF* scenario. Among other things and relative to the long-run situation with constant tax rates, aggregate output falls by 5.83 percent, aggregate consumption by 2.59 percent, and the Gini coefficient for total income by 7.77 percent, while the Gini coefficient for wealth inequality rises by 1.19 percent.

Transition We now discuss the demographic transition of the economy for a situation in which the social security and the education tax rates converge linearly to their long-run values in the final stationary political equilibrium. Specifically, we assume that both tax rates start at their respective initial stationary political equilibrium level in 2020 and either increase or decrease linearly to their final stationary political equilibrium level by 2100. From then on, both tax rates are assumed to be constant.[32] Figure 1.7 shows the percent (percentage point) deviations of public policy instruments, economic aggregates, and inequality measures over time, relative to the "pure aging" transition in which both tax rates remain at their initial stationary political equilibrium value in 2020, similar to the long-run analysis and for all three fertility scenarios, $\{BF, LF, HF\}$. Deviations for the year 2180 correspond to the values discussed above.

The education tax rate declines linearly to its long-run value, reducing the aggregate public resources spent on education over time and negatively affecting human capital in the economy relative to a situation in which the tax rates remain at their 2020 values. The social security tax rate increases linearly to its long-run value, leading to a significant relative increase in individual pension payments over time. Aggregate output diverges more and more from its constant tax rate path due to declining capital and effective labor. The former diverges from its constant tax rate path because individual pension payments increase significantly over time, thereby strongly discouraging capital accumulation over the life cycle. The latter declines because of a relative reduction in the average human capital level in the economy due to reduced public spending in the education sector and distorted individual labor supply through an increase in total tax liabilities. Tax liabilities increase because the increase in the social security tax dominates the decline in the education tax. We observe a small increase in aggregate consumption in the first period as tax rates begin to converge to their long-run values. Aggregate capital is fixed, but aggregate effective labor falls directly relative to its initial value in 2020. The relative scarcity of effective labor leads to an increase in its marginal product and, consequently, to an increase in the wage rate relative to the constant tax rate case. A higher wage

[32]The pure stationary political equilibrium behaves similarly in all periods along the transition. The reallocation of public resources is contingent upon the trajectory of the old-age dependency ratio over time. In the *BF* and the *HF* scenarios, we anticipate an even higher social security tax rate and a lower education tax rate along the transition because the old-age dependency ratio is above its final value in 2180 for some years along the transition, as illustrated in Figure 1.6c.

Figure 1.7: Transition relative to the constant tax rate case.



(a) Education tax. (b) Educ. spending. (c) Social security tax. (d) Indiv. pensions.

(e) Production. (f) Consumption. (g) Capital. (h) Effective labor.

(i) Wage rate. (j) Interest rate. (k) Gini wealth. (l) Gini total income.

Note: This figure shows the transition paths of public policy instruments, economic aggregates, and inequality measures for the situation in which the tax rates converge linearly to their final stationary political equilibrium values by 2100 relative to the "pure aging" transition in which the tax rates are constant at their initial 2020 values. The transitions are plotted as percentage deviations (%) or percentage-point deviations ($\% - p.$) for the three different fertility scenarios, $\{BF, LF, HF\}$. For details, see text.

rate dominates the increase in tax liabilities in the first period after the policy adjustment, leading to a relative increase in after-tax income and, consequently, higher consumption. The interest rate declines in the first period after the policy adjustment as a relative oversupply of aggregate capital leads to a decline in its marginal product and, thus, to a reduction in the interest rate relative to the constant tax rate case. A reduction in the interest rates hurts wealthy individuals more, leading to a slight decline in the wealth Gini on impact. It then converges to a much higher level by 2180. The Gini coefficient for total income inequality falls directly due to the redistributive effect of relatively higher pension payments, especially among retirees. Again, a comparison of the transition paths for all three fertility scenarios shows that a lower population growth rate over time and in the long run relative to the *BF* scenario amplifies the effects of population aging on economic aggregates and inequality, while a higher population growth rate mitigates the effects.

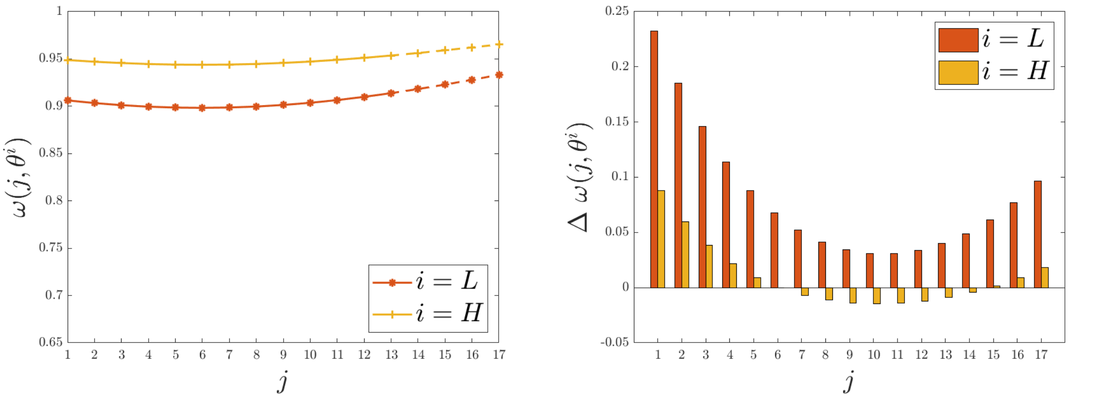
Compulsory voting policy Given the negative output effects of population aging through its implied shift of public resources more towards the elderly and, therefore, more towards consumptive government spending on pensions and away from productive government spending on education, this trend calls for policies to counteract the detrimental effect of population aging on aggregate production. We perform a counterfactual experiment, consisting of a *Compulsory Voting Policy (CVP)*. By enforcing a voter turnout rate of 100 percent, this policy potentially eliminates the bias in political participation toward the elderly stemming from differential voting behavior. But, as turnout rates of 100 percent seem to be unrealistic even with a *CVP* in place, we assume that in the counterfactual, the voter turnout rates are the same as those observed for Belgium. For parliamentary elections at the national level, this is one of the few countries worldwide with a *CVP* in place. To specify the voter turnout rates for the Belgian counterfactual, we perform the same probit regression from (1.55) based on survey data for Belgium from European Social Survey (2023), round 8, year 2016.[33] The Belgian sample includes 1,495 observations with an average voter turnout rate of 91.71 percent.[34]

Figure 1.8 illustrates the predicted Belgian voter turnout rates that are used in the counterfactual experiment and the adjustment in the turnout rates relative to the German baseline case. Voter turnout rates in Belgium are high, hardly

[33] Regression results for different ESS rounds and years can be found in Appendix 1.C, Table 1.11.

[34] The sample's implied average voter turnout rate is quite close to the reported voter turnout of 89.4 percent for the 2014 Belgian parliamentary elections.

Figure 1.8: Voter turnout rate adjustments in the *CVP* counterfactual.



(a) Voter turnout rates, Belgium. (b) Voter turnout rates adjustments, *CVP*.

Note: This figure shows the estimated voter turnout rates across age and deterministic productivity types in Belgium and the voter turnout adjustments for the *CVP* counterfactual in which it is assumed that the Belgian voter turnout rates prevail in Germany. For details, see text.

age-dependent, but generally lower for non-tertiary-educated (L-type) individuals across all age groups.[35] A counterfactual experiment with exactly the same turnout rates as in Belgium creates substantially higher turnout rates for L-type individuals across all age groups and generally higher turnout rates for younger individuals. Their relevance for the design of public policies implicitly increases. Voter turnout rates across all age groups for L-type individuals increase by at least 3.1 percentage points for 70 to 74-year-old individuals ($j = 11$) and up to 23.2 percentage points for 20 to 24-year-old individuals ($j = 1$). Voter turnout rates for H-type individuals increase at the top and especially at the bottom of the age distribution by up to 8.8 percentage points for the youngest age cohort. At the same time, they even decline slightly for old workers and young retirees, with a maximum reduction in the voter turnout rates for 65 to 69-year-old individuals ($j = 10$) by 1.5 percentage points.

We now evaluate the long-run effect of population aging on the allocation of public resources, economic aggregates, and inequality with a *CVP* in place. We compare the long-run stationary equilibrium after the exogenous demographic transition in 2180 to the long-run stationary political equilibrium with constant 2020 tax rates, but the demographic variables adjusted over time. Furthermore, we compare the long-run effects in a situation where the *CVP* is in place to the long-run effects without the compulsory voting policy, *w/o CVP*, but with a tax adjustment. We again

[35]In terms of average marginal effects with respect to the education level, the probit model predicts in this case that switching from a non-tertiary to a tertiary education degree increases the probability of voting on average by around 4 percent. Age (group) effects are not significant.

Table 1.7: Long-run effects of population aging for different fertility scenarios with *CVP*.

	Δ *Constant taxes (%)*			Δ *W/o CVP (%-p.)*		
Variable	*(1) BF*	*(2) LF*	*(3) HF*	*(4) BF*	*(5) LF*	*(6) HF*
τ^e	-0.42*	-0.79*	-0.08*	+0.04	+0.07	+0.01
τ^p	+3.05*	+5.78*	-0.35*	-4.94	-4.68	-6.44
$\bar{\kappa}$	+4.57*	+6.63*	-0.66*	-7.40	-5.37	-12.14
E	-8.32	-15.30	-0.68	+4.72	+4.41	+6.43
pen	+18.46	+34.49	-1.93	-26.72	-24.44	-36.26
$\frac{E}{Y}$	-0.28*	-0.53*	-0.05*	+0.02	+0.04	+0.01
$\frac{Pen}{Y}$	+2.05*	+3.87*	-0.23*	-3.31	-3.13	-4.32
Y	-2.39	-4.22	+0.51	+4.51	+3.99	+6.34
C	-0.38	-0.58	+0.41	+2.50	+2.26	+3.36
K	-6.05	-10.85	+1.01	+9.48	+8.26	+13.64
L^{eff}	-0.53	-0.78	+0.26	+1.80	+1.54	+2.55
I	-6.61	-11.90	+0.97	+9.73	+8.47	+14.01
Beq	-4.57	-8.10	+0.95	+7.22	+6.03	+10.88
w	-1.86	-3.48	+0.25	+2.81	+2.56	+3.87
r	+0.34*	+0.61*	-0.05*	-0.54	-0.48	-0.74
$Gini_a$	+0.81	+1.46	-0.05	-0.94	-0.83	-1.23
$Gini_{y^{tot}}$	-4.70	-8.70	+0.54	+6.21	+5.65	+8.31

Note: This table reports the deviations of the stationary political equilibrium for the counterfactual experiment with a *CVP* in place after the exogenous demographic transition in 2180 relative to the long-run equilibrium that prevails for constant tax rates (Δ *Constant taxes*) and relative to the long-run equilibrium without the compulsory voting policy (Δ *W/o CVP*). Deviations are reported in percent and if marked with * as percentage point deviations. For details, see text.

differentiate across the three fertility scenarios. Table 1.7 reports the corresponding results.

In the *BF* scenario, the implicit increase in the importance of younger (and L-type) individuals in the political process through the *CVP* nevertheless gives rise to an increase in the social security tax rate of 3.05 percentage points relative to the constant tax rate case. But it leads to a social security tax rate of 4.94 percentage points below the stationary political equilibrium in 2180 in the *w/o CVP* case. This dampening effect of the *CVP* on the social security tax rate significantly affects the incentives to accumulate wealth over the life cycle, leading to a relative increase in aggregate capital of 9.48 percentage points compared to the *w/o CVP* case, although aggregate capital still declines relative to the constant tax rate case by 6.05 percent. The mitigated rise of the social security tax relative to the *w/o CVP* case leads to a relative decline in the average pension replacement rate by 7.40 percentage points and to a relative reduction of individual pensions by 26.72

percentage points. Compared to the constant tax rate case, the replacement rate and the individual pensions are still 4.57 percentage points and 18.46 percent higher, respectively. Aggregate effective labor increases by 1.80 percentage points relative to the *w/o CVP* case. This increase is driven by a relatively higher education tax rate (+0.04 percentage points), significantly higher public education spending (+4.72 percentage points), and consequently a higher average human capital level in the economy. Moreover, as tax liabilities decline in relative terms, the distortionary effects on individual labor supply are reduced, thereby reinforcing the increase in aggregate effective labor relative to the *w/o CVP* case. The relative increases in aggregate capital and effective labor result in a positive output effect relative to the *w/o CVP* case (+4.51 percentage points), but still a negative effect relative to the constant tax rate case (-2.39 percent). Both the wage rate and interest rate adjustments in the *CVP* case are dampened relative to the *w/o CVP* case. The former increases by 2.81 percentage points, and the latter decreases by 0.54 percentage points. This is attributable to a relative reduction in capital scarcity and a dampening effect on the respective marginal product. The increase in the Gini coefficient for wealth is also dampened relative to the *w/o CVP* case (-0.94 percentage points), as capital accumulation incentives are higher, especially across L-type individuals due to reduced individual pension payments. The Gini coefficient for total income increases relative to the *w/o CVP* case (+6.21 percentage points), also due to reduced pension payments.[36]

A comparison of the effects across the *BF* and *LF* scenarios reveals that the counterfactual experiment with the *CVP* in place leads to qualitatively similar results. It is noteworthy that in the *HF* scenario, the *CVP* creates positive output and consumption effects, not only in comparison to the *w/o CVP* case (+6.34 and +3.36 percentage points) but even relative to the constant tax rate case (+0.51 and +0.41 percent). The positive long-run effect on output is attributed to a relative increase in aggregate capital (+1.01 percent) and effective labor (+0.26 percent). The combination of higher long-run population growth rates with the *CVP* results in a slight decline in the social security tax rate relative to the constant tax rate case (-0.35 percentage points), a reduction in the average pension replacement rate (-0.66 percentage points), and consequently in a reduction of individual pensions payments (-1.93 percent). Individuals have higher incentives to accumulate capital

[36] A comparison of the transition paths for the linear convergence of the tax rates to their long-run stationary political equilibrium values by 2180 for the *CVP* and the *w/o CVP* cases highlights the dampening impact of the *CVP* on economic aggregates and inequality over time, see Appendix 1.D, Figure 1.16.

over the life cycle. Aggregate capital is 1.01 percent higher compared to the constant tax rate case. Despite the slight reduction in public education spending (-0.68 percent), inducing a negative effect on the average level of human capital in the economy, the reduction in tax liabilities serves to mitigate distortions in individual labor supply. The latter positive effect on effective labor outweighs the former negative effect, resulting in a slight increase in aggregate effective labor by 0.26 percent. Consequently, the wage rate increases by 0.25 percent, driven by the reduction in the relative scarcity of capital in the economy. In contrast and relative to the constant tax rate case, the interest rate declines by 0.05 percentage points. As capital accumulation over the life cycle is incentivized, especially among L-type individuals, we observe a slight reduction in the Gini coefficient for wealth (-0.05 percent). The total income Gini coefficient increases by 0.54 percent due to the reduced use of the redistributive government instrument, the individual pension payments.[37]

1.6 Conclusion

This paper examines the implications of population aging for the allocation of public resources, economic aggregates, and inequality. To this end, we construct a medium-scale overlapping generations model with heterogeneous agents and incomplete markets calibrated to the German economy. A probabilistic voting setting serves as the vehicle to transform individual, age- and education-type specific demand for public resources into actual public policy. Population aging shifts public policy more in the direction of the elderly. It creates a significant increase in the amount of consumptive government spending in the form of pensions and a reduction in the amount of productive spending in the form of public education spending relative to a situation in which public policy is independent of the age structure. This results in a significant long-run reduction of aggregate output relative to the constant tax rate case, a reduction in aggregate consumption, an increase in wealth inequality, and a reduction in total income inequality. The magnitude of these effects decreases strongly with the size of future population growth rates. In a counterfactual experiment, we implement a compulsory voting policy that aligns the German voter turnout rates with those observed in Belgium. This policy increases the political weight of younger and less-educated individuals and has mitigating effects. In combination

[37] Again, a comparison of the transition paths for the linear convergence of the tax rates to their long-run stationary political equilibrium values by 2100 for the *CVP* and the *w/o CVP* cases relative to the constant tax rate case demonstrates the impact of the *CVP* on economic aggregates and inequality over time, see Appendix 1.D, Figure 1.18.

with high future population growth rates, the compulsory voting policy has even the potential to enhance aggregate output and aggregate consumption beyond the levels attainable with constant tax rates. Positive output effects are then accompanied by a slight reduction in wealth inequality, but total income inequality increases.

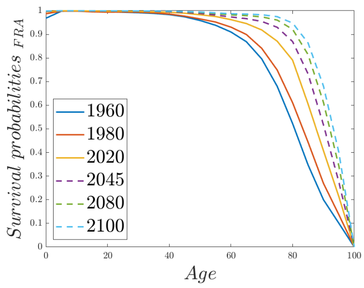
It is crucial to acknowledge that the strong redistributive impact of public pension payments depends on the underlying assumptions pertaining to the pension system in the model. In future work, we want to model the pension system in more detail so that individual pensions are partially dependent on an individual's earnings history but are still redistributive across retirees. Furthermore, altruism plays also an important role, as we observe high intended bequest in reality as well as parents who are specifically concerned about their children's human capital level. Including this channel into the model will, first, help in fitting the wealth distribution and, second, increase the older individual's demand for public education spending, more in line with what we observe from public opinion survey data (Busemeyer et al., 2018).

Moreover, a public education spending floor analogous to the lower bound for public military spending frequently discussed by and called for by NATO member countries may prove an interesting policy instrument in reducing the negative output effects induced by population aging through its impact on the allocation of public resources. A second interesting policy to be further investigated is a long-run increase in the retirement age by one model period and its consequences on preferences for the allocation of public resources, economic aggregates, and inequality.

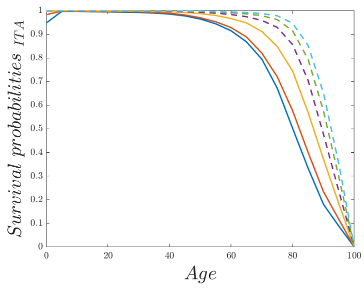
Appendix to Chapter 1

1.A Introduction

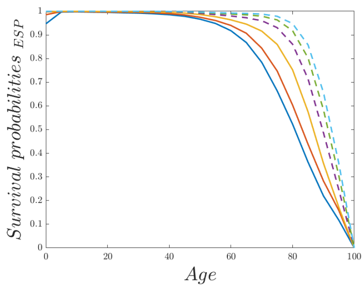
Figure 1.9: Survival probabilities across major European countries.



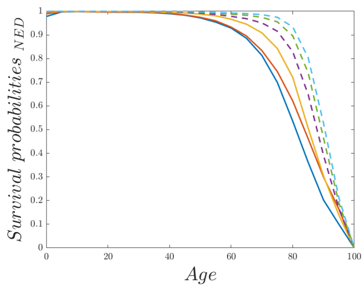
(a) Survival prob. France.



(b) Survival prob. Italy.



(c) Survival prob. Spain.



(d) Survival prob. Netherlands.

Note: This figure shows survival probabilities for France, Italy, Spain, and the Netherlands (broken lines represent projections). Data for the survival probabilities is based on United Nations (2022a,b). The behavior across countries (generally increasing survival probabilities over time) is very similar, also in comparison to the survival probabilities for Germany, observable from Figure 1.1a.

1.B Simplified Model

1.B.1 Indirect utility functions in the simplified model

This section describes the steps to come up with detailed expressions for the indirect utility functions in the simplified model. The indirect utility function of a currently living old L-type individual is generally of the following form

$$\mathcal{U}^L_{o,t} = \log\left(c^L_{o,t}\right).$$

Plugging in (1.35), (1.41), (1.42), (1.44) and (1.47) and rearranging yields

$$\begin{aligned}\mathcal{U}^L_{o,t} &= \log\left(\Omega_Y\right) + \log\left(\frac{1+n_t}{\psi_{o,t}}\right) + \alpha\log\left(\hat{K}_t\right) + (1-\alpha)\log\left(h_{y,t}\right)\\ &+ \log\left((\frac{2\alpha}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\right),\end{aligned} \tag{1.56}$$

with the old age wealth ratio as $\lambda_{o,t} = \frac{a^H_{o,t}}{a^L_{o,t}}$. The indirect utility function of a currently living old H-type individual is generally of the following form

$$\mathcal{U}^H_{o,t} = \log\left(c^H_{o,t}\right). \tag{1.57}$$

Plugging in (1.35), (1.41), (1.42), (1.44) and (1.47) and rearranging yields

$$\begin{aligned}\mathcal{U}^H_{o,t} &= \log\left(\Omega_Y\right) + \log\left(\frac{1+n_t}{\psi_{o,t}}\right) + \alpha\log\left(\hat{K}_t\right) + (1-\alpha)\log\left(h_{y,t}\right)\\ &+ \log\left((\frac{2\alpha\lambda_{o,t}}{1+\lambda_{o,t}}) + (1-\alpha)\tau^p_t\right).\end{aligned} \tag{1.58}$$

The indirect utility function of a currently living young individual of deterministic productivity-type $i = \{H, L\}$, is generally of the following form

$$\mathcal{U}^i_{y,t} = \log\left(c^i_{y,t}\right) + \beta\cdot\psi_{o,t+1}\cdot\log\left(c^i_{o,t+1}\right), \tag{1.59}$$

with

$$\begin{aligned}\log\left(c^i_{y,t}\right) &= \log\left(\Omega_Y\right) + \log\left(1-\alpha\right) - \log\left(1+\beta\psi_{o,t+1}\right) + \alpha\log\left(\hat{K}_t\right) + (1-\alpha)\log\left(h_{y,t}\right)\\ &+ \log\left(1-\tau^e_t-\tau^p_t\right) + \log\left(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_{t+1}\right)\\ &- \log\left((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\tau^p_{t+1}\right)\end{aligned} \tag{1.60}$$

following from the use of (1.36), (1.38), (1.41), (1.42), (1.44), (1.47) and rearranging, and

$$\begin{aligned}
\log\Big(c^i_{o,t+1}\Big) &= (1-\alpha)\log\Big(\Omega_H\Big) + \big(1+\alpha+(1-\alpha)\iota\big)\log\Big(\Omega_Y\Big) + \alpha\log\Big(\alpha\Big) + \alpha\log\Big(\beta\Big) \\
&+ \big(\alpha+(1-\alpha)\iota\big)\log\Big(1-\alpha\Big) + (1-\alpha)\log\Big(\frac{1+n_{t+1}}{\psi_{o,t+1}}\Big) - \log\Big(1+\beta\psi_{o,t+1}\Big) \\
&+ \alpha\big(\alpha+(1-\alpha)\iota\big)\log\Big(\hat{K}_t\Big) + (1-\alpha)\big(1+\alpha(1-\iota)\big)\log\Big(h_{y,t}\Big) \\
&+ \alpha\log\Big(1-\tau^e_t-\tau^p_t\Big) + (1-\alpha)\iota\log\Big(\tau^e_t\Big) \\
&+ \log\Big(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_{t+1}\Big) \\
&- \alpha\log\Big((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\tau^p_{t+1}\Big)
\end{aligned} \tag{1.61}$$

following from the use of (1.10), (1.36), (1.37) (1.38), (1.41), (1.42), (1.44), (1.45) and rearranging. Ignoring all terms that are independent of policy variables and imposing the assumption that $\tau^g_t = \tau^g_{t+1},\ g = \{e,p\}$, yields the "t.i.p"-terms of the indirect utility functions. It follows for a currently living old L-type individual

$$\mathcal{U}^L_{o,t}\Big|_{t.i.p.} = \log\Big(c^L_{o,t}\Big|_{t.i.p.}\Big) = \log\Big(\big(\frac{2\alpha}{1+\lambda_{o,t}}\big) + (1-\alpha)\tau^p_t\Big), \tag{1.62}$$

for a currently living old H-type individual

$$\mathcal{U}^H_{o,t}\Big|_{t.i.p.} = \log\Big(c^H_{o,t}\Big|_{t.i.p.}\Big) = \log\Big(\big(\frac{2\alpha\lambda_{o,t}}{1+\lambda_{o,t}}\big) + (1-\alpha)\tau^p_t\Big), \tag{1.63}$$

and for a currently living young individual of deterministic productivity type $i = \{H, L\}$,

$$\mathcal{U}^i_{y,t}\Big|_{t.i.p.} = \log\Big(c^i_{y,t}\Big|_{t.i.p.}\Big) + \beta\cdot\psi_{o,t+1}\cdot\log\Big(c^i_{o,t+1}\Big|_{t.i.p.}\Big), \tag{1.64}$$

with

$$\begin{aligned}
\log\Big(c^i_{y,t}\Big|_{t.i.p.}\Big) &= \log\Big(1-\tau^e_t-\tau^p_t\Big) + \log\Big(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\underbrace{\tau^p_{t+1}}_{=\tau^p_t}\Big) \\
&- \log\Big((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\underbrace{\tau^p_{t+1}}_{=\tau^p_t}\Big),
\end{aligned} \tag{1.65}$$

and

$$\log\left(c^i_{o,t+1}\Big|_{t.i.p.}\right) = \alpha\log\left(1-\tau^e_t-\tau^p_t\right) + (1-\alpha)\iota\log\left(\tau^e_t\right)$$
$$+\log\Big(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\underbrace{\tau^p_{t+1}}_{=\tau^p_t}\Big)$$
$$-\alpha\log\Big((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\underbrace{\tau^p_{t+1}}_{=\tau^p_t}\Big). \tag{1.66}$$

Plugging in (1.65) and (1.66) into (1.64) and rearranging yields

$$\mathcal{U}^i_{y,t}\Big|_{t.i.p.} = (1+\beta\psi_{o,t+1}\alpha)\log\left(1-\tau^e_t-\tau^p_t\right) + \beta\psi_{o,t+1}(1-\alpha)\iota\log\left(\tau^e_t\right)$$
$$+(1+\beta\psi_{o,t+1})\log\left(\theta^i(1+\beta\psi_{o,t+1})\alpha + (\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_t\right)$$
$$-(1+\beta\psi_{o,t+1}\alpha)\log\left((1+\beta\psi_{o,t+1})\alpha + (1-\alpha)\tau^p_t\right). \tag{1.67}$$

1.B.2 First-order conditions

The time-dependent first-order condition of the political objective function in (1.52) with respect to the social security tax, τ^p_t, is given as

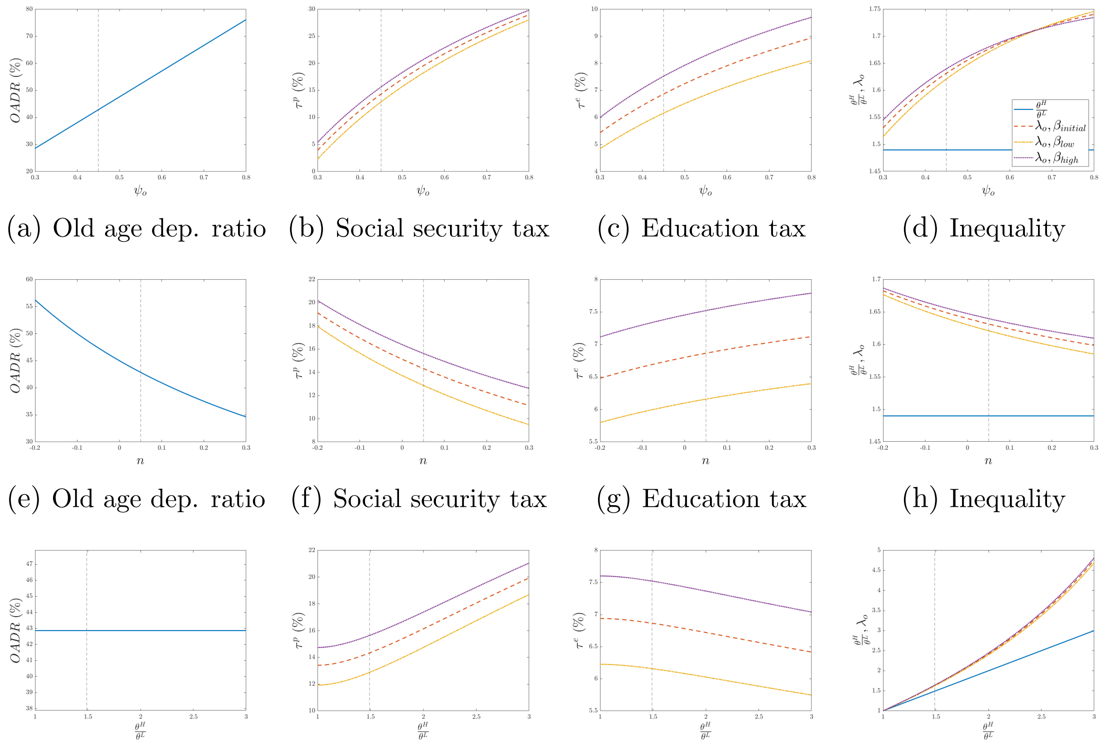
$$\frac{\partial\mathcal{W}_t\Big|_{t.i.p.}}{\partial\tau^p_t} = \psi_{o,t}\cdot\left(\omega(o,\theta^L)\cdot\frac{(1-\alpha)}{(\frac{2\alpha}{1+\lambda_{o,t}})+(1-\alpha)\tau^p_t} + \omega(o,\theta^H)\cdot\frac{(1-\alpha)}{(\frac{2\alpha\lambda_{o,t}}{1+\lambda_{o,t}})+(1-\alpha)\tau^p_t}\right)$$
$$+(1+n_t)\cdot\Bigg(\sum_{i=\{H,L\}}\omega(y,\theta^i)\cdot\Bigg(\frac{(1+\beta\psi_{o,t+1})(1-\alpha)(\theta^i+\beta\psi_{o,t+1})}{\theta^i(1+\beta\psi_{o,t+1})\alpha+(\theta^i+\beta\psi_{o,t+1})(1-\alpha)\tau^p_t}$$
$$-\frac{(1+\beta\psi_{o,t+1})\alpha}{1-\tau^e_t-\tau^p_t} - \frac{(1+\beta\psi_{o,t+1}\alpha)(1-\alpha)}{(1+\beta\psi_{o,t+1})\alpha+(1-\alpha)\tau^p_t}\Bigg)\Bigg) \overset{!}{=} 0, \tag{1.68}$$

and the first-order condition with respect to the education tax, τ^e_t, as

$$\frac{\partial\mathcal{W}_t\Big|_{t.i.p.}}{\partial\tau^e_t} = \frac{\beta\psi_{o,t+1}(1-\alpha)\iota}{\tau^e_t} - \frac{1+\beta\psi_{o,t+1}\alpha}{1-\tau^e_t-\tau^p_t} \overset{!}{=} 0. \tag{1.69}$$

1.B.3 Comparative statics for different parameter variations

Figure 1.10: Comparative statics for variations in the discount factor.



(a) Old age dep. ratio (b) Social security tax (c) Education tax (d) Inequality

(e) Old age dep. ratio (f) Social security tax (g) Education tax (h) Inequality

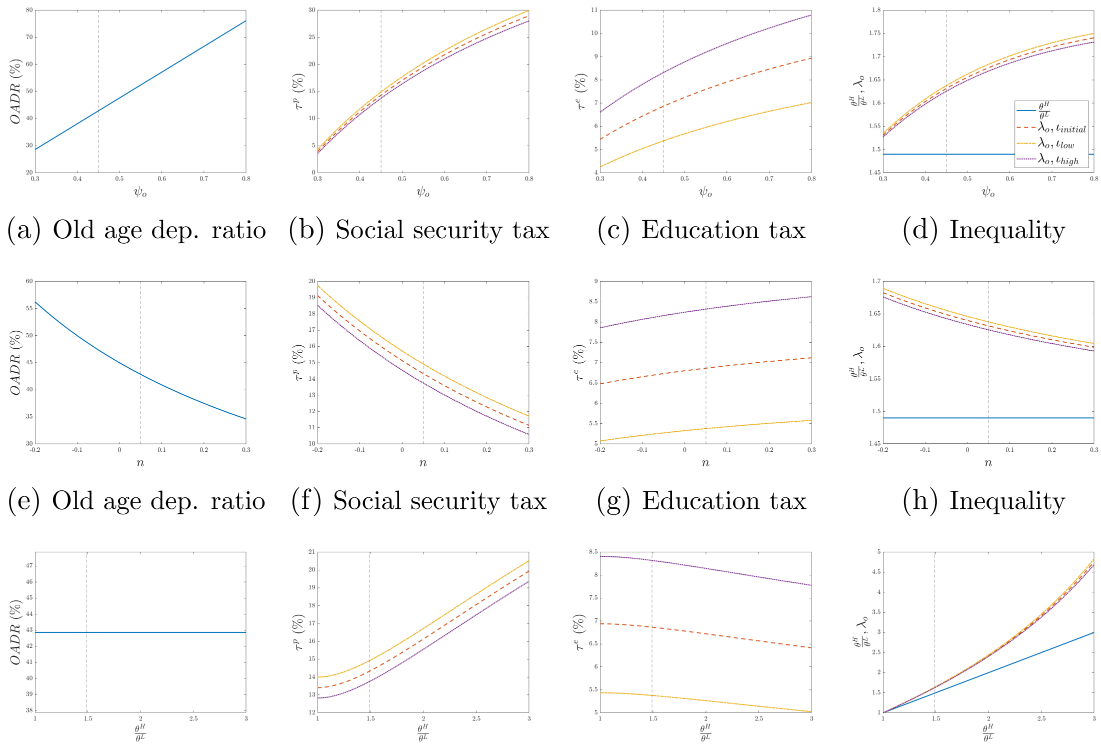
(i) Old age dep. ratio (j) Social security tax (k) Education tax (l) Inequality

Note: This figure shows comparative static exercises for the old age dependency ratio, the social security, the education tax, and ex-post inequality (measured as the wealth ratio) for variations in the survival probability to old age, ψ_o, in the first row; variations in the population growth rate, n, in the second row; and variations in ex-ante inequality, measured as the ratio of deterministic H-type to L-type productivity, $\frac{\theta^H}{\theta^L}$, in the third row, depending on different values of the discount factor, β. The initial value for the discount factor, $\beta_{initial}$, is 0.72 (dashed orange lines). A lower discount factor means $\beta_{low} = 0.62$ (dashed-dotted yellow lines), and a higher discount factor means $\beta_{high} = 0.82$ (dotted purple lines). All other parameters are chosen in line with the parameterization in Section 1.3. The vertical lines in all panels show the initially parametrized value of the respective variable.

A higher discount factor, β, creates higher ex-post inequality and more demand for public policy as the population ages (see Figure 1.10). Individuals are generally more concerned about their second lifetime period, and all margins affecting the preferences for public policy that are realized in the second lifetime period become relatively more important. They save more (which increases ex-post inequality) and benefit more from a higher tax base through an increase in the education tax and higher pension payments through an increase in the social security tax.

A higher elasticity of human capital with respect to per capita public spending on education, ι, relative to the baseline parameterization, has ambiguous effects on the wealth ratio as the population ages, depending on the demographic variable, but

Figure 1.11: Comparative statics for variations in the elast. of h.c. w.r.t. public education spending.



(a) Old age dep. ratio (b) Social security tax (c) Education tax (d) Inequality

(e) Old age dep. ratio (f) Social security tax (g) Education tax (h) Inequality

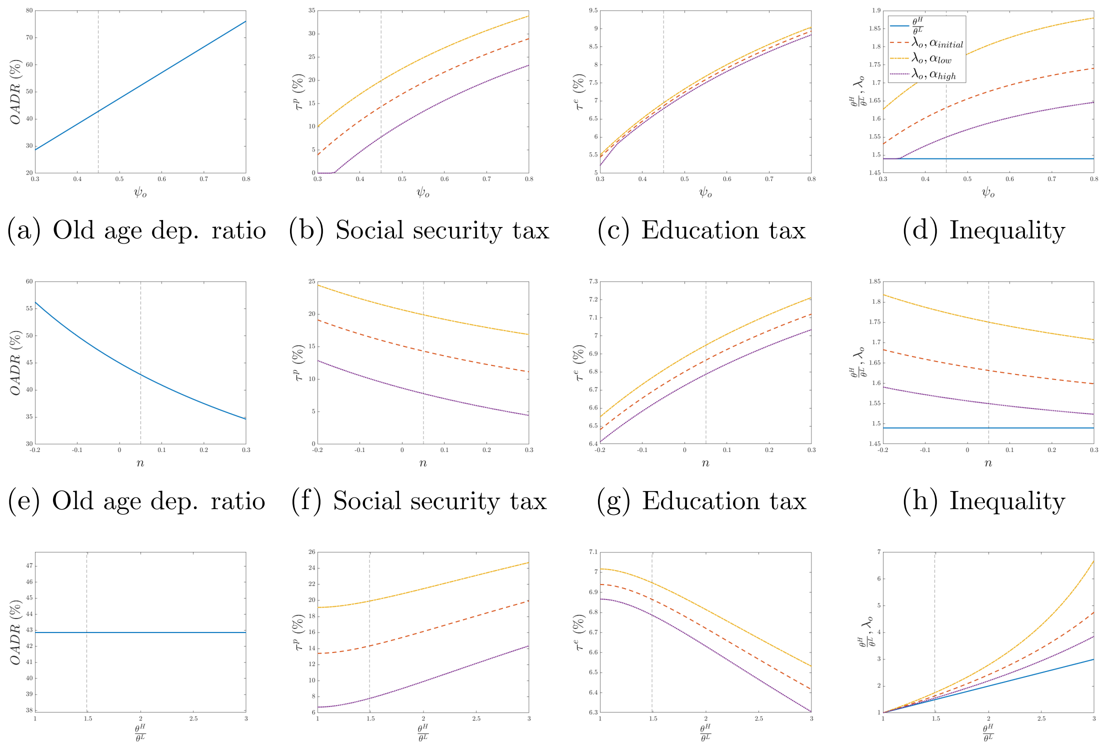
(i) Old age dep. ratio (j) Social security tax (k) Education tax (l) Inequality

Note: This figure shows comparative static exercises for the old age dependency ratio, the social security, the education tax, and ex-post inequality (measured as the wealth ratio) for variations in the survival probability to old age, ψ_o, in the first row; variations in the population growth rate, n, in the second row; and variations in ex-ante inequality, measured as the ratio of deterministic H-type to L-type productivity, $\frac{\theta^H}{\theta^L}$, in the third row, depending on different values of the elasticity of human capital with respect to public education spending, ι. The initial value for the elasticity, $\iota_{initial}$, is 0.44 (dashed orange lines). A lower elasticity means $\iota_{low} = 0.62$ (dashed-dotted yellow lines), and a higher elasticity means $\iota_{high} = 0.82$ (dotted purple lines). All other parameters are chosen in line with the parameterization in Section 1.3. The vertical lines in all panels show the initially parameterized value of the respective variable.

leads to a declining social security tax and a significant increase in the education tax (see Figure 1.11). Public education spending becomes more efficient in expanding human capital and increases the importance of the tax base effect that materializes when today's young individuals are old.

A lower capital share, α, leads to an increase in ex-post inequality, an increase in the social security tax, and an increase in the education tax as the population ages, relative to the baseline parameterization (see Figure 1.12).

Figure 1.12: Comparative statics for variations in the capital share.



(a) Old age dep. ratio (b) Social security tax (c) Education tax (d) Inequality

(e) Old age dep. ratio (f) Social security tax (g) Education tax (h) Inequality

(i) Old age dep. ratio (j) Social security tax (k) Education tax (l) Inequality

Note: This figure shows comparative static exercises for the old age dependency ratio, the social security, the education tax, and ex-post inequality (measured as the wealth ratio) for variations in the survival probability to old age, ψ_o, in the first row; variations in the population growth rate, n, in the second row; and variations in ex-ante inequality, measured as the ratio of deterministic H-type to L-type productivity, $\frac{\theta^H}{\theta^L}$, in the third row, depending on different values of the capital share, α. The initial value for the capital share, $\alpha_{initial}$, is 0.33 (dashed orange lines). A lower capital share means $\alpha_{low} = 0.28$ (dashed-dotted yellow lines), and a higher capital share means $\iota_{high} = 0.38$ (dotted purple lines). All other parameters are chosen in line with the parameterization in Section 1.3. The vertical lines in all panels show the initially parameterized value of the respective variable.

1.C Calibration

1.C.1 Survival probabilities

The survival probabilities are based on data from United Nations (2022b) and United Nations (2022a). The data reported in Table 1.8 are yearly survival probabilities converted to five-year values. The annual survival probabilities for the years 2020 and 2021 are based on "File MORT/06-1-1: Single age lifetable, for both sexes combined, by region, subregion and country, annually 1950-2021, estimates, 1986-2021, probability of surviving, $p(x,n)$", while all other annual values are based on "File MORT/07-1: Abridged lifetable, for both sexes combined, by region, subregion and country, annually for 1950-2100, medium fertility variant, 2022-2100, probability

Table 1.8: Survival probabilities.

Year	2020	2025	2030	2035	2040	2045
t	0	1	2	3	4	5
$\psi_{1,t}$	1	1	1	1	1	1
$\psi_{2,t}$	0.99863557	0.99882615	0.99894803	0.99904344	0.99912088	0.99918850
$\psi_{3,t}$	0.99840239	0.99861325	0.99875105	0.99886053	0.99894920	0.99902756
$\psi_{4,t}$	0.99763642	0.99794126	0.99811449	0.99826882	0.99839677	0.99850991
$\psi_{5,t}$	0.99636234	0.99698554	0.99722614	0.99743620	0.99762683	0.99779569
$\psi_{6,t}$	0.99440545	0.99532296	0.99568700	0.99599959	0.99627640	0.99654454
$\psi_{7,t}$	0.99116067	0.99210357	0.99268653	0.99319047	0.99363190	0.99405183
$\psi_{8,t}$	0.98472138	0.98621705	0.98719326	0.98802452	0.98875624	0.98944648
$\psi_{9,t}$	0.97307256	0.97620621	0.97782868	0.97923819	0.98044910	0.98159172
$\psi_{10,t}$	0.95618310	0.96211574	0.96471097	0.96703270	0.96905241	0.97088409
$\psi_{11,t}$	0.93429545	0.94443770	0.94852072	0.95225466	0.95558211	0.95863268
$\psi_{12,t}$	0.90231150	0.91971059	0.92614928	0.93198400	0.93727618	0.94221683
$\psi_{13,t}$	0.86087308	0.87646412	0.88692625	0.89598002	0.90418699	0.91200812
$\psi_{14,t}$	0.73993200	0.77335182	0.78870371	0.80259854	0.81496850	0.82699987
$\psi_{15,t}$	0.57940102	0.61270433	0.63091529	0.64866168	0.66518040	0.68106171
$\psi_{16,t}$	0.38616466	0.39676785	0.41240988	0.42817081	0.44389752	0.45964668
$\psi_{17,t}$	0.20244241	0.19707261	0.20569554	0.21467747	0.22380840	0.23341928
$\psi_{18,t}$	0	0	0	0	0	0
Year	2050	2055	2060	2065	2070	2075
t	6	7	8	9	10	11
$\psi_{1,t}$	1	1	1	1	1	1
$\psi_{2,t}$	0.99924651	0.99929938	0.99934756	0.99939170	0.99943281	0.99946999
$\psi_{3,t}$	0.99909525	0.99915756	0.99921489	0.99926777	0.99931742	0.99936257
$\psi_{4,t}$	0.99860959	0.99870227	0.99878873	0.99886953	0.99894624	0.99901672
$\psi_{5,t}$	0.99794230	0.99807900	0.99820628	0.99832553	0.99843918	0.99854381
$\psi_{6,t}$	0.99677776	0.99699163	0.99719110	0.99737740	0.99755527	0.99771952
$\psi_{7,t}$	0.99445321	0.99482307	0.99516385	0.99548368	0.99578906	0.99607226
$\psi_{8,t}$	0.99009530	0.99075650	0.99136882	0.99193541	0.99247911	0.99298358
$\psi_{9,t}$	0.98265248	0.98371207	0.98480287	0.98581345	0.98676603	0.98765347
$\psi_{10,t}$	0.97256644	0.97420234	0.97583496	0.97751016	0.97908108	0.98051182
$\psi_{11,t}$	0.96132373	0.96389876	0.96637147	0.96880089	0.97128014	0.97351859
$\psi_{12,t}$	0.94662040	0.95068093	0.95451482	0.95813911	0.96169190	0.96512383
$\psi_{13,t}$	0.91912355	0.92575920	0.93185675	0.93756542	0.94302214	0.94813707
$\psi_{14,t}$	0.83838590	0.84943133	0.85988045	0.86963928	0.87909601	0.88795943
$\psi_{15,t}$	0.69644107	0.71198361	0.72727314	0.74203107	0.75642253	0.77015266
$\psi_{16,t}$	0.47487496	0.49068780	0.50691669	0.52327711	0.53989719	0.55597528
$\psi_{17,t}$	0.24302506	0.25301866	0.26346176	0.27437390	0.28590700	0.29750668
$\psi_{18,t}$	0	0	0	0	0	0
Year	2080	2085	2090	2095	2100-∞	
t	12	13	14	15	16-∞	
$\psi_{1,t}$	1	1	1	1	1	
$\psi_{2,t}$	0.99950523	0.99953824	0.99956938	0.99959939	0.99961652	
$\psi_{3,t}$	0.99940559	0.99944603	0.99948440	0.99952136	0.99954250	
$\psi_{4,t}$	0.99908433	0.99914818	0.99920925	0.99926812	0.99930181	
$\psi_{5,t}$	0.99864436	0.99873932	0.99883031	0.99891808	0.99896832	
$\psi_{6,t}$	0.99787753	0.99802687	0.99817003	0.99830811	0.99838720	
$\psi_{7,t}$	0.99634599	0.99660528	0.99685454	0.99709497	0.99723269	
$\psi_{8,t}$	0.99347311	0.99393896	0.99438805	0.99482198	0.99507064	
$\psi_{9,t}$	0.98851277	0.98933289	0.99012634	0.99089433	0.99133490	
$\psi_{10,t}$	0.98189488	0.98320647	0.98447384	0.98570108	0.98640438	
$\psi_{11,t}$	0.97562583	0.97760568	0.97949231	0.98130060	0.98233025	
$\psi_{12,t}$	0.96832013	0.97124609	0.97400302	0.97660044	0.97806449	
$\psi_{13,t}$	0.95321901	0.95784743	0.96213317	0.96614565	0.96838935	
$\psi_{14,t}$	0.89673726	0.90540608	0.91361797	0.92135348	0.92575539	
$\psi_{15,t}$	0.78384733	0.79738248	0.81131204	0.82475293	0.83244592	
$\psi_{16,t}$	0.57244550	0.58893935	0.60617688	0.62425332	0.63492343	
$\psi_{17,t}$	0.30957819	0.32198477	0.33517920	0.34916355	0.35795225	
$\psi_{18,t}$	0	0	0	0	0	

Note: This table reports exogenously chosen survival probabilities for the initial stationary political equilibrium in 2020 and the demographic transition. The baseline data is taken from United Nations (2022a,b). Annual values are converted to 5-year values.

of surviving, $p(x,n)$" for Germany.

1.C.2 Population growth rates

The population growth rates are based on data from United Nations (2024), "Rate of population change (PopChangeRT)", "Median" for the baseline fertility (BF) scenario, "Low-fertility" for the low-fertility (LF) scenario and "High-fertility" for the high-fertility (HF) scenario. The data reported in Table 1.9 are yearly population growth rates converted to five-year values.

Table 1.9: Population growth rates.

Year	2020	2025	2030	2035	2040	2045
t	0	1	2	3	4	5
$n_{BF,t}$ (%)	0.9210	-1.8030	-1.3427	-1.3714	-1.3091	-1.4960
$n_{LF,t}$ (%)	0.9211	-2.5830	-2.4741	-2.7287	-2.7395	-3.0716
$n_{HF,t}$ (%)	0.9211	-1.0310	-0.2418	-0.0680	0.0370	-0.0580
Year	2050	2055	2060	2065	2070	2075
t	6	7	8	9	10	11
$n_{BF,t}$ (%)	-1.6628	-1.7970	-1.4980	-1.2220	-1.0654	-1.0030
$n_{LF,t}$ (%)	-3.4446	-3.8396	-3.7689	-3.6719	-3.6757	-3.7989
$n_{HF,t}$ (%)	-0.0740	0.0800	0.6878	1.1906	1.4686	1.6092
Year	2080	2085	2090	2095	2100-∞	
t	12	13	14	15	16-∞	
$n_{BF,t}$ (%)	-0.7647	-0.5488	-0.2468	-0.1949	-0.2448	
$n_{LF,t}$ (%)	-3.7262	-3.6631	-3.4397	-3.4922	-3.6262	
$n_{HF,t}$ (%)	1.8942	2.1808	2.5608	2.7242	2.7446	

Note: This table reports exogenously chosen population growth rates for the initial stationary political equilibrium in 2020 and the demographic transition for the three fertility scenarios, $\{BF, LF, HF\}$. The baseline data is taken from United Nations (2024). Annual values are converted to five-year values.

1.C.3 Voter turnout rates

Data Voter turnout rates for Germany and Belgium are calibrated by the use of data from different rounds of European Social Survey (2023).

The dependent variable "*Voted*" is a binary variable that takes the value 1 (0) if the individual responded with "Yes (No)" to the following question: "Some people don't vote nowadays for one reason or another. Did you vote in the last [country] national election in [month/year]?".

The explanatory variable "*Tertiary*" is also a binary variable that takes the value 1 (0) if the individual has a (no) tertiary education degree. The status of "No tertiary education degree" includes the following formal education levels: ES-ISCED I, less than lower secondary education; ES-ISCED II, lower secondary education; ES-ISCED IIIb, lower tier upper secondary education; ES-ISCED IIIa, upper tier upper secondary education; ES-ISCED IV, advanced vocational education, sub-degree, while the status of "Tertiary education degree" includes the following formal education levels: ES-ISCED V1, lower tertiary education, BA level; ES-ISCED V2, higher tertiary education, $\geqslant$ MA level.

The explanatory variable "*Age*" is a discrete variable with possible values ranging from 1 to 13. In accordance with the quantitative model, individuals are grouped by their respective age in 5-year steps. Group 1 includes individuals aged 18-24, group 2 individuals aged 25-29, group 3 individuals aged 30-34, group 4 individuals aged 35-39, group 5 individuals aged 40-44, group 6 individuals aged 45-49, group 7 individuals aged 50-54, group 8 individuals aged 55-59, group 9 individuals aged 60-64, group 10 individuals aged 65-69, group 11 individuals aged 70-74, group 12 individuals aged 75-79, and the last group 13 consists of individuals aged 80+. The choice of the last age group is due to the lack of data for older individuals.

Probit model results All results are based on the full probit model from (1.55). Table 1.10 presents results for different ESS rounds and years for Germany, Table 1.11 presents results for Belgium. Predicted probabilities of voting for different ESS rounds and years based on these results are depicted in Figure 1.13 for Germany and Belgium in Figure 1.14 respectively.

Average marginal effects Figure 1.15 depicts the average marginal effects estimated by the probit models for different ESS rounds and years in Germany and Belgium respectively. Specifically, panel (a) and panel (c) show how - ceteris paribus - a marginal increase in the education variable (here: a switch from non-tertiary to

Table 1.10: Probit model results for Germany.

	Dependent variable: Voted						
	(1) 11/2023#	(2) 8/2016	(3) 7/2014	(4) 4/2008	(5) 3/2006	(6) 2/2004	(7) 1/2002
Tertiary	0.682***	0.634***	0.456***	0.678***	0.787***	0.908***	0.644***
	(0.106)	(0.092)	(0.080)	(0.100)	(0.108)	(0.101)	(0.102)
Age	0.040	0.144***	0.055	0.291***	0.134***	0.143***	0.148***
	(0.042)	(0.041)	(0.039)	(0.041)	(0.038)	(0.041)	(0.042)
Age^2	0.001	−0.006**	−0.001	−0.018***	−0.007***	−0.007**	−0.009***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Constant	0.751***	0.313***	0.456***	−0.093	0.218**	0.201*	0.457***
	(0.124)	(0.119)	(0.080)	(0.121)	(0.108)	(0.111)	(0.120)
Observations	2,144	2,466	2,778	2,488	2,636	2,502	2,638
Avg. Turnout	88.48%	84.47%	81.81%	81.73%	77.65%	81.26%	83.52%

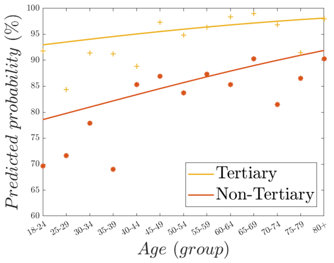
Note: This table reports probit model results, based on the full specification in (1.55) and data from all different ESS rounds in the respective years in which Germany is included in the ESS sample. Robust standard errors are given in brackets. It holds: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. #The reliability of German data for the ESS round 11 in the year 2023 is limited because the relevant weighting measure is missing in the dataset. The respective results are presented without weighting observations properly.

Table 1.11: Probit model results for Belgium.

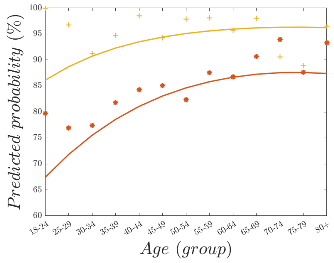
	Dependent variable: Voted									
	(1) 10/2020	(2) 9/2018	(3) 8/2016	(4) 7/2014	(5) 6/2012	(6) 5/2010	(7) 4/2008	(8) 3/2006	(9) 2/2004	(10) 1/2002
Tertiary	0.424***	0.335***	0.316***	0.418***	0.177*	0.363***	0.123	0.277**	0.277**	0.437***
	(0.118)	(0.104)	(0.104)	(0.115)	(0.100)	(0.103)	(0.110)	(0.126)	(0.114)	(0.107)
Age	0.192***	0.348***	-0.022	0.074	0.088*	0.185***	0.181***	0.115*	0.155***	0.206***
	(0.059)	(0.053)	(0.057)	(0.047)	(0.047)	(0.049)	(0.052)	(0.062)	(0.053)	(0.052)
Age^2	−0.008*	−0.020***	0.002	−0.006*	−0.008**	−0.014***	−0.013***	−0.009*	−0.012***	−0.012***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)	(0.004)	(0.004)	(0.005)	(0.004)	(0.004)
Constant	0.254	−0.052	1.338***	1.073***	1.049***	0.619***	0.875***	1.026***	1.000***	0.331**
	(0.173)	(0.143)	(0.175)	(0.135)	(0.145)	(0.143)	(0.152)	(0.188)	(0.149)	(0.132)
Observations	1,171	1,511	1,495	1,575	1,630	1,562	1,548	1,557	1,616	1,620
Avg. Turnout	87.73%	88.55%	91.71%	89.94%	88.94%	87.15%	91.64%	91.43%	92.70%	86.01%

Note: This table reports probit model results, based on the full specification in (1.55) and data from all different ESS rounds in the respective years in which Belgium is included in the ESS sample. Robust standard errors are given in brackets. It holds: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

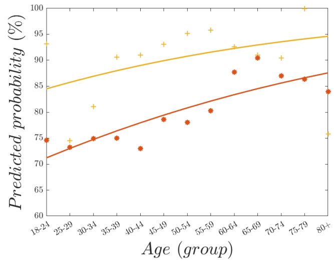
Figure 1.13: Predicted probabilities of voting for different ages and education levels for Germany.



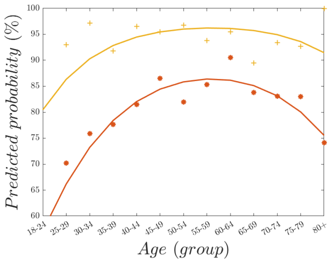
(a) ESS round 11, year 2023*



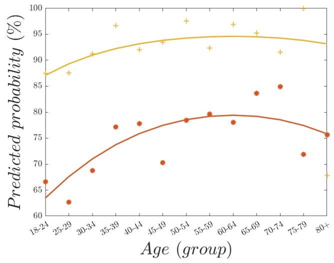
(b) ESS round 8, year 2016



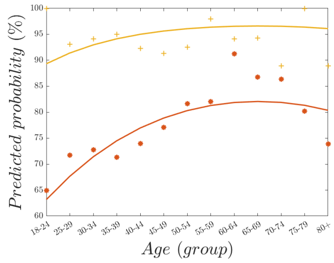
(c) ESS round 7, year 2014



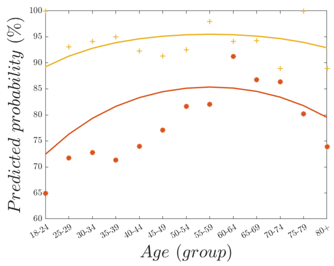
(d) ESS round 4, year 2008



(e) ESS round 3, year 2006



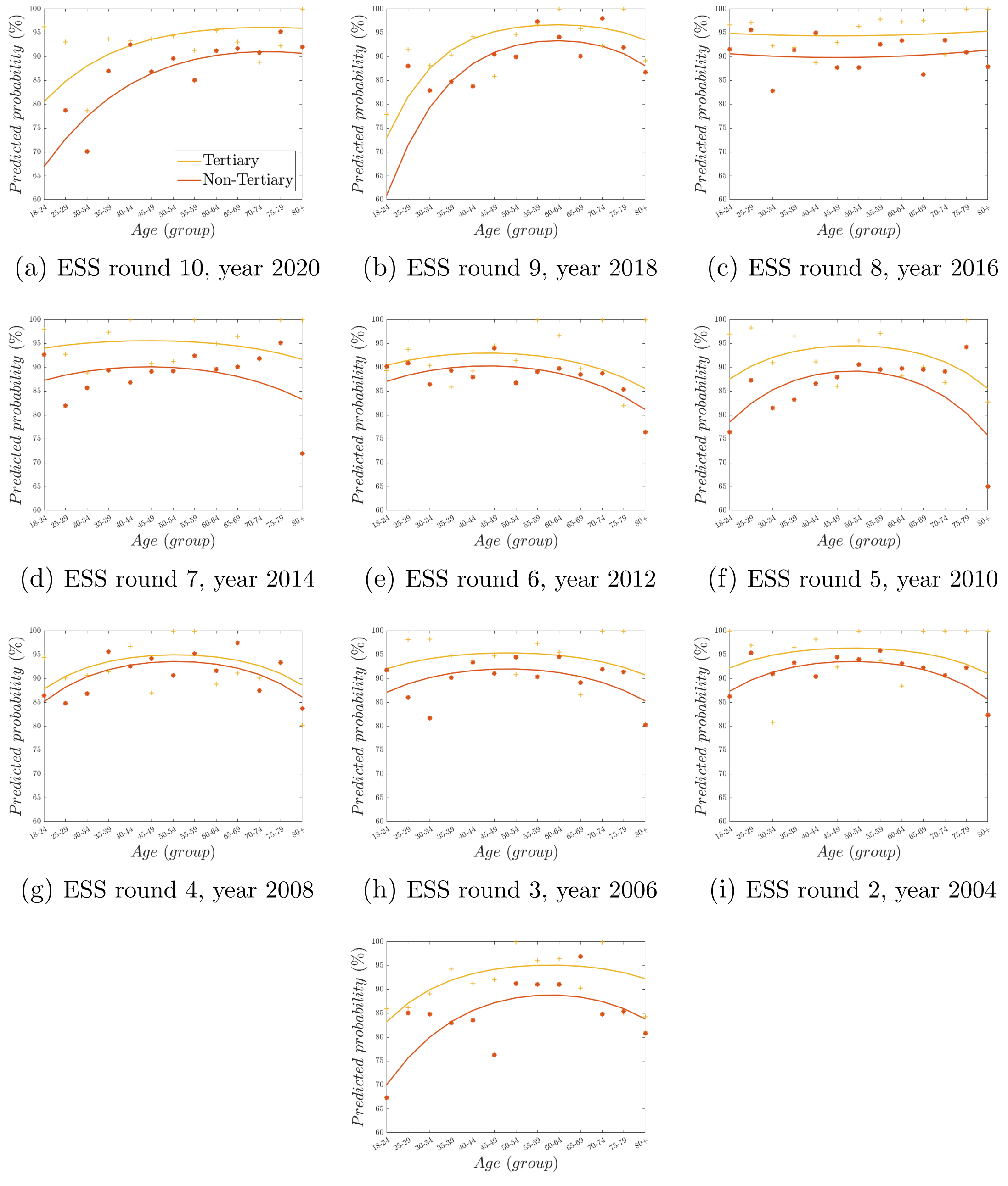
(f) ESS round 2, year 2004



(g) ESS round 1, year 2002

Note: The figure reports predicted probabilities of voting for different ESS rounds and years for Germany, based on the probit model results from Table 1.10 in the respective column. The (asterisks) pluses represent average voter turnout rates per age group and (non-) tertiary education degree. *The reliability of German data for ESS round 11, year 2023, is limited because the relevant weighting measure is missing in the dataset. Results are presented without weighting observations.

Figure 1.14: Predicted probabilities of voting for different ages and education levels for Belgium.



(a) ESS round 10, year 2020 (b) ESS round 9, year 2018 (c) ESS round 8, year 2016

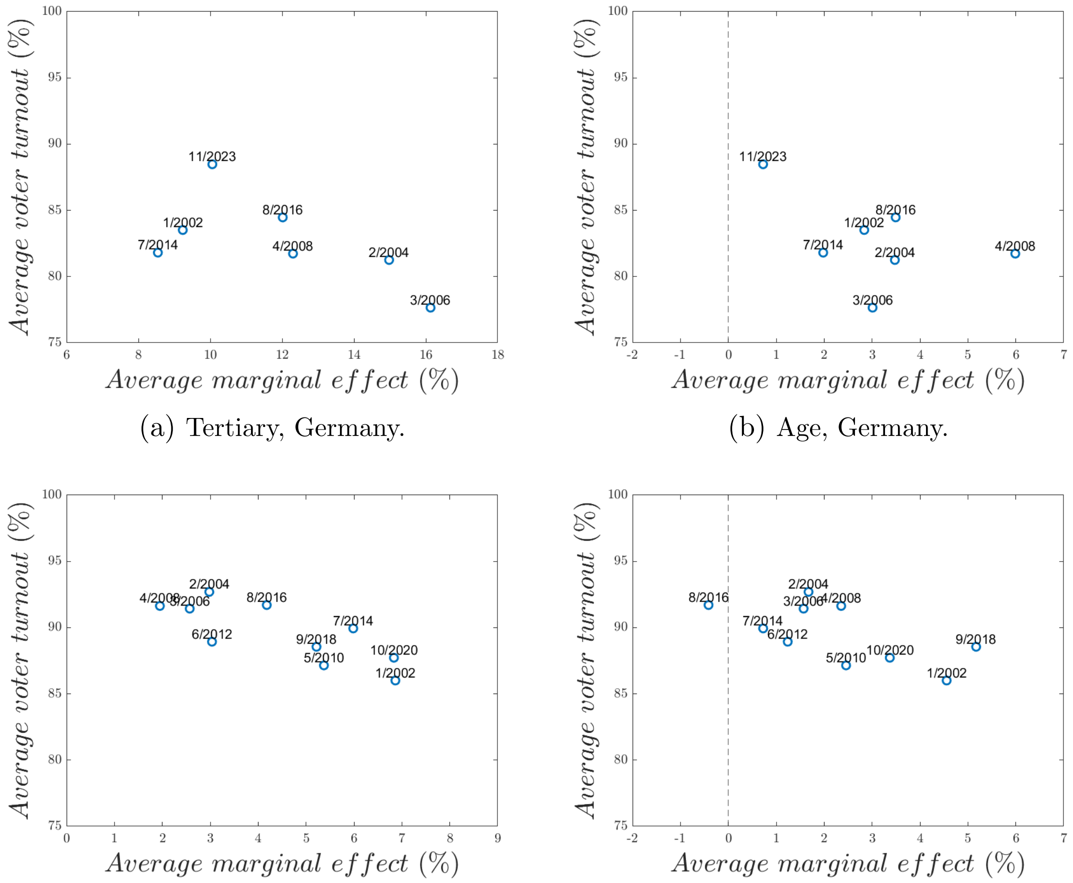
(d) ESS round 7, year 2014 (e) ESS round 6, year 2012 (f) ESS round 5, year 2010

(g) ESS round 4, year 2008 (h) ESS round 3, year 2006 (i) ESS round 2, year 2004

(j) ESS round 1, year 2002

Note: The figure reports predicted probabilities of voting for different ESS rounds and years for Belgium, based on the probit model results from Table 1.11 in the respective column. The (asterisks) pluses represent average voter turnout rates per age group and (non-) tertiary education degree.

Figure 1.15: Average marginal effects.



(a) Tertiary, Germany.

(b) Age, Germany.

(c) Tertiary, Belgium.

(d) Age, Belgium.

Note: This figure shows the average marginal effects of *Tertiary* and *Age* on the probability of voting for the different ESS rounds and years in Germany and Belgium, respectively.

tertiary education) affects the individual's average probability of voting. Panel (b) and panel (d) show how - ceteris paribus - a marginal increase in the age variable (here: a switch from one age group to a one-step older age group) affects the individual's average probability of voting. Switching from a non-tertiary education degree to a tertiary education degree increases the probability of voting on average by 8 to 16 percent in Germany. The same switch in Belgium (with a compulsory voting policy in place) leads on average to an increase in the probability of voting of around 4 to 6 percent. Switching from one age group to the next older age group increases the probability of voting on average in Germany by around 1 to 6 percent, and comparably strong in Belgium by around -0.5 to 5 percent.

Parameter values for the quantitative model Table 1.12 reports the calibrated voter turnout rates for the German case, the (theoretical) compulsory voting case and the observed compulsory voting case in Belgium.

Table 1.12: Voter turnout rates across countries.

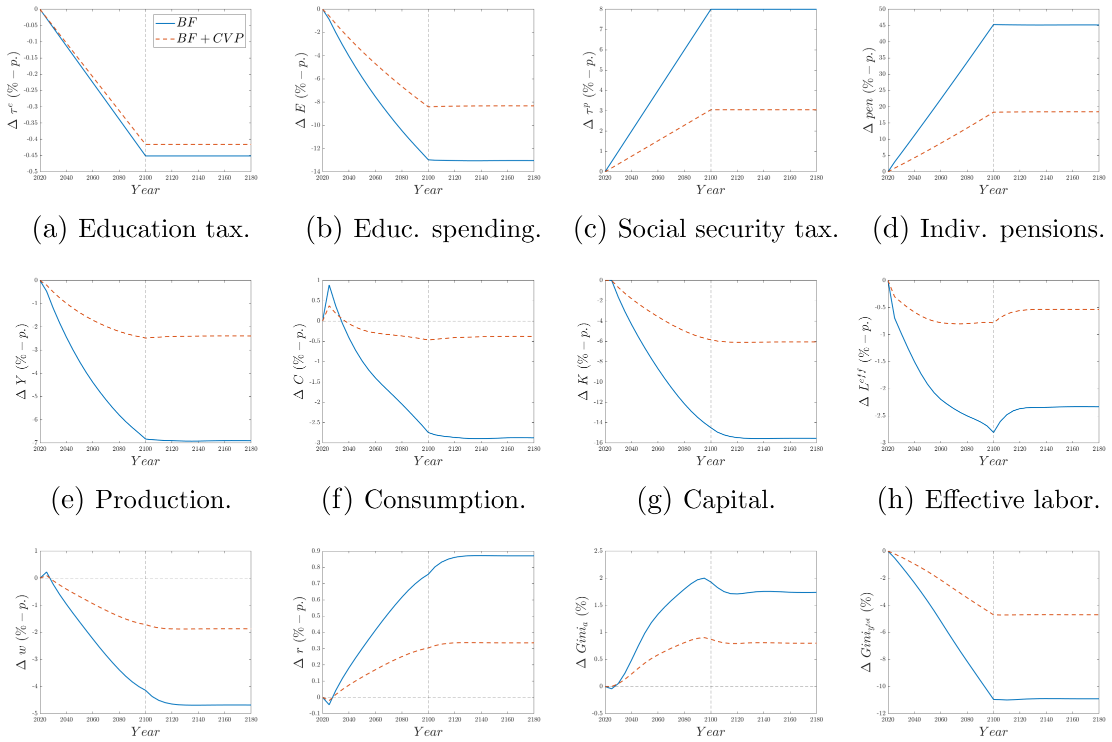
		Germany		Belgium	
j	Age	$i = L$	$i = H$	$i = L$	$i = H$
1	20-24	0.674	0.860	0.906	0.949
2	25-29	0.718	0.886	0.903	0.947
3	30-34	0.755	0.907	0.901	0.946
4	35-39	0.786	0.923	0.900	0.945
5	40-44	0.811	0.935	0.899	0.944
6	45-49	0.831	0.944	0.898	0.944
7	50-54	0.846	0.951	0.899	0.944
8	55-59	0.858	0.956	0.900	0.945
9	60-64	0.867	0.957	0.901	0.946
10	65-69	0.873	0.962	0.904	0.947
11	70-74	0.876	0.963	0.907	0.949
12	75-79	0.876	0.963	0.910	0.951
13	80-84	0.874	0.962	0.914	0.954
14	85-89	0.870*	0.961*	0.918*	0.956*
15	90-94	0.862*	0.957*	0.923*	0.959*
16	95-99	0.851*	0.953*	0.928*	0.962*
17	100+	0.836*	0.947*	0.933*	0.965*

Note: This table reports the calibrated voter turnout rates for Germany and Belgium. Voter turnout rates for Germany and Belgium are based on data from the ESS round 8, year 2016. *Voter turnout rates for age groups 85-89, 90-94, 95-99, and 100+ are based on out-of-sample predictions.

1.D Quantitative results

We observe mitigating effects in the *BF* and *LF* scenarios when we compare the transition paths of the *w/o CVP* and the *CVP* cases relative to the constant tax rate case, see Figure 1.16 and Figure 1.17, respectively. For the *HF* scenario, we observe increasingly positive effects on aggregate output over time relative to the constant tax rate case for the *CVP* case, see Figure 1.18. The output effect, in comparison to the constant tax rate case, is already positive on impact and increasingly positive over time. Given that aggregate capital is fixed in the initial period, we observe a slight decline in aggregate consumption on impact due to a reduction in the wage rate, driven by the relative scarcity of aggregate capital in comparison to effective labor. In subsequent periods, aggregate consumption increases relative to the constant tax rate case. The Gini coefficient for wealth increases on impact due to a slight increase in the interest rate, which especially benefits wealthier individuals. The Gini coefficient for total income increases directly due to the reduced use of redistributive individual pension payments.

Figure 1.16: Transition rel. to the constant tax rate case for *CVP* vs *w/o CVP* in the *BF* scenario.



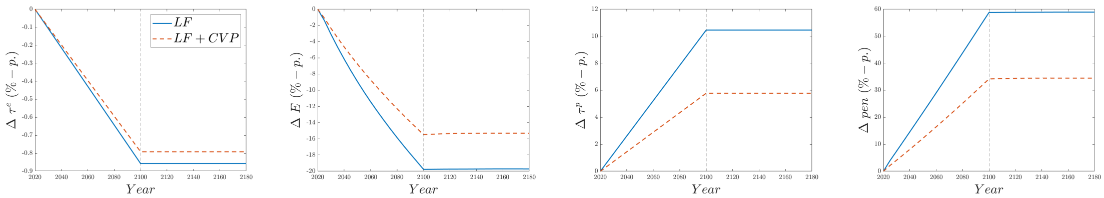
(a) Education tax. (b) Educ. spending. (c) Social security tax. (d) Indiv. pensions.

(e) Production. (f) Consumption. (g) Capital. (h) Effective labor.

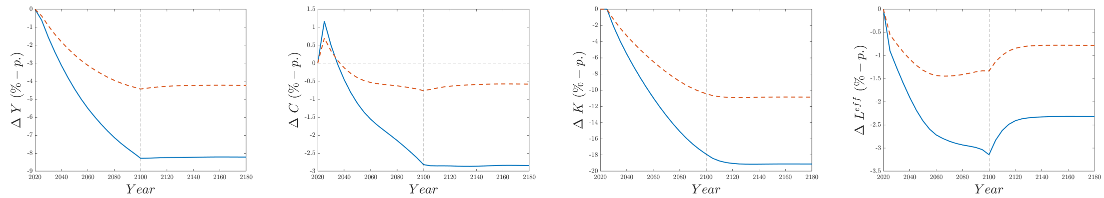
(i) Wage rate. (j) Interest rate. (k) Gini wealth. (l) Gini total income.

Note: This figure shows the transition paths of public policy instruments, economic aggregates, and inequality measures for the *BF* scenario for the situation in which the tax rates converge linearly to their final stationary political equilibrium by 2100 in the *w/o CVP* and the *CVP* case relative to the "pure aging" transition in which the tax rates are constant at their initial 2020 values. The transitions are plotted as percentage deviations (%) or percentage-point deviations ($\% - p.$).

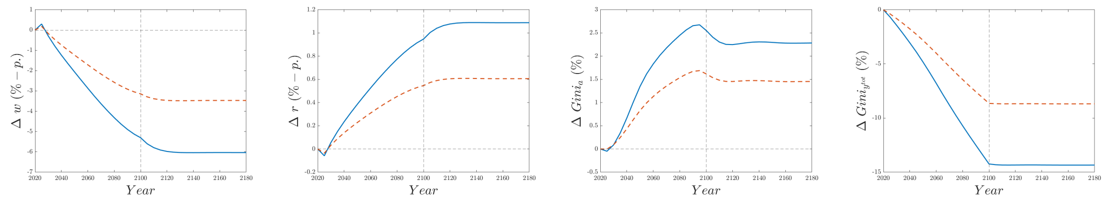
Figure 1.17: Transition rel. to the constant tax rate case for *CVP* vs *w/o CVP* in the *LF* scenario.



(a) Education tax. (b) Educ. spending. (c) Social security tax. (d) Indiv. pensions.



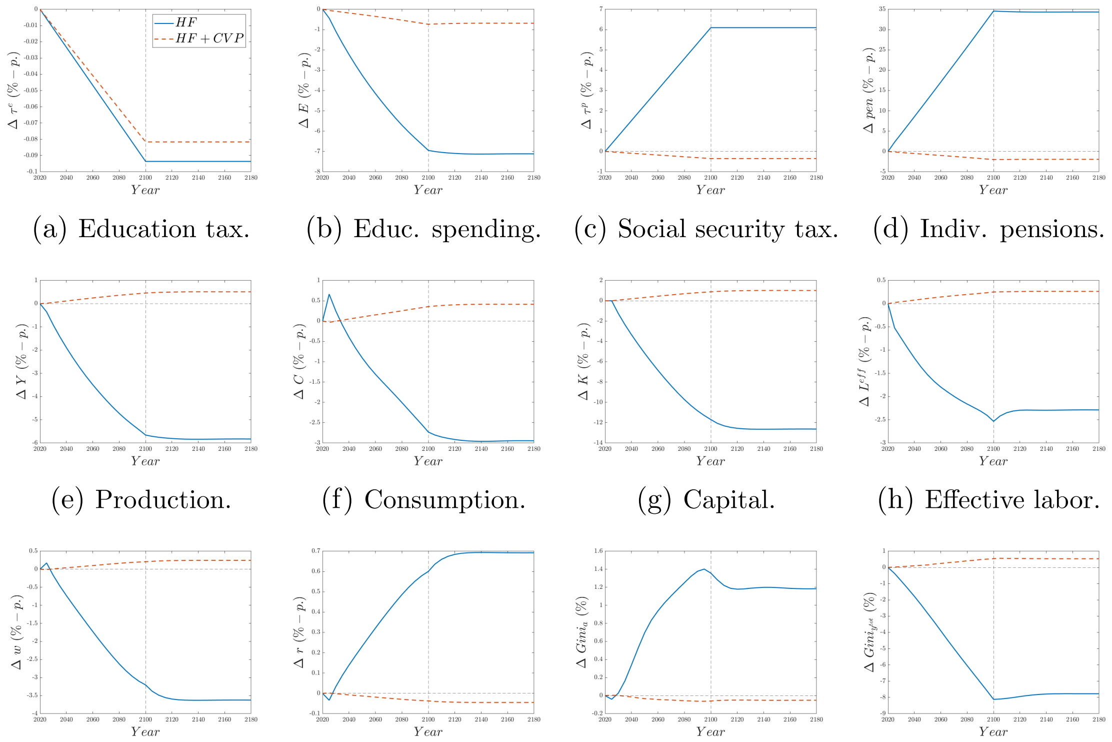
(e) Production. (f) Consumption. (g) Capital. (h) Effective labor.



(i) Wage rate. (j) Interest rate. (k) Gini wealth. (l) Gini total income.

Note: This figure shows the transition paths of public policy instruments, economic aggregates, and inequality measures for the *LF* scenario for the situation in which the tax rates converge linearly to their final stationary political equilibrium by 2100 in the *w/o CVP* and the *CVP* case relative to the "pure aging" transition in which the tax rates are constant at their initial 2020 values. The transitions are plotted as percentage deviations (%) or percentage-point deviations ($\% - p.$).

Figure 1.18: Transition rel. to the constant tax rate case for *CVP* vs *w/o CVP* in the *HF* scenario.



(a) Education tax. (b) Educ. spending. (c) Social security tax. (d) Indiv. pensions.

(e) Production. (f) Consumption. (g) Capital. (h) Effective labor.

(i) Wage rate. (j) Interest rate. (k) Gini wealth. (l) Gini total income.

Note: This figure shows the transition paths of public policy instruments, economic aggregates, and inequality measures for the *HF* scenario for the situation in which the tax rates converge linearly to their final stationary political equilibrium by 2100 in the *w/o CVP* and the *CVP* case relative to the ”pure aging” transition in which the tax rates are constant at their initial 2020 values. The transitions are plotted as percentage deviations (%) or percentage-point deviations ($\% - p.$).

Chapter 2

Fiscal policy and human capital in the race against the machine*

Co-authored with **Daniele Angelini** (University of Vienna) and **Stefan Niemann** (University of Konstanz)

Abstract

We analyze the policy trade-offs facing fiscal policy in a dynamic growth model with automation, education choice, and human capital formation. Although beneficial for economic growth, automation contributes to wage inequality. When human capital formation is affected by government spending, fiscal policy can enhance welfare through a coordinated increase in labor and robot taxes. The composition of taxes financing spending on transfers and education is key in determining the effects on economic growth and inequality, as the robot tax is the more redistributive instrument. We calibrate our model to the US economy and determine the welfare-maximizing tax policy. Optimality requires an initial reduction in the robot tax to foster automation-driven growth, followed by its gradual increase to address widening inequality. Education subsidies can only be welfare-improving if they are financed through the labor tax. When private contributions to higher education are sufficiently high, the optimal robot tax is zero.

*For helpful discussions and comments, we are grateful to Andrea Ichino, Klaus Prettner, Ctirad Slavík, conference audiences in Brussels (UNTANGLED 2022), Frankfurt (CORA 2022), Rome (INFER 2022), Rotterdam (EEA 2024), Vienna (NOeG 2022), Genoa (AIEL 2023), Lisbon (ASSET 2023), Regensburg (VfS 2023), and seminar audiences at the Universities of Freiburg, Konstanz, St. Gallen, Tübingen and Vienna.

2.1 Introduction

Technological advancement is recognized to be a principal driver of economic growth. However, in the last decades, the increased efficiency of automated technology – that is, the automated operation of production tasks through the use of robots, software technologies, artificial intelligence, etc. – has also significantly contributed to rising inequality due to the skill-biased nature of this form of technological progress (cf. e.g. Autor, 2019). Indeed, high-skilled workers often stand to benefit from an increase in the productivity (or a reduction in the price) of automated technologies as the tasks performed by them are complementary to machines. By contrast, low-skilled workers are more likely to be substituted by machines. Automation thus induces a pattern of rising skill premia along with stagnating, or even falling, wages for less-educated workers.

Importantly, however, skill premia and the resulting inequality across different types of workers reflect not only technological developments that determine the demand for skills, but also their supply, which is crucially shaped by education (cf. e.g. Goldin and Katz, 2010). In consequence, policy options in the 'race against the machine' must be assessed in terms of their impact on both the demand and the supply of skills.

Starting from this basic insight, this paper examines the trade-offs facing fiscal policy in the context of a dynamic general equilibrium model in which both technological progress and human capital formation are endogenous. Technological progress is skill-biased and facilitated by R&D which creates patents for automation capital. Human capital formation entails not only an extensive margin via the education choices (basic versus higher education) individuals take at the beginning of their working life, but also an intensive margin via the amount of resources devoted to the different stages of education. To capture this effect along the intensive margin, we consider a *hierarchical education system* with a sequential process for basic (primary and secondary) and higher (college/tertiary) education. Publicly funded education spending thus augments workers' human capital in two stages. Whereas all workers benefit from spending on basic education, only those enrolled in higher education get the additional benefits from education spending at the tertiary level.

We embed these mechanisms for technological progress and human capital formation into an overlapping generations model, which successfully captures the secular trend of sustained productivity growth alongside a rising college share, an increasing skill premium and a declining labor share. R&D-driven growth thus induces automation and is accompanied by increasing inequality between high-skilled and low-skilled workers. Fiscal policy – formalized initially in terms of variations in tax policy for a given configuration of public spending under a balanced budget – can affect these dynamics via two channels: *the redistribution and the human capital channel*. To the extent that part of the tax revenue is used to transfer resources from richer households (high-skilled workers) to poorer households (low-skilled workers), the redistribution channel implies reduced inequality. But to the extent that some tax revenue is used to fund education spending, the human capital channel works in the opposite direction since the hierarchical education system benefits proportionally more the high-skilled workers. Contrasting a labor tax (i.e., a linear tax on wage income) and a robot tax (i.e., an ad-valorem tax on machines), we find that the magnitude of these effects crucially depends on the way transfers and education spending are financed. The redistribution channel through the robot tax is, indeed, stronger than the redistribution channel when government spending is financed through the labor tax. This is because the robot tax has a direct negative effect on high-skilled workers as complements to machines, while the labor tax affects high- and low-skilled workers proportionally.

Since the two channels work in opposite directions, the net effect of taxation on inequality is generally ambiguous. We therefore calibrate the general equilibrium model – and in particular the breakdown of fiscal policy – to US data and observe that, following an increase in the labor tax relative to the calibrated status quo, both economic growth and inequality increase. By contrast, an increase in the robot tax has opposite effects on economic growth and inequality. In other words, given the structure of the US economy and the allocation of fiscal revenue for transfer payments and education funding, we find that, for the labor tax, the human capital channel dominates the redistribution channel; for the robot tax, the dominance is reversed.

While one-dimensional tax policy interventions (changes in either the labor or the robot tax) entail a fundamental trade-off between economic growth and inequality, we identify conditions for coordinated two-dimensional tax policy packages (combined changes in the two tax rates) to achieve both higher growth and lower inequality. For instance, we observe that a joint increase in the robot tax (which reduces inequality through redistribution) and in the labor tax (which increases growth via the human capital channel) can break the growth-inequality trade-off. This result highlights the importance of accounting for endogenous human capital accumulation along the intensive margin: In a version of the model in which we ignore the human capital-enhancing effect of education spending, a joint increase of both taxes would always lead to a reduction in production.

Taking this insight to a normative setting in which the optimal tax policy over time is characterized for a utilitarian welfare function, we find that the government should initially reduce the robot tax significantly and compensate for the loss in revenues with a higher labor tax. Subsequently, the government should progressively increase the robot tax and reduce the labor tax. This dynamic pattern of taxation initially provides incentives for increased R&D and automation. As machine productivity increases and the skill premium widens, the government then finds it optimal to increase the robot tax and reduce the labor tax to contain inequality.

A decomposition exercise disentangles the determination of the optimal tax policy via technological progress, education choices, and human capital formation along the intensive margin, respectively. When the latter is missing so that the intensive margin human capital channel is not operating, it becomes optimal to finance government spending exclusively via robot taxes: Absent a motive for education spending, the only task left for fiscal policy is to redistribute, which can be achieved more effectively via the robot tax and becomes increasingly important as automation proceeds.

As our approach highlights the interaction between the revenue (taxation) and the spending side of fiscal policy, we also study the role of education subsidies – formalized as tax-funded transfer payments to individuals undertaking higher education. When per-capita education spending is kept constant for both basic and higher education so that the intensive margin of human capital formation remains unchanged, there is no scope for education subsidies to increase aggregate welfare. However, welfare gains are attainable when the per-capita spending on basic education adjusts in response to the policy. It is thus crucial that the subsidy policy's extensive margin effects via education choice are accompanied by intensive margin effects via augmented human capital formation. When education subsidies can be targeted specifically to individuals who would not have undertaken higher education without the subsidy, the welfare effects can be further improved. Importantly, however, for all these education policies beneficial welfare effects can only be obtained under financing via the labor tax, whereas funding via the robot tax always has adverse welfare consequences. Accordingly, despite the hierarchical nature of the education system, the labor tax robustly emerges as the preferred instrument to finance education subsidies.

Finally, we consider a model extension in which individuals can privately invest in their higher education. Variations in public education spending then induce substitution effects that crowd out private contributions and result in a diminished magnitude of the human capital channel. As the importance of this mechanism hinges on the underlying funding mix for higher education, the implications for optimal fiscal policy now depend on the specific environment: For a 'European setting' where higher education is largely financed by the government, the optimal financing for the government's redistribution and education policy involves a positive robot tax. But for a 'US setting' where higher education is mostly privately funded, the optimal robot tax is zero. This difference is again rooted in the interplay between the human capital channel and the redistribution channel, but is also amenable to an intuitive normative interpretation. When high-skilled workers do not sufficiently contribute to their education, it is optimal to achieve redistribution by taxing them indirectly through a positive robot tax. When they instead contribute sufficiently, the indirect taxation through the robot tax becomes suboptimal as redistribution can be achieved more efficiently via the labor tax.

Related Literature Our paper contributes to several strands of the literature. Most closely related to our work is the paper by Prettner and Strulik (2020), which is also the specific point of departure for our model. Relative to other studies of automation-driven growth like Acemoglu and Restrepo (2018) or Hémous and Olsen (2022), we thus share the emphasis on the household side of the economy while technology is kept relatively simple.[1] Like Prettner and Strulik (2020), we examine inequality and redistribution in the context of an economy in which both technology and education are endogenous. However, we conceptualize education not just in terms of an extensive margin choice that generates skilled versus unskilled workers, but also in terms of the intensive margin effects of public education spending on the effective human capital commanded by these groups. Public policy therefore has interacting effects via the redistribution and the human capital channel, which entails important positive and normative implications for the scope, design and composition of desirable tax policies.

More broadly, our paper also contributes to a growing body of research investigating the joint dynamics of growth and inequality, driven by automation and hu-

[1] Both Acemoglu and Restrepo (2018) and Hémous and Olsen (2022) do not consider human capital accumulation along the extensive or the intensive margin. On the production side, they allow for a richer structure where final output is produced by a variety of tasks or intermediate inputs, and where endogenous growth comes from new tasks or intermediate inputs generated by R&D. By contrast, we follow Prettner and Strulik (2020) and assume that R&D creates patents for automation capital, consistent with the evidence in Mann and Püttmann (2023).

man capital. Concerning innovation and automation, Krusell et al. (2000) identify capital-skill complementarity as a key mechanism generating inequality. Similarly, Brynjolfsson and McAfee (2011), Frey and Osborne (2017), Graetz and Michaels (2018), Acemoglu and Restrepo (2020) highlight the negative consequences of automation for wages and employment, particularly for workers with lower education. Common to these papers is that they analyze the impact of automation technologies on inequality along the skill distribution assuming an exogenous supply of high- and low-skilled workers. On the other hand, Goldin and Katz (2010), Acemoglu et al. (2012) and Goldin et al. (2020) emphasize the role of (higher) education in the context of increased adoption of automated technologies. Our model incorporates this 'race between education and technology' by considering endogenous education choices in the face of a widening skill premium under automation.[2] We extend the analysis by also allowing public policies to affect human capital formation via the intensive margin and provide a detailed analysis of fiscal policy.

This connects our work to papers analyzing the effects of tax and education policies on human capital accumulation, growth and inequality. For example, Guvenen et al. (2013) study the role of taxation for human capital formation via a generic accumulation equation. Considering an occupational choice model where school quality is endogenous to public education spending, Artige and Cavenaile (2023) find that there is a theoretically ambiguous relationship between public education and inequality and hence also between growth and inequality. In a similar vein, our paper follows the literature on public education finance (Restuccia and Urrutia, 2004; Blankenau, 2005; Arcalean and Schiopu, 2010) and models a hierarchical education system in which basic education spending affects all workers, while college education spending affects only high-skill workers. Differently from these papers, however, we examine the relevance of such an education system for educational sorting and inequality in a setting with endogenous technological progress from R&D and adoption of automation.

Considering the implications for desirable tax and education policies, Krueger and Ludwig (2013, 2016) characterize the optimal mix of progressive income taxes and education subsidies in an overlapping generations model with endogenous human capital under incomplete financial markets. They find that the welfare-maximizing fiscal policy features a progressive labor income tax code combined with a sizable

[2] An early study with a similar focus is He and Liu (2008) who present a unified framework driven by skill-biased technological change where both skill accumulation and wage inequality arise endogenously. However, investment-specific technological change is fed as an exogenous process into the model and therefore remains invariant to both human capital formation and fiscal policy.

subsidy for college education. This highlights the complementarity between the redistributive role of progressive taxation and appropriate education subsidies to offset the tax-induced labor supply distortions along the intensive and extensive margin (cf. Bénabou, 2002). In addition to education transfers, our work emphasizes the importance also of spending which augments the quality (intensive margin) of education and thus materializes via the human capital channel. Moreover, we obtain detailed results for the desirable breakdown of funding via the labor versus the robot tax in an environment with endogenous technological change.

Finally, given the fundamental importance of the equity-efficiency trade-off for the appropriate design of fiscal policy, our work is also related to the public finance literature on optimal taxation following Mirrlees (1971) and Diamond and Mirrlees (1971). In particular, we refer to the recent literature on robot and capital taxation (Slavik and Yazici, 2014; Jacobs and Thuemmel, 2022; Guerreiro et al., 2022; Thuemmel, 2022; Costinot and Werning, 2022; Beraja and Zorzi, 2024) in which production efficiency is a crucial policy objective.[3] Similar to Guerreiro et al. (2022) and Beraja and Zorzi (2024), we show that the optimal robot tax can be different from zero. However, while in their papers this is driven by reallocation concerns, e.g. the presence of older workers in the labor market who are constrained by their initial education choices, in our model the positive robot tax reflects that its redistributive role is accompanied by its growth-enhancing effect through the human capital channel. Moreover, in contrast to these papers, which find that the optimal robot tax is zero in the long-run, our model suggests a progressive increase in the robot tax over time as an efficient way to reduce growing wage inequality. To put these findings into perspective, it is important to recall that our approach differs from the classical optimal taxation approach where the consequences of tax policy are generally studied under either exogenous spending needs or lump-sum redistribution. By contrast,

[3] In this literature, information frictions constrain the government's tax-and-transfer system not to discriminate across unobservable types. In the particular two type-case of 'skilled' versus 'unskilled' workers considered in Stiglitz (1982), production efficiency (and thus a zero robot tax) is optimal when worker types are exogenous and they enter production as perfect substitutes. With imperfect substitutability across types, this is no longer the case, provided labor supply distortions along the intensive margin are the relevant concern. But adding an extensive margin via skill acquisition tends to restore the optimality of production efficiency, that is, the absence of robot taxes (cf. Guerreiro et al., 2022). By contrast, in our economy, worker types are observable so that the tax-and-transfer system can condition on skills in a discriminatory way. Imperfect substitutability in production and endogenous skill acquisition, though, are shared features in both environments. In addition, in our economy workers' wages are endogenous not only due to interaction in production, but also due to the human capital generated via the government's tax-financed education policy. This justifies deviations from production efficiency via positive robot taxes. Over time, this motive actually becomes stronger because of the skill-biased nature of the technological progress which is endogenously generated in our model.

our model provides an integrated assessment of the government's tax and spending policy, whereby our baseline takes the composition of spending for transfers versus education as given and focuses on the optimal mix of labor and robot taxes.

The rest of this paper is structured as follows. Section 3.3 sets up our model, before Section 2.3 details the interaction between the redistribution channel and the human capital channel in a partial equilibrium environment with given supply of skills. Section 2.4 presents our calibration strategy and the general equilibrium dynamics of the calibrated economy. Section 2.5 and Section 2.6 provide a detailed analysis of tax and education policies, respectively. Section 2.7 extends the model to account for privately funded education spending and Section 3.6 concludes.

2.2 Model

Similar to Prettner and Strulik (2020), we consider an overlapping generations economy in which individuals live for two periods. Having completed basic (i.e., primary and secondary) education, individuals enter the economy as young adults with a unit endowment of time. Then, they decide whether or not to spend a certain (fixed) fraction of their time studying to obtain higher (i.e., tertiary/college) education. If they decide against higher education, individuals allocate their full unit time endowment between leisure and labor as low-skilled workers. If they spend time in higher education, they allocate their remaining time between leisure and labor as high-skilled workers. On the one hand, higher education is associated with an opportunity cost in terms of reduced marketable time; on the other hand, it augments individuals' human capital (intensive margin of human capital) and endows them with skills that differentiate them from unskilled workers (extensive margin of human capital). Both types of workers use their labor market income for consumption and savings for their second period of life when they are retired and simply consume the return to their savings. After the second period, individuals die with certainty. Time t evolves discretely, each period corresponds to one generation. The population size is constant in every period and equal to N.

Individuals differ in their ability to complete a college degree, which affects education decisions via the disutility (of effort) while acquiring higher education. In consequence, each generation is partitioned into two groups: those who opt into higher education and become high-skilled workers, and those who do not and become low-skilled workers. The two groups are distinct both in their human capital and the way they interact with machines in production. Low-skilled workers are employed in the final production sector and can be substituted by machines. By contrast, high-skilled workers are employed either in the final production sector as complements to machines, or in the R&D sector for developing the blueprints for machines that are used in the final production sector.

The government raises taxes through a labor tax (linear tax on wage income) and a robot tax (ad-valorem tax on the use of machines in the final production sector) and uses the revenue to finance expenditure on education and transfers. Education spending is allocated to basic education and higher education. While basic education spending affects the human capital of both low-skilled and high-skilled workers, higher education spending directly affects only the human capital of high-skilled workers. Transfers are differentiated across worker types allowing for progressivity in the model.

2.2.1 Households

Individuals obtain utility from consumption and leisure, and disutility from completing higher education. Lifetime utility of an agent of type $j \in \{H, L\}$ is given by:

$$\mathcal{U}_{j,t} = \log(c_{j,t}) + \beta \log(\bar{R}s_{j,t}) + \gamma \log(z_{j,t}) - \mathbb{1}_{[j=H]}\, v(a), \tag{2.1}$$

where $c_{j,t}$ is the consumption of the young agent in period t; $\beta \in (0, 1)$ is the discount factor; $\bar{R}s_{j,t}$ is the consumption of the old agent in period $t+1$ (consisting of savings $s_{j,t}$ and gross interest payments $\bar{R}$); $\gamma > 0$ is a preference weight; and $z_{j,t}$ is leisure. Following Prettner and Strulik (2020), we make the simplifying assumption of a small open economy such that the interest rate $\bar{R}$ is determined on the world capital market and, therefore, exogenously given. The last term in (2.1) is the effort cost from higher education. Individuals are heterogeneous in terms of their innate ability a. Individuals with a higher ability suffer lower effort costs from completing higher education. In particular, we assume:

$$v(a) = \begin{cases} \psi_1 \cdot \log(\frac{\psi_2}{a - \underline{a}}), & \text{if } \ a \geqslant \underline{a} \\ +\infty, & \text{if } \ a < \underline{a}, \end{cases} \tag{2.2}$$

where $\psi_1 > 0$ and $\psi_2 > 0$ determine the level and the slope of the effort cost, and $\underline{a} > 0$ captures the idea that not all agents are able to obtain a college degree.

Given their ability level a, individuals maximize their lifetime utility by choosing consumption, savings, and leisure in period t subject to the following budget constraint:

$$(1-\tau_{W,t})(1-\eta_j-z_{j,t})w_{j,t}+\hat{T}_{j,t}=c_{j,t}+s_{j,t}, \tag{2.3}$$

where $\tau_{W,t}$ represents the linear tax rate on wage income; η_j is the time spent to acquire higher education, which is equal to zero for agents who do not go to college ($\eta_L=0$) and equal to $\eta>0$ for agents obtaining a college degree ($\eta_H=\eta$); $w_{j,t}$ is the type-specific wage; and $\hat{T}_{j,t}$ is the per-capita transfer to an agent of type j.[4] As old individuals do not work, they only consume their savings. From the household utility maximization problem, we obtain:

$$c_{j,t} = \left(\frac{1}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t}+\hat{T}_{j,t}\right), \tag{2.4}$$

$$s_{j,t} = \left(\frac{\beta}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t}+\hat{T}_{j,t}\right), \tag{2.5}$$

$$z_{j,t} = \left(\frac{\gamma}{(1+\beta+\gamma)(1-\tau_{W,t})w_{j,t}}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t}+\hat{T}_{j,t}\right). \tag{2.6}$$

Given the ability level a, an individual decides to go to college to acquire higher education if $\mathcal{U}_{H,t}(a)\geqslant\mathcal{U}_{L,t}$. Hence, there exists a threshold level a_t^* such that if $a\geqslant a_t^*$ the individual attends college, and if $a<a_t^*$ the individual does not. From the indifference condition, $\mathcal{U}_{H,t}(a)=\mathcal{U}_{L,t}$, we obtain:

$$a_t^*=\psi_2\left(\frac{c_{H,t}(w_{H,t})}{c_{L,t}(w_{L,t})}\right)^{-\frac{1+\beta+\gamma}{\psi_1}}\left(\frac{w_{H,t}}{w_{L,t}}\right)^{\frac{\gamma}{\psi_1}}+\underline{a}. \tag{2.7}$$

The threshold level depends negatively on the high-skilled wage rate ($\frac{\partial a_t^*}{\partial w_{H,t}}<0$) and positively on the low-skilled wage rate ($\frac{\partial a_t^*}{\partial w_{L,t}}>0$). In other words, ceteris paribus, a rise in the high-skilled wage rate encourages individuals to pursue higher education, whereas an increase in the low-skilled wage rate diminishes the incentive for skill acquisition. Assuming that individual ability a is distributed according to a cumulative distribution function $\mathcal{F}$, this implies that the mass of low-skilled workers is given by $L_t=\mathcal{F}(a_t^*)N$, and the mass of high-skilled workers by $H_t=(1-\mathcal{F}(a_t^*))N$, where $H_t=H_{Y,t}+H_{A,t}$, i.e., high-skilled workers are either employed in the final production sector or the R&D sector.

[4]Given a total volume of transfers $T_{j,t}$ to young individuals of type j, the per-capita payments are computed as $\hat{T}_{L,t}\equiv T_{L,t}/L_t$ and $\hat{T}_{H,t}\equiv T_{H,t}/H_t$, where L_t and H_t denote the mass of low- and high-skilled workers, respectively. Since per-capita transfers are not necessarily uniform across types, even under linear labor taxation, the tax-and-transfer system can be progressive (or regressive).

2.2.2 Final production sector

Aggregate output is produced according to the following production function:

$$Y_t = \left(h_{H,t}\tilde{H}_{Y,t}\right)^{1-\alpha}\left(\left(h_{L,t}\tilde{L}_t\right)^{\alpha} + \sum_{i=1}^{A_t}(x_{i,t})^{\alpha}\right), \tag{2.8}$$

where $\tilde{H}_{Y,t} \equiv (1-z_{H,t}-\eta)H_{Y,t}$ is high-skilled labor employed in the final goods sector; $\tilde{L}_t \equiv (1-z_{L,t})L_t$ is low-skilled labor; $h_{j,t}$ is the human capital of an agent of type j at time t; $x_{i,t}$ are machines (or robots) of type i; $\alpha \in (0,1)$ is the elasticity of output with respect to (effective) labor that can be easily automated; and A_t represents the technological frontier. This production function captures the main features of automated technologies, namely: the relative complementarity between high-skilled workers and machines, the labor-saving nature of machines with respect to low-skilled workers – who are relatively substitutable by machines – and the evolution of automated technologies through shifts in the technological frontier, A_t.[5]

Let $p_{i,t}$ denote the price of a machine of type i and $\tau_{R,t}$ the ad-valorem tax on the use of machines in the final production sector, i.e., the robot tax. The profit maximization problem faced by competitive firms in the final production sector is:

$$\max_{\left\{\tilde{H}_{Y,t},\tilde{L}_t,\{x_{i,t}\}_{i=1}^{A_t}\right\}} Y_t - w_{H,t}\tilde{H}_{Y,t} - w_{L,t}\tilde{L}_t - (1+\tau_{R,t})\sum_{i=1}^{A_t}p_{i,t}x_{i,t}, \tag{2.9}$$

from which factor prices are obtained as:

$$w_{H,t} = (1-\alpha)\left(h_{H,t}\tilde{H}_{Y,t}\right)^{-\alpha}h_{H,t}\left((h_{L,t}\tilde{L}_t)^{\alpha} + \sum_{i=1}^{A_t}(x_{i,t})^{\alpha}\right), \tag{2.10}$$

$$w_{L,t} = \alpha\left(\frac{h_{H,t}\tilde{H}_{Y,t}}{h_{L,t}\tilde{L}_t}\right)^{1-\alpha}h_{L,t}, \tag{2.11}$$

$$(1+\tau_{R,t})p_{i,t} = \alpha\left(\frac{h_{H,t}\tilde{H}_{Y,t}}{x_{i,t}}\right)^{1-\alpha}. \tag{2.12}$$

The effect of technological progress (in the form of an increase in A_t, i.e., the variety of machines used in the production process measuring the technological frontier) is different across skill groups. On the one hand, technological progress is quasi labor-

[5]The production function in (2.8) implies that high-skilled wage rates are directly and positively affected by technological progress, but low-skilled wages are not. These properties are consistent with the empirically observed pattern of increasing high-skilled wages and stagnating low-skilled wages in the last decades (Autor, 2019).

augmenting in the sense that it increases the productivity of high-skilled labor in the final production sector – see (2.10). On the other hand, productivity of low-skilled individuals is not directly affected by technological progress – see (2.11) – leading to a decline of the relative importance of low-skilled labor in the final production sector when technological progress occurs.

2.2.3 R&D sector

The R&D sector produces the blueprints for new machines by employing only high-skilled labor. Similar to Romer (1990) and Jones (1995, 2022a), we consider the following process for expanding the technological frontier via R&D:

$$A_t - A_{t-1} = \bar{\delta}_t h_{H,t} \tilde{H}_{A,t}, \tag{2.13}$$

where $\tilde{H}_{A,t} \equiv (1 - z_{H,t} - \eta) H_{A,t}$ represents high-skilled labor employed in the R&D sector; $\bar{\delta}_t \equiv \delta \frac{(A_{t-1})^{\lambda_1}}{\left(h_{H,t}\tilde{H}_{A,t}\right)^{1-\lambda_2}}$ is a measure of the productivity in the R&D sector capturing intertemporal knowledge spillovers (measured by $\lambda_1 \in (0,1]$) and congestion externalities (measured by $(1-\lambda_2)$ with $\lambda_2 \in [0,1]$), and δ is a scaling parameter. R&D firms' profits are given by the revenues generated by selling patents net of labor costs, $p_{A,t}\bar{\delta}_t h_{H,t}\tilde{H}_{A,t} - w_{A,t}\tilde{H}_{A,t}$, where $p_{A,t}$ denotes the price of blueprints and $w_{A,t}$ is the wage rate in the R&D sector. Optimality requires that $w_{A,t} = p_{A,t}\bar{\delta}_t h_{H,t}$.[6]

2.2.4 Intermediate goods sector

The intermediate goods sector rents capital to produce machines. We consider a linear technology, $x_{i,t} = k_{i,t}$, where $k_{i,t}$ is the amount of capital used by the intermediate firms producing machines of type i, and assume that physical capital depreciates fully within one model period. Firms in the intermediate goods sector either produce the latest vintage (denoted by n) or the older vintage machines (denoted by m). Producers of older vintage machines do not need to acquire patents and operate under perfect competition. Free entry then implies zero profits, i.e., $\pi_{m,t} = 0$. Producers of the latest vintage machines use patents from the R&D sector as input, which endows them with a certain degree of market power. Free entry

[6] Patent protection is assumed to last for one model period. This is a reasonable assumption as the standard patent duration in the US is 20 years (US Patent and Trademark Office, 2023), i.e., similar to the length of one model period. For the intermediate goods sector, it implies that the latest vintage producers but not the older vintage producers have to pay for patents to produce machines.

implies that the profits, $\pi_{n,t}$, for the producers of the latest vintage machines must be equal to the patent costs, i.e., $\pi_{n,t} = p_{A,t}$. The profit maximization problem faced by the latest vintage machine producers is given by:

$$\max_{x_{n,t}} p_{n,t}(x_{n,t})x_{n,t} - \bar{R}x_{n,t} \tag{2.14}$$

subject to (2.12). Optimality requires:

$$\frac{\partial p_{n,t}(x_{n,t})}{\partial x_{n,t}} \frac{x_{n,t}}{p_{n,t}} + 1 = \frac{\bar{R}}{p_{n,t}} \quad \Longleftrightarrow \quad p_{n,t} = \frac{\bar{R}}{\alpha} \quad \Longleftrightarrow \quad \pi_{n,t} = \frac{1-\alpha}{\alpha}\bar{R}x_{n,t}, \tag{2.15}$$

from which the supply of machines of the latest vintage is obtained as:

$$x_{n,t} = \left(\frac{\alpha^2}{\bar{R}(1+\tau_{R,t})}\right)^{\frac{1}{1-\alpha}} h_{H,t}\tilde{H}_{Y,t}. \tag{2.16}$$

Older vintage machine producers, instead, face the following problem:

$$\max_{x_{m,t}} p_{m,t}x_{m,t} - \bar{R}x_{m,t}, \tag{2.17}$$

from which we obtain the optimality condition $p_{m,t} = \bar{R}$ and the supply of machines of older vintage:

$$x_{m,t} = \left(\frac{\alpha}{\bar{R}(1+\tau_{R,t})}\right)^{\frac{1}{1-\alpha}} h_{H,t}\tilde{H}_{Y,t}. \tag{2.18}$$

Combining (2.16) and (2.18), we obtain $x_{m,t} = \alpha^{\frac{1}{\alpha-1}} x_{n,t}$. Finally, aggregating over all vintages, we can rewrite the final goods production function as:

$$Y_t = \left(h_{H,t}\tilde{H}_{Y,t}\right)^{1-\alpha} \left(\left(h_{L,t}\tilde{L}_t\right)^{\alpha} + \tilde{A}_t\left(x_t\right)^{\alpha}\right), \tag{2.19}$$

where $x_t \equiv x_{n,t}$ and $\tilde{A}_t \equiv \left(\alpha^{\frac{\alpha}{\alpha-1}} - 1\right) A_{t-1} + A_t$.[7]

2.2.5 Human capital

Human capital formation takes place via education, the effectiveness of which is determined by the amount and composition of public education spending, E_t. We assume a hierarchical public education system with a sequential process for basic and

[7] Indeed, $\sum_{i=1}^{A_t}\left(x_{i,t}\right)^{\alpha} = A_{t-1}\left(x_{m,t}\right)^{\alpha} + \left(A_t - A_{t-1}\right)\left(x_{n,t}\right)^{\alpha} = \left(\left(\alpha^{\frac{\alpha}{\alpha-1}} - 1\right) A_{t-1} + A_t\right)\left(x_t\right)^{\alpha} = \tilde{A}_t\left(x_t\right)^{\alpha}$.

higher education following the literature on public education finance (Restuccia and Urrutia, 2004; Blankenau, 2005; Arcalean and Schiopu, 2010). Accordingly, basic human capital, $h_{B,t}$, is determined only by public spending on basic education, $E_{B,t}$, while the human capital of high-skilled workers, $h_{H,t}$, depends on both the spending on higher education, $E_{H,t}$, and the human capital previously acquired through basic education. Total public education spending is the sum of the expenditures across the two tiers, i.e., $E_t = E_{B,t} + E_{H,t}$.

Basic human capital and human capital of the low-skilled workers, $h_{L,t}$, coincide:

$$h_{L,t} = h_{B,t} = B \cdot \left(\hat{E}_{B,t}\right)^{\mu_B}, \tag{2.20}$$

where $\hat{E}_{B,t} \equiv E_{B,t}/N$ is the per-capita level of public education spending for basic education. Building on the human capital acquired from basic education, those individuals selecting into higher education acquire additional skills, which (i) differentiate them from unskilled workers and (ii) raise their human capital. Specifically, we assume:

$$h_{H,t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \left(\hat{E}_{H,t}\right)^{\mu_H}, \tag{2.21}$$

where $\hat{E}_{H,t} \equiv E_{H,t}/H_t$ is the per-capita level of public education spending for higher education. The parameters $B > 0$ and $B_H > 0$ are productivity parameters, while $\mu_B \in (0,1)$ and $\mu_H \in (0,1)$ govern the elasticity of human capital formation to public spending inputs at the basic and higher level, respectively.

Notice that the above specification of human capital formation entails a role for public education spending via both the extensive margin (by drawing a larger number of individuals into higher education) and the intensive margin (by making education at both tiers more productive).

2.2.6 Fiscal policy

The government raises revenues by taxing labor and robots. Total tax revenues, $\mathcal{G}_t$, are given by the sum of labor, $\mathcal{G}_{W,t}$, and robot tax revenues, $\mathcal{G}_{R,t}$, defined as:

$$\mathcal{G}_{W,t} = \tau_{W,t}\left(w_{H,t}\tilde{H}_{Y,t} + w_{A,t}\tilde{H}_{A,t} + w_{L,t}\tilde{L}_t\right), \tag{2.22}$$

$$\mathcal{G}_{R,t} = \tau_{R,t}\sum_{i=1}^{A_t} p_{i,t}x_{i,t} = \tau_{R,t}\hat{A}_t\bar{R}x_t, \tag{2.23}$$

where $\hat{A}_t \equiv \alpha^{\frac{1}{\alpha-1}} A_{t-1} + \alpha^{-1}(A_t - A_{t-1})$.[8]

On the spending side, tax revenues are used to finance public education, E_t, and transfers, T_t, such that the budget is balanced, i.e., $\mathcal{G}_t = E_t + T_t$. We define $\phi_t \in (0,1]$ as the share of total public spending allocated to total education, and $\phi_{B,t} \in (0,1)$ as the share of total education spending allocated to basic education. This implies that we can rewrite total public education spending, total transfer spending, basic education spending, and higher education spending as: $E_t = \phi_t \mathcal{G}_t$; $T_t = (1-\phi_t)\mathcal{G}_t$; $E_{B,t} = \phi_{B,t} E_t$; and $E_{H,t} = (1-\phi_{B,t})E_t$, respectively. We further define the share of transfers to low-skilled individuals as $\omega_t \in [0,1]$ and rewrite the total transfers to low- and high-skilled agents as $T_{L,t} = \omega_t T_t$ and $T_{H,t} = (1-\omega_t)T_t$, respectively.

2.2.7 Competitive equilibrium

For a given balanced-budget fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega\}_t$, the competitive equilibrium is such that (i) households maximize their utility; (ii) firms in the intermediate, final, and R&D sectors maximize their profits; (iii) the markets for low- and high-skilled labor, and the markets for machines, final goods, and patents clear; (iv) the population constraint holds, i.e., $N = H_t + L_t$, and (v) the no-arbitrage condition in the high-skilled labor market holds, i.e., $w_{H,t} = w_{A,t}$.[9]

2.3 Partial equilibrium analysis

Before turning to the model analysis for a calibrated environment, this section examines the main channels through which a change in taxation affects inequality. Key to our results is the fact that taxation generates fiscal revenues, which are used not only for transfer payments but also for public education. In consequence, tax policy affects inequality both via its redistributive effects and its effects on human capital formation. To highlight these effects, we proceed with a partial equilibrium analysis, keeping the aggregate supply of skills constant both along the education choice and the individual labor supply, i.e., we keep the extensive margin of human capital formation fixed. This is achieved by fixing the ability threshold a^* for selecting into higher education and considering the case of inelastic individual labor supply ($\gamma = 0$).[10] As a measure of inequality, we consider the consumption ratio be-

[8] Indeed, $\sum^{A_t} p_{i,t}x_{i,t} = A_{t-1}\bar{R}x_{m,t} + (A_t - A_{t-1})\frac{\bar{R}}{\alpha}x_{n,t} = (\alpha^{\frac{1}{\alpha-1}} A_{t-1} + \alpha^{-1}(A_t - A_{t-1}))\bar{R}x_t = \hat{A}_t \bar{R} x_t$.

[9] The equilibrium conditions are detailed in Appendix 2.A.

[10] For the rest of this section, we drop time subscripts as they are not necessary for the analysis.

tween high- and low-skilled workers.[11] Our inequality measure is, therefore, defined as:

$$\frac{c_H}{c_L} = \frac{(1-\tau_W)(1-\eta)w_H + \hat{T}_H}{(1-\tau_W)w_L + \hat{T}_L}. \tag{2.24}$$

Taxation affects the consumption ratio through two main channels: the *redistribution channel* (RE) and the *(intensive margin) human capital channel* (HC). The redistribution channel accounts for the direct effect of taxes on disposable income and transfers, while the human capital channel accounts for the effect of education spending on wages through human capital:

$$\begin{aligned}\frac{d\ c_H/c_L}{d\ \tau_W} = & \underbrace{\frac{\partial c_H/c_L}{\partial \tau_W} + \sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \tau_W}}_{\frac{d\ c_H/c_L}{d\ \tau_W}\big|_{\text{RE}}} \\ & + \underbrace{\sum_{j\in H,L}\left(\frac{\partial c_H/c_L}{\partial w_H}\frac{\partial w_H}{\partial h_j} + \frac{\partial c_H/c_L}{\partial w_L}\frac{\partial w_L}{\partial h_j}\right)\frac{\partial h_j}{\partial \tau_W}}_{\frac{d\ c_H/c_L}{d\ \tau_W}\big|_{\text{HC}}},\end{aligned} \tag{2.25}$$

$$\begin{aligned}\frac{d\ c_H/c_L}{d\ \tau_R} = & \underbrace{\frac{\partial c_H/c_L}{\partial w_H}\frac{\partial w_H}{\partial \tau_R} + \sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \tau_R}}_{\frac{d\ c_H/c_L}{d\ \tau_R}\big|_{\text{RE}}} \\ & + \underbrace{\sum_{j\in H,L}\left(\frac{\partial c_H/c_L}{\partial w_H}\frac{\partial w_H}{\partial h_j} + \frac{\partial c_H/c_L}{\partial w_L}\frac{\partial w_L}{\partial h_j}\right)\frac{\partial h_j}{\partial \tau_R}}_{\frac{d\ c_H/c_L}{d\ \tau_R}\big|_{\text{HC}}}.\end{aligned} \tag{2.26}$$

Redistribution channel Within the redistribution channel, we can identify distinct mechanisms through which taxation affects consumption inequality. Consid-

[11] The consumption ratio for young and old agents is the same due to the constant saving rate under log utility.

ering a marginal increase in the labor tax, τ_W, we can distinguish three effects:

$$\left.\frac{d\ c_H/c_L}{d\ \tau_W}\right|_{\text{RE}} = \underbrace{\frac{\partial\ c_H/c_L}{\partial\ \tau_W}}_{\text{RE}_W(1)} + \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_W}}_{\text{RE}_W(2)}$$
$$+ \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j'\in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j''\in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_W}}_{\text{RE}_W(3)}, \tag{2.27}$$

where $\text{RE}_W(1)$ captures the direct negative effect on *disposable income*; $\text{RE}_W(2)$, the *tax rate* effect, positively affecting transfers due to the higher tax rate; and $\text{RE}_W(3)$, the *tax base* effect that increases transfers through the positive effect on wages driven by the higher education spending.[12] We can show (see Appendix 2.B) that:

$$\left.\frac{d\ c_H/c_L}{d\ \tau_W}\right|_{\text{RE}} < 0 \qquad \Longleftrightarrow \qquad \omega > \frac{w_L L}{w_L L + w_H(1-\eta)H} \equiv \tilde{\omega}. \tag{2.28}$$

Accordingly, the redistribution channel works to reduce consumption inequality if the share of transfers given to low-skilled workers is sufficiently high, namely exceeding their relative share of labor income. Intuitively, this means that if the low-skilled workers get more transfers than their contribution to the government budget through labor taxes, then their relative consumption increases.

Consider now a marginal change in the robot tax, τ_R. As for the labor tax, we can distinguish three effects: the effect on high-skilled workers' wages and consumption arising due to their *complementarity* in production to machines, $\text{RE}_R(1)$; the *tax rate* effect, $\text{RE}_R(2)$; and the *tax base* effect, $\text{RE}_R(3)$, which unfold in analogy to the case of the labor tax:

$$\left.\frac{d\ c_H/c_L}{d\ \tau_R}\right|_{\text{RE}} = \underbrace{\frac{\partial\ c_H/c_L}{\partial\ w_H}\frac{\partial\ w_H}{\partial\ \tau_R}}_{\text{RE}_R(1)} + \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_R}}_{\text{RE}_R(2)}$$
$$+ \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j'\in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j''\in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_R}}_{\text{RE}_R(3)}. \tag{2.29}$$

[12] As $\text{RE}_W(3)$ rests on the interaction of human capital and transfers, it could in principle also be subsumed under the human capital channel. Abstracting from the intensive margin of human capital formation, $\text{RE}_W(3)$ disappears; condition (2.28) holds identically also in this case.

As for the labor tax, $\text{RE}_R(2)$ and $\text{RE}_R(3)$ are negative if low-skilled workers obtain proportionally more transfers relative to their labor income share than the high-skilled workers, i.e., if $\omega > \tilde{\omega}$. However, differently from the labor tax, $\text{RE}_R(1)$ is always negative since the robot tax affects disposable income not uniformly across the two skill groups, but instead has a direct negative effect only on the wages of the high-skilled workers and no direct effect on the wages of the low-skilled workers. This implies that $\omega > \tilde{\omega}$ is a sufficient (but not necessary) condition for the redistribution channel to reduce inequality through a change in the robot tax. Since this condition is sufficient for the redistribution effect to reduce consumption inequality through τ_R, while it is a necessary condition for τ_W, the robot tax is more redistributive. Intuitively, since the robot tax directly affects the wages of high-skilled workers only, while the labor tax has a symmetric direct effect on the wages of low- and high-skilled workers, the robot tax has a stronger redistributive effect. We can summarize these results with the following proposition.

Proposition 2.3.1. *An increase in taxation reduces consumption inequality, c_H/c_L, through the redistribution channel (RE) if $\omega > \tilde{\omega}$. This is a necessary condition for the linear labor tax, τ_W, and a sufficient condition for the ad-valorem robot tax, τ_R.*

Proof. See Appendix 2.B. □

Human capital channel To highlight the human capital channel, we abstract from transfers by assuming $\phi = 1$.[13] The consumption ratio then simplifies to:

$$\frac{c_H}{c_L} = (1-\eta)\frac{w_H}{w_L}. \tag{2.30}$$

Within the human capital channel, considering a marginal increase of either labor or robot taxes, we can distinguish two mechanisms, for $g \in \{W, R\}$: the direct human capital effect on wages via increased *education spending*, $\text{HC}_g(1)$; and the additional human capital effect on wages via increased *R&D activity* and machine intensity $\tilde{A}$, $\text{HC}_g(2)$. Specifically, we have:

$$\left.\frac{d\ w_H/w_L}{d\ \tau_g}\right|_{\text{HC}} = \underbrace{\frac{\partial w_H/w_L}{\partial h_H/h_L}\frac{\partial h_H/h_L}{\partial \tau_g}}_{\text{HC}_g(1)} + \underbrace{\frac{\partial w_H/w_L}{\partial \tilde{A}}\frac{\partial \tilde{A}}{\partial h_H}\frac{\partial h_H}{\partial \tau_g}}_{\text{HC}_g(2)}. \tag{2.31}$$

[13] This is without loss of generality as the effects via transfers are already captured within the redistribution channel.

We find that an increase in taxes (labor or robot) always increases the human capital ratio, h_H/h_L. This result is driven by the assumption of a hierarchical education system. Indeed, while an increase in the spending for basic education benefits the human capital of both types of workers, an increase in spending in higher education only benefits the human capital of high-skilled workers. Therefore, an increase in aggregate education spending financed by increased taxation leads to an increase in both basic and college education spending, which benefits mostly the high-skilled workers. This implies that $\text{HC}_g(1)$ is always positive. Also, the second term, $\text{HC}_g(2)$, is always positive as an increase in the human capital of high-skilled workers – via the R&D process – leads to higher machine intensity, $\tilde{A}$, and thus – via their complementarity in production – to higher wages of high-skilled workers. This implies that higher taxes (labor or robot) unambiguously increase the wage ratio w_H/w_L and hence consumption inequality through the human capital channel. The following proposition summarizes these findings.

Proposition 2.3.2. *An increase in taxation via the linear labor tax, τ_W, or the ad-valorem robot tax, τ_R, unambiguously increases consumption inequality, c_H/c_L, through the human capital channel (HC).*

Proof. See Appendix 2.B. □

Since the redistribution channel reduces consumption inequality in the empirically relevant situation in which low-skilled workers receive proportionally more transfers, while the human capital channel always increases consumption inequality, the overall effect of taxation is ambiguous. We therefore proceed with a quantitative exercise for a calibrated environment to determine the net effect of a change in tax policy on inequality. To simultaneously analyze the effect on production growth, we also take into account the endogenous household response in terms of educational choices (extensive margin of human capital formation) and individual labor supply. That is, we allow for adjustments in the ability threshold a^* and calibrate $\gamma > 0$. Although these general equilibrium adjustments modify the precise nature of the redistribution and the human capital channels, their sign is preserved.

2.4 Calibration and model dynamics

2.4.1 Calibration

We calibrate our model to the US economy of the year 2020 and assume that each model period corresponds to 25 years. The model has 19 parameters, eleven of which are set externally and eight internally calibrated. On top of these, we specify fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega_t(\rho)\}$ assuming time-invariant tax rates and public education spending shares, and allowing the share of transfers to low-skilled agents to vary to maintain a constant progressivity level, ρ, of the tax-and-transfer system.

External calibration We set $\beta = 0.55$, corresponding to an annual discount factor of about 0.98. The parameter $\gamma = 1.44$ is set to match the average US gross saving rate of 0.184 from 1996-2020 (US Bureau of Economic Analysis, 2023). The elasticity of output with respect to effective human labor that can easily be automated is set in line with Prettner and Strulik (2020) who propose a value of $\alpha = 0.80$.[14] Following Prettner and Strulik (2020), we assume that a) innate learning abilities are normally distributed with a mean $\mu_a = 100$ and standard deviation $\sigma_a = 15$ mimicking the empirically observed IQ distribution, b) only half of the population has the potential to obtain higher education, i.e., $\underline{a} = 100$, and c) the fraction of time that high-skilled workers need to spend in higher education is $\eta = 0.11$. The size of one generation is normalized to $N = 1000$. The intertemporal knowledge spillover parameter ($\lambda_1 = 0.67$) and the congestion externality parameter ($\lambda_2 = 0.44$) are set in line with the estimates for knowledge production in a class of semi-endogenous growth models obtained by Coe and Helpman (1995), Bottazzi and Peri (2007) and McMorrow and Röger (2009). The interest rate factor $\bar{R} = 2.32$ is set to match the average (annual) real interest rate for the US from 1996-2020 of 3.43 percent (World Bank, 2023).

Internal calibration The remaining parameters are internally calibrated by minimizing the quadratic distance between model moments and empirically observed targets. The R&D productivity parameter δ, the disutility parameters for educational effort (ψ_1 and ψ_2) and the parameters governing the effectiveness of the education system (μ_B, μ_H, B and B_H) are set to fit the following seven targets: human capital

[14] This value is justified based on information from the International Federation of Robotics (Müller, 2024) indicating a 60 percent decline in the quality-adjusted price of robots between 1993 and 2005 together with an increase in the stock of robots by about 300 percent over the same period. From (2.12), the implied price elasticity of robot demand of 5 then pins down $\alpha = 0.8$.

Table 2.1: Parameters for the baseline model.

External		Internal		Policy	
Parameter	Value	Parameter	Value	Parameter	Value
β	0.55	δ	0.584	τ_W	0.28
γ	1.44	ψ_1	0.479	τ_R	0.05
α	0.80	ψ_2	17.09	ϕ	0.27
μ_a	100	μ_B	0.354	ϕ_B	0.78
σ_a	15	μ_H	0.223	ρ	0.18
$\underline{a}$	100	B	1.720		
η	0.11	B_H	6.236		
N	1000	A_0	87.3		
λ_1	0.67				
λ_2	0.44				
$\bar{R}$	2.32				

Note: See text for details.

level of the high-skilled individuals in year 2020 normalized to unity; share of college graduates of 34.7 percent in the year 2020 (US Census Bureau, 2023b); college wage premium of 1.86 in 2020 (US Census Bureau, 2023a);[15] average annual TFP growth rate for 1996-2020 of approximately 0.91 percent (OECD, 2022a); employment share in the R&D sector of around 1 percent in year 2020 (OECD, 2023d); average elasticity of low-skilled wages with respect to per-capita spending on basic education of 0.54 (Jackson et al., 2015);[16] and average elasticity of college education with respect to its price of 1.2 (Dynarski, 2003).[17] Finally, we ex-post set A_0, the level parameter representing the technological frontier of the economy in the initial model period, to 87.3 to minimize the loss from the internal calibration.

Policy parameters The baseline configuration of fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega_t(\rho)\}$ is determined as follows: The average labor income tax rate ($\tau_W = 0.28$) is taken from OECD (2022c) and the average robot tax ($\tau_R = 0.05$) is set in line with Ace-

[15]The college wage premium is calculated as the ratio of the mean annual earnings of the total population with a Bachelor's degree relative to high school graduates.

[16]Jackson et al. (2015) find that a 10 percent increase in per-pupil spending in each year for all 12 years of public school leads to about 7 percent higher wages. Since this effect captures a mix of low-skilled and high-skilled wages, we use the college share and the college premium reported above to infer the effect on low-skilled individuals only. This results in an elasticity of $0.7/(0.653 + 0.347 \times 1.86) = 0.54$.

[17]Dynarski (2003) studies the effects of financial aid on college enrollment and estimates the elasticity of college *attendance* with respect to overall schooling costs (comprising both the direct cost of tuition and the opportunity cost of foregone earnings) at about 1.5. In order to arrive at the relevant elasticity measure for college *completion*, thus taking into account the effect of drop-outs, we exploit information on the additional years of education generated by financial aid, which are also reported by Dynarski (2003). The downward adjustment results in an elasticity of college completion of about 1.2.

moglu et al. (2020).[18] The share of government spending on education used for higher (college) education amounts to 0.89 percent of GDP in the US for the year 2019, whereas the share spent on basic (primary and secondary) education is 3.22 percent for the same year (OECD, 2023c). Therefore, total government spending on education amounts to 4.11 percent of GDP, with a share of basic education spending of total government spending on education of $\phi_B = 0.78$. We observe in the data that total social spending relative to GDP net of public pension payments makes up a share of 11.17 percent in 2019 (OECD, 2023e,b). Summing up both parts of the government budget and calculating the share of government spending on education within total government spending then leads to $\phi = 0.27$. The share of total lump-sum transfer payments to low-skilled individuals, ω_t, is specified as time-varying and set such that the implied progressivity of the model's tax-and-transfer system is constant over time and in line with $\rho = 0.18$, the value estimated for the US by Heathcote et al. (2017).[19]

2.4.2 Model validation

The parameters used for the initial calibration are summarized in Table 2.1. Table 2.2 reports the fit of the calibrated baseline model to the respective moments in the data. Six out of seven moments are matched exactly. The only exception is the employment share in the R&D sector, which the model predicts at a value of 1.69 percent for the year 2020, relative to a value of 1 percent in the data. As the model abstracts from the use of capital in the R&D sector, this is a natural outcome of the model economy, as the importance of human labor is overstated by assumption.

Figure 2.1 provides further validation of the model by comparing the inferred

[18] Acemoglu et al. (2020) estimate time paths of effective tax rates on different types of capital (structures, software and equipment) computed from effective tax rates on capital and depreciation allowances for C-corporations, S-corporations and other pass-through businesses, and the differential taxation of capital financed with debt and equity. We use the 2018 value for the estimated tax rate on software and equipment of around 5 percent. The estimated tax rate on structures is slightly higher (around 7 percent). Therefore, our parameter choice is located at the lower end of the spectrum for the capital tax in the US in 2018.

[19] In detail, we calculate the discrete elasticity of post-government ($\tilde{y}_{i,t}$) to pre-government ($y_{i,t}$) earnings; this elasticity is then evaluated at the low-skilled income level, with ω_t adjusting such that the following condition is fulfilled in each period,

$$\frac{\Delta \tilde{y}_{i,t}}{\Delta y_{i,t}} \frac{y_{i,t}}{\tilde{y}_{i,t}} = \frac{(1-\tau_{W,t})[w_{H,t}\tilde{h}_t - w_{L,t}\tilde{l}_t] + [\hat{T}_{H,t} - \hat{T}_{L,t}]}{[w_{H,t}\tilde{h}_t - w_{L,t}\tilde{l}_t]} \frac{w_{L,t}\tilde{l}_t}{(1-\tau_{W,t})w_{L,t}\tilde{l}_t + \hat{T}_{L,t}} = 1 - \rho = 0.82,$$

where $\hat{T}_{L,t} = \omega_t \cdot \frac{T_t}{L_t}$, $\hat{T}_{H,t} = (1-\omega_t) \cdot \frac{T_t}{H_t}$, and $\tilde{h}_t$ and $\tilde{l}_t$ denote the effective individual labor supply of high-skilled and low-skilled workers, respectively.

Table 2.2: Goodness of fit of the baseline model.

Target	Data	Model
high-skilled human capital (normalization)	1.00	1.00
college share (%)	34.7	34.7
R&D employment share (%)	1.00	1.69
college wage premium	1.86	1.86
elasticity of college attendance wrt. its overall price	1.20	1.20
elasticity of low-skilled wages wrt. p.-c. spending on lower educ.	0.54	0.54
TFP growth (annual, %)	0.91	0.91

Note: See text for details.

dynamics from the baseline calibration (blue solid lines) with actual US observations from 1970 to 2020 (red dotted lines). The model predicts a smooth positive trend in average TFP growth over time, which broadly aligns with real-world observations. Additionally, it captures the significant increase in the stock of robots used in production, a trend also evident in empirical data.[20] The model also captures the rise in the proportion of the population pursuing higher education, with the 2020 value serving as a targeted moment in the endogenous calibration routine. While the model does not precisely replicate the exact R&D employment share due to the absence of capital in this sector, it successfully captures the overall growth trend of R&D employment over time. Moreover, the model successfully reproduces the substantial increase in the skill premium in the US over the past five decades, once again relative to the 2020 value as a targeted calibration moment. Finally, we observe increasing inequality as measured by the evolution of the (pre-tax) Gini coefficient for labor income over time, both in the model and in the data.[21] With a 15.0 percent reduction from the pre-tax to post-tax income Gini coefficient, the progressive tax-and-transfer system embedded in the model also closely replicates the observed average reduction of 16.1 percent in the data for the period 1996–2020.

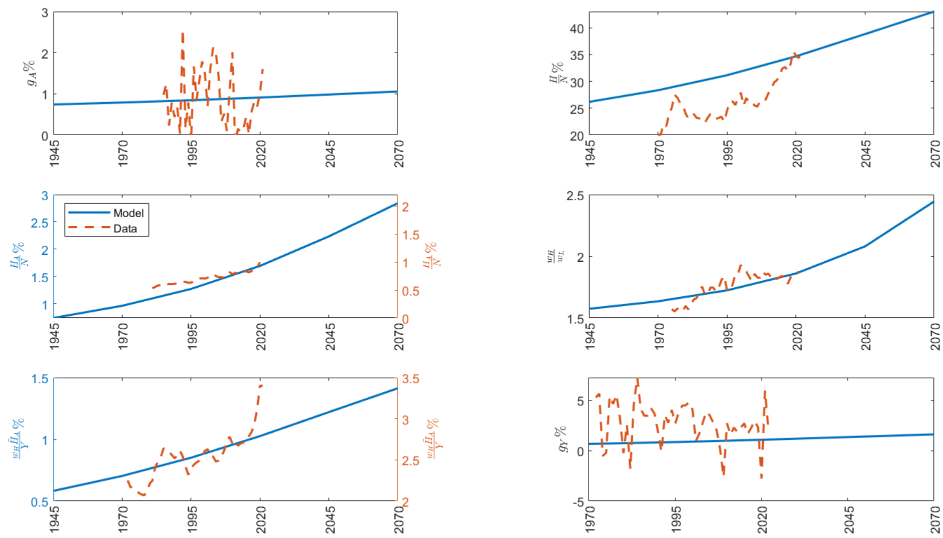
2.4.3 Model dynamics

Figure 2.2 illustrates the general equilibrium dynamics for the calibrated economy, which displays endogenous growth and endogenous skill acquisition under the baseline fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega_t(\rho)\}$. We observe that the R&D-induced productivity growth of machines leads to an exponential increase in TFP, production, and

[20] Both the number of robots in the model and in real-world data are normalized relative to their respective 2020 values.

[21] Consistent with our measure for the college wage premium, the empirical Gini coefficient is calculated based on the mean annual earnings of two population groups: high school graduates (unskilled) versus those with a Bachelor's degree (skilled).

Figure 2.1: Model validation.



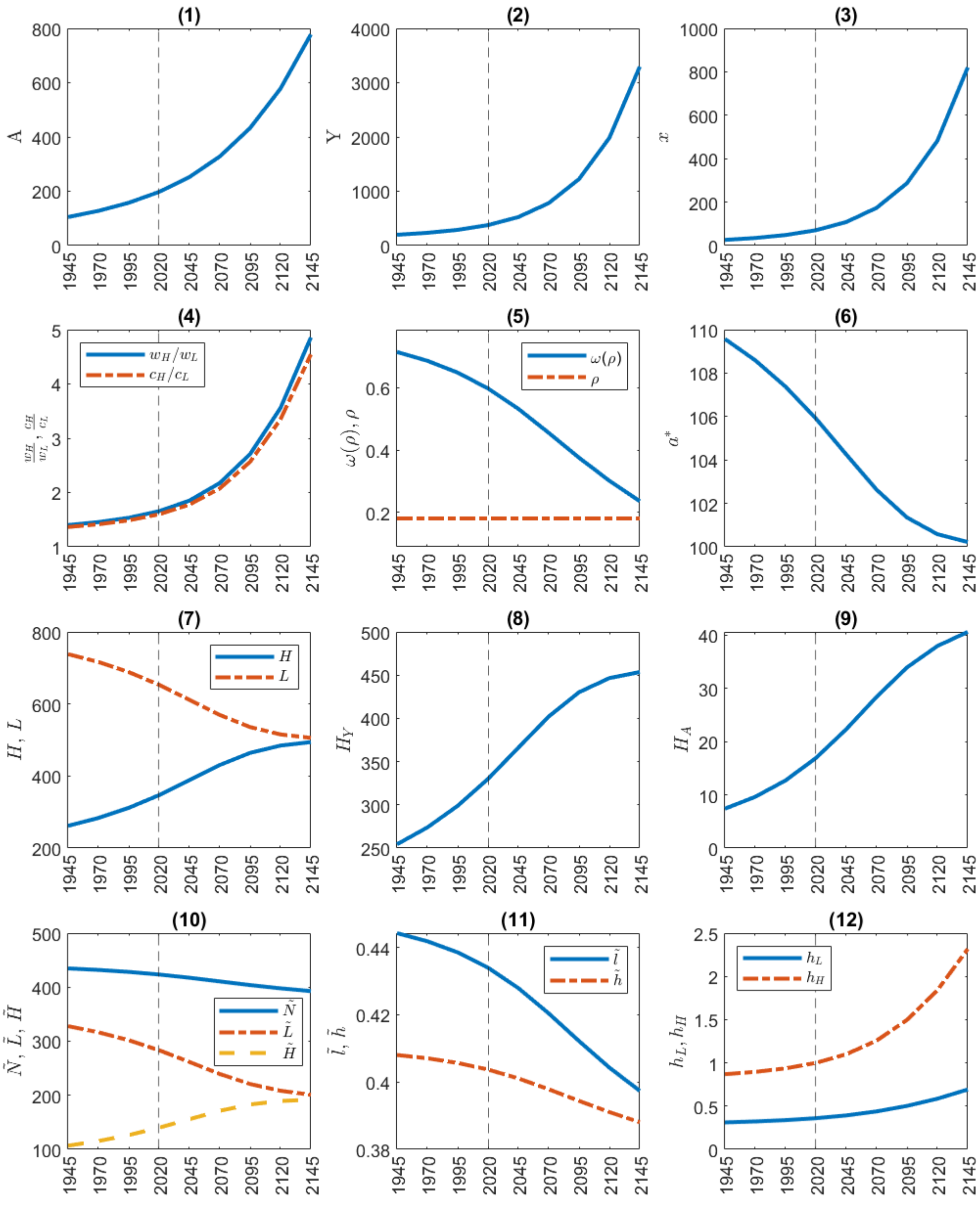
Note: Blue solid lines represent model-generated moments, while red dotted lines correspond to real-world data for the US. Model growth rates are converted to annual values, whereas real-world growth rates are shown as five-year moving averages. Data on TFP growth are taken from OECD (2022a), on the stock of robots from Müller (2024), on the college share from US Census Bureau (2023b), on the R&D employment share growth from OECD (2023d), and the skill premium and the Gini coefficient for labor income are calculated based on data from US Census Bureau (2023a). See text for details.

automation (i.e., the use of machines in the final production sector) over time. Due to workers' different degrees of complementarity with machines, the increased productivity of machines disproportionally benefits the high-skilled workers, exponentially increasing the skill premium measured via the pre-tax ratio of high- to low-skilled wages, w_H/w_L. Although the tax-and-transfer system is progressive, the consumption ratio c_H/c_L (equivalent to the after-tax and transfer income ratio) follows a similar pattern. Throughout, post-government income inequality is slightly smaller than its pre-government value as transfers are used to redistribute resources from high- to low-skilled individuals.

The increase in the skill premium creates stronger incentives to undertake education (extensive margin of human capital formation) leading to a reduction in the number of low-skilled workers. As the share of low-skilled workers declines, the share of transfers to low-skilled agents, ω_t, declines as well to keep the progressivity level constant. Vice versa, the number of high-skilled workers increases in both the final production and R&D sectors.

Changes in the composition of the type of workers are also accompanied by adjustments in the individual labor supply affecting the aggregate supply of labor,

Figure 2.2: Model dynamics.



Note: The model is calibrated to the US economy in 2020. See text for details.

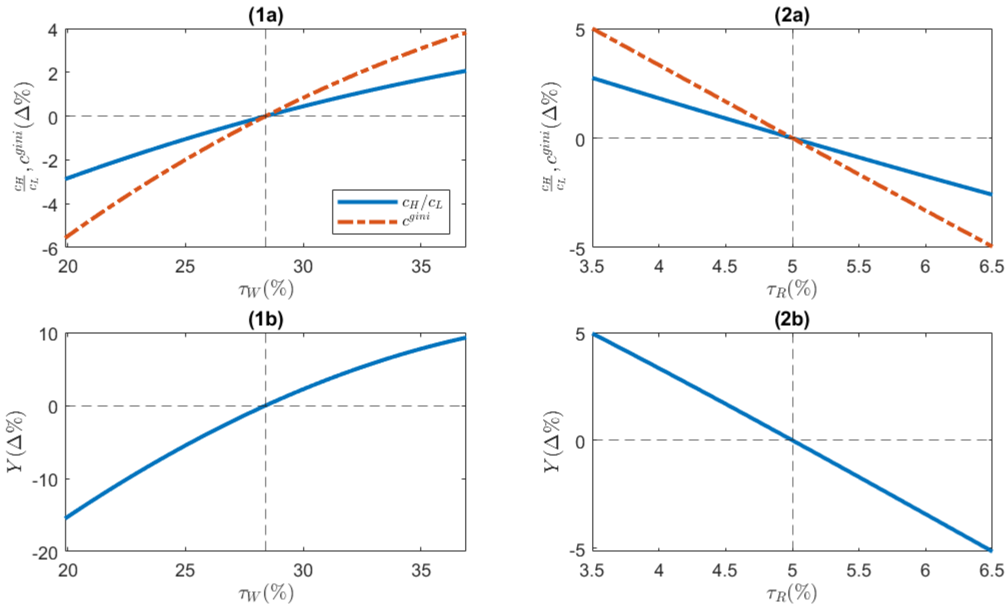
$\tilde{N}$. While the individual labor supply of high-skilled workers, $\tilde{h} \equiv 1-\eta-z_H$, exhibits a modest decline over time, the individual labor supply of low-skilled workers, $\tilde{l} \equiv 1-z_L$, decreases more substantially as the increase in the per-capita transfers, driven by economic growth, mostly affect low-skilled workers. Although the individual supply of high-skilled labor slightly declines, aggregate high-skilled labor supply $\tilde{H}$ rises, driven by the higher number of high-skilled individuals over time. The opposite is true for the aggregate labor supply of low-skilled individuals, $\tilde{L}$, driven by a decline in both individual labor supply and the number of low-skilled workers in the economy. Summing the effects across the two skill groups, we observe a mild contraction in aggregate labor supply.

Finally, human capital increases over time for both low- and high-skilled individuals (intensive margin of human capital formation). Indeed, under the baseline fiscal policy, education spending is a constant fraction of GDP and, as production expands over time, the spending on both basic and higher education increases, leading to an increase in human capital. The human capital gradient h_H/h_L rises over time, confirming the argument from the partial equilibrium analysis that higher education spending under a hierarchical education system creates higher inequality as it disproportionally benefits high-skilled individuals. There exists, therefore, a fundamental trade-off between higher economic growth and lower inequality.

2.5 Tax policy

In view of the above trade-off, we proceed by examining the implications of different tax policies for production growth and inequality within our general equilibrium framework. We, initially, consider the effect of one-dimensional tax policy interventions (an exogenous change in either the labor or the robot tax) on production growth and inequality. We, then, consider coordinated two-dimensional tax policy packages (a combined change in both taxes) highlighting the scope for tax policies that can reduce inequality without harming production growth. We, finally, characterize the dynamic optimal tax policy maximizing aggregate welfare and provide a decomposition exercise to examine the underlying determinants of the optimal tax structure.

Figure 2.3: One-dimensional tax policy interventions.



Note: Percentage deviations of inequality (first row) and production (second row) in 2045 from the baseline situation for a change in either the labor tax (first column) or the robot tax (second column).

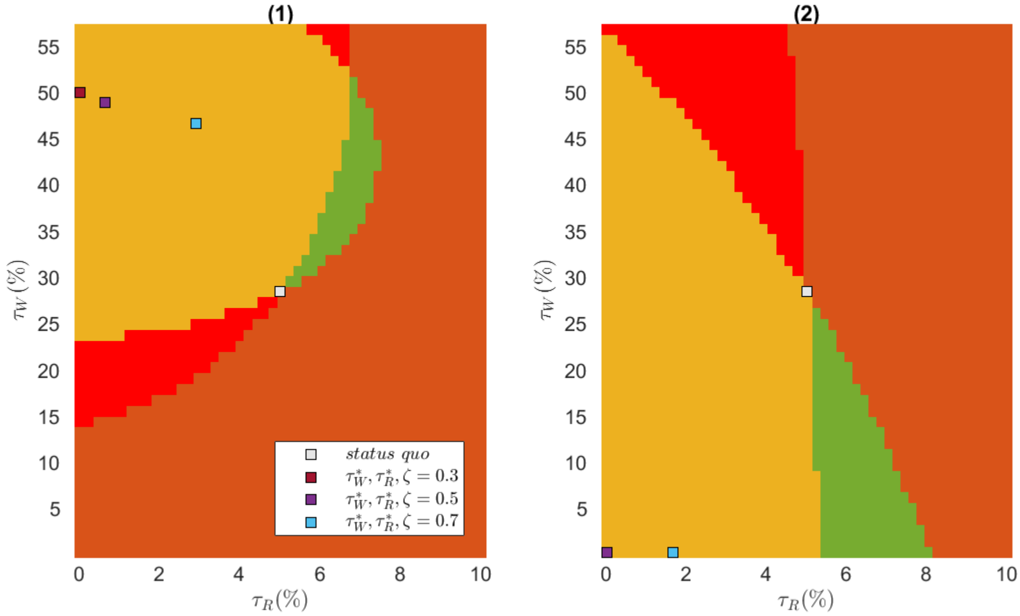
2.5.1 Exogenous tax policy

Figure 2.3 shows the effect of one-dimensional tax policy interventions (a change in either the labor or the robot tax) on inequality – measured alternatively in terms of the consumption ratio (high-skilled relative to low-skilled) or the Gini coefficient – and production growth.[22] We observe that increasing the labor tax compared to the initially calibrated situation leads to a rise in inequality (panel 1a), while increasing the robot tax has the opposite effect (panel 2a). For the labor tax, the human capital channel thus dominates the redistribution channel, whereas the reverse is true for the robot tax. This general equilibrium result is in line with the theoretical proposition from Section 2.3 showing that the robot tax is the more redistributive tax. The increase in either the labor or the robot tax, however, entails a fundamental trade-off between production growth and equality. We, indeed, observe that the increase in the labor tax increases both inequality (panel 1a) and production growth (panel 1b), while the increase in the robot tax reduces both (panels 2a and 2b).

Figure 2.4 considers coordinated two-dimensional tax policy packages (changes in both the labor and robot tax). Panel 1 shows the effect on production growth and inequality of different tax reforms in the year 2045 relative to the status quo

[22]In addition to inequality at the individual level, the Gini coefficient also reflects composition effects across the two skill groups.

Figure 2.4: Coordinated two-dimensional tax policy packages.



Note: Panel 1: economy with intensive margin human capital formation. Panel 2: counterfactual without intensive margin human capital formation. Grey dot: status quo calibrated to the US economy for 2045; in green: benign region (higher production, lower inequality); in red: unwelcome region (lower production, higher inequality); in yellow and orange: trade-off regions (higher production, higher inequality – in yellow; lower production, lower inequality – in orange). The red-burgundy, purple, and light blue dots, respectively, represent the welfare-maximizing labor and robot tax for different welfare weights of the social planner, $\zeta \in \{0.3, 0.5, 0.7\}$.

(grey dot), highlighting four different regions: two trade-off regions, in which production and inequality both increase (yellow) or reduce (orange); the benign region, in which production increases and inequality reduces (green); and finally the region with unwelcome consequences along both dimensions (red). As seen, there exists a combination of higher labor and robot taxes that leads to both higher production and lower inequality, thus breaking the production growth-equality trade-off entailed in the one-dimensional policy reforms.[23]

Panel 2, instead, shows the effect of a coordinated two-dimensional tax reform for a counterfactual economy in which we abstract from the intensive margin of human capital formation keeping the extensive margin of human capital formation (endogenous skill choice) active as in Prettner and Strulik (2020). In particular, we exogenously fix the time paths of both low- and high-skilled human capital before the tax adjustment, thus eliminating the endogenous response of human capital at

[23] For a moderate increase in both the labor and the robot tax (green region), the positive effect of a higher labor tax on production growth is stronger than the negative effect of the higher robot tax, and the positive effect of the higher labor tax on inequality is more than compensated by the reduction in inequality due to the increase in the robot tax.

the intensive margin to changes in fiscal policy. For this model without human capital formation at the intensive margin, we observe that a joint increase in both taxes would necessarily lead to lower production growth and inequality as taxation is purely redistributive and does not entail a productivity-enhancing effect through the intensive margin of human capital formation.

2.5.2 Optimal tax policy

As a simultaneous increase in both labor and robot taxes can lead to an increase in production and a reduction in inequality when we consider the intensive margin of human capital formation, we can now think about the welfare-optimizing tax policy within this framework. We consider the following welfare function:

$$\Omega_t = \zeta \cdot \underbrace{\mathcal{F}(a_t^*) \cdot N}_{=L_t} \cdot \mathcal{U}_{L,t} + (1-\zeta) \cdot \underbrace{(1-\mathcal{F}(a_t^*)) \cdot N}_{=H_t} \cdot \mathcal{U}_{H,t}, \tag{2.32}$$

where $\zeta \in [0, 1]$ is the weight that the social planner places on the welfare of the low-skilled workers implicitly measuring the planner's preference for equality relative to production growth.[24] We focus on the optimal combination of labor and robot taxes while keeping the progressivity level of the tax-and-transfer system constant.[25]

Figure 2.4, panel 1 shows that for the utilitarian welfare weight, i.e., $\zeta = 0.5$ (purple dot), the welfare-optimizing tax policy implies increasing the labor tax and lowering the robot tax (though not to zero) relative to the situation in 2045; this policy leads to higher production at the cost of higher inequality. A similar pattern also applies under different levels of ζ, namely $\zeta = 0.3$ (red-burgundy dot) and $\zeta = 0.7$ (light blue dot).[26]

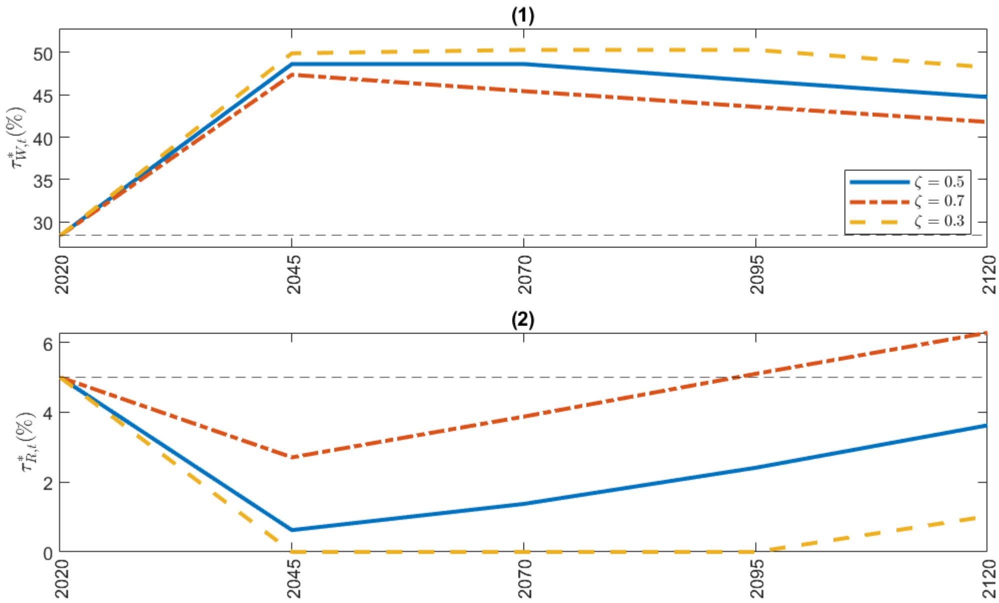
Figure 2.5 complements this analysis by detailing the dynamics of the optimal

[24] To ease the comparison with the results in Prettner and Strulik (2020), we follow their metric for welfare optimality. Different from the standard Ramsey problem, the welfare function in (2.32) is static in the sense that it neglects the dynamics of A_t. It can be rationalized, however, as emerging from a political economy framework where policy is determined such as to maximize the lifetime utility of the generations currently alive. As the model abstracts from a pension system and the interest rate is exogenous, the utility of the current old generation is actually invariant to the policy set in the current period. Hence, the optimal tax policy can be determined by considering only the lifetime utility of the current young generation.

[25] As a robustness check, we analyze the optimal tax policy under varying degrees of progressivity. An increase in the progressivity level makes the tax-and-transfer system more redistributive, calling for a slight reduction in the robot tax for future periods (see Appendix 2.D).

[26] Notice that the competitive equilibrium delivers too little R&D relative to a planner solution which internalizes the effects of monopoly markups, intertemporal knowledge spillovers and congestion externalities. So there is no built-in efficiency rationale favoring a positive robot tax.

Figure 2.5: Dynamic optimal tax policy.



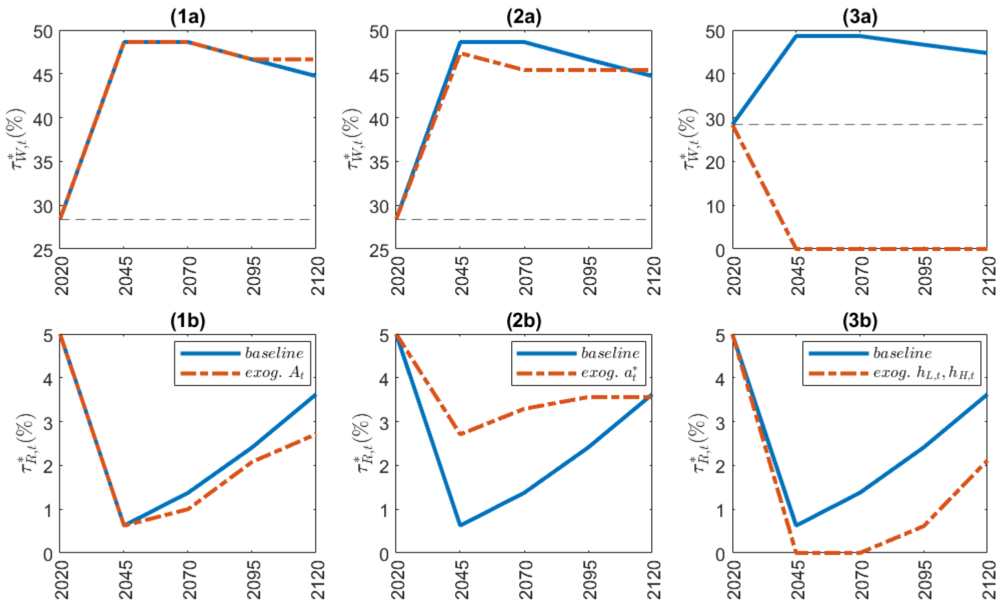
Note: Panels 1 and 2 show the welfare-optimizing labor tax and robot tax, respectively, dependent on the welfare weight, $\zeta \in \{0.3, 0.5, 0.7\}$. Values for the year 2045 correspond to the respective dots in Figure 2.4, panel 1.

tax system over time. Initially, the planner should substantially increase the labor tax (panel 1) and reduce the robot tax (panel 2) relative to the baseline situation in 2020. This policy fosters economic growth by boosting human capital formation at both the intensive and extensive margins and increasing the incentives to invest in R&D which boosts machines' productivity. In later periods, the government should then progressively increase the robot tax and reduce the labor tax to mitigate the increasing wage gap. This result crucially depends on the intensive margin of human capital formation. In a model without this intensive margin (Prettner and Strulik, 2020), indeed, we observe that, although the optimal robot tax may in principle be positive depending on the welfare weights, it is generally zero or very close to zero due to its adverse growth effects. In our model in which we consider the intensive margin of human capital formation, instead, the optimal robot tax becomes significantly positive following the initial policy change.[27] The underlying reason is that the revenue from the robot tax can be used to fund (i) productive education spending and (ii) redistributive transfers. Compared to the labor tax, the robot tax is the more effective tool for redistribution (cf. Section 2.3). Accordingly, as the planner's preference for equality increases from $\zeta = 0.5$ to $\zeta = 0.7$, the pattern of the optimal

[27]The tax rates displayed in Figure 2.5 correspond to a revenue share coming from the robot tax of around 9% in 2045, rising to 28% in the long run.

tax policy shifts away from the labor tax towards the robot tax.

Figure 2.6: Decomposition of the optimal tax policy.



Note: Blue solid lines represent the baseline model, i.e., full adjustment of technological progress, extensive margin of human capital adjustment (share of low- and high-skilled workers), and intensive margin of human capital adjustment. Red dash-dotted lines in panels 1a and 1b represent the model in which the time path of technological progress is exogenous; red dash-dotted lines in panels 2a and 2b represent the model in which the time path of the extensive margin of human capital is exogenous; red dash-dotted lines in panels 3a and 3b represent the model in which the time path of the intensive margin of human capital is exogenous.

Decomposition Figure 2.6 presents a decomposition analysis of the relevant margins – technological progress, extensive margin of human capital (education decision), and intensive margin of human capital formation – determining the optimal tax policy. Panels 1a and 1b describe the optimal tax policy when technological progress, A, is not affected by the change in policy (red dash-dotted lines), compared to the baseline model in which all the variables are endogenously determined (blue solid lines).[28] The profile of optimal taxation under an exogenous time path of technological progress differs from the optimal baseline policy and entails a lower rate for the robot tax and a higher rate for the labor tax. This is because the initial drop of the robot tax in the baseline model induces a higher rate of technological progress (higher A) which, in turn, increases inequality. By contrast, under

[28]The time path of technological progress, A, is exogenous and equals the time path that would have prevailed under the constant calibrated policy ($\tau_W = 0.28$, $\tau_R = 0.05$). The same strategy also applies to our experiments when abstracting from the extensive margin of human capital (i.e., we assume exogenous skill choice), and the intensive margin of human capital formation.

exogenous technology, this mechanism is shut down, implying a reduced need to redistribute and hence a lower robot tax.

Panels 2a and 2b examine the case in which the time path of the number of high- and low-skilled workers, L and H, is exogenously determined (by fixing the time path of a^*) and does not react to changes in taxation (red dash-dotted lines), compared to the baseline model. As seen, the welfare-optimal robot tax is higher and the welfare-optimal labor tax is lower under exogenous skill choice. In this case, since education decisions do not respond to the initial drop in the robot tax, the number of high-skilled workers is lower than in the baseline model with endogenous skill choice. The corresponding higher number of low-skilled workers thus calls for increased redistribution, which is achieved via a higher robot tax.

Panels 3a and 3b again illustrate the different redistributive nature of the labor and the robot tax. The red dash-dotted lines depict optimal taxes when the path for human capital, h_L and h_H, is exogenously determined, compared to the baseline model with endogenous adjustment. When the intensive margin of human capital formation is not operating, it is efficient to finance government spending using exclusively robot taxes. The reason is that there is no motive for education spending when human capital accumulation is exogenous. The only role of the government is thus to redistribute, and since the robot tax achieves this more effectively, the government exclusively relies on this instrument. Notice, however, that also the robot tax is optimally equal to zero for some time (here in 2045 and 2070), before it is phased in at increasingly positive values. This pattern emerges because, initially (i.e., for a relatively low state of automation, A), both taxes are optimally used only for education spending (and hence equal to zero when there is no intensive margin of human capital formation). Later, as technological progress continues and inequality raises, the optimal policy relies on taxation also for redistribution and employs the more effective tool to this end.[29]

To summarize, the decomposition analysis highlights the role of endogenous technological progress, skill choice, and intensive margin human capital formation as determinants of the optimal tax policy. While endogenous technological progress leads to a higher optimal robot tax, endogenous education decisions (extensive margin of human capital) induce adjustments in the opposite direction. Finally, the intensive

[29]In detail, the optimal robot tax is equal to zero in 2045 and 2070 and becomes positive only in later periods when the redistributive motive becomes more pressing due to the significant increase in inequality. Expressed in terms of the underlying optimal tax rates in the baseline model, the redistribution motive accounts for 0% of the robot tax in 2045 and 2070, 25.4% in 2095, and 58.3% in 2120.

margin of human capital formation is critically needed to justify a positive labor tax as part of the optimal fiscal policy; moreover, the optimal robot tax is always higher than in the counterfactual setup in which the intensive margin of human capital formation is not operating.

2.6 Education subsidies

In this section, we examine different education policies with respect to their impact on production growth, inequality, and welfare. Specifically, we consider education subsidies, defined as additional transfers to high-skilled individuals financed through either an increase in labor or the robot tax.[30] We begin with the case of *non-targeted education subsidies* (*NT-ES*) in which the additional transfers are provided to all individuals who acquire higher education, irrespective of whether they would have acquired higher education also in the absence of transfers. Given this setup, we first assume that per-capita spending for both basic and higher education is kept constant.[31] This allows us to keep constant the level of human capital acquired through basic and higher education, thus highlighting the effect of the subsidies when the human capital channel is shut down (*w/o HC*). Alternatively, we maintain the assumption that the level of per-capita spending for higher education is kept constant, but allow adjustments in the per-capita spending for basic education.[32] Accordingly, the tax-and-transfer policy now has a direct effect on human capital formation at the basic level, and – via the hierarchical education system – an indirect one at the higher level (*with HC*). Finally, we analyze the effect of *targeted education subsidies* (*T-ES*), i.e., additional transfers paid only to the marginal individuals who would not have acquired higher education in the absence of transfers, whereby we again allow for adjustments in the per-capita spending for basic education (*with HC*).

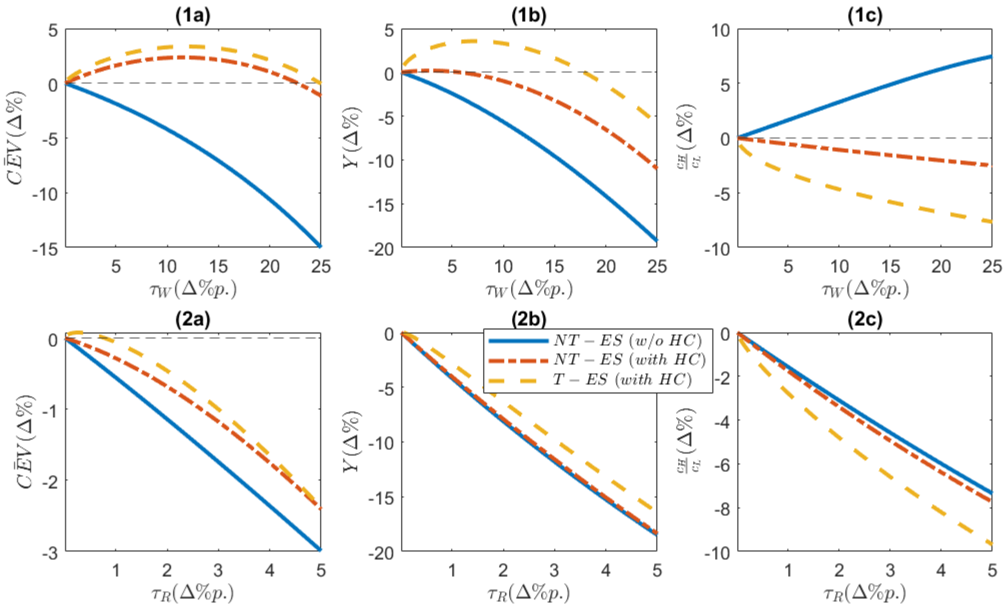
Figure 2.7 shows the effect of the different education policies on welfare in terms of average consumption-equivalent variation ($C\bar{E}V$), production growth, and inequality, contrasting the financing of the subsidies through an increase in the labor tax (panels 1a-c) or an increase in the robot tax (panels 2a-c).

[30] See Appendix 2.E for the detailed specification of the model version with education subsidies.

[31] Formally, this is achieved by fixing ω at its baseline value and letting ϕ and ϕ_B adjust to accommodate the additional transfer payments to high-skilled individuals and the induced changes in skill choice, respectively.

[32] For this scenario, ω and ϕ_B remain fixed at their baseline values, while ϕ and $\hat{E}_B$ adjust.

Figure 2.7: Education subsidies.



Note: Percentage deviations of aggregate welfare (measured as the average consumption equivalent variation, first column), production (second column), and inequality (third column) in 2045 from the baseline situation under education subsidies financed either with an increase in the labor tax (first row) or the robot tax (second row). Blue solid lines denote non-targeted education subsidies under constant per-capita spending on both basic and higher education, *NT-ES (w/o HC)*; red dash-dotted lines denote non-targeted education subsidies with adjustment of the per-capita spending on basic education, *NT-ES (with HC)*; yellow dashed lines denote targeted education subsidies with adjustment of the per-capita spending on basic education, *T-ES (with HC)*. Results are qualitatively similar when considering different levels of ζ (see Figure 2.11 and Table 2.6 in Appendix 2.E).

Labor tax-financed education subsidies When the funding for untargeted education subsidies comes from increases in the labor tax and the human capital channel is controlled for, the transfer payments have unambiguously negative welfare effects for any increase in tax rate (blue solid line, panel 1a). These adverse consequences arise due to (i) reduced production growth, caused by the distortion of labor supply under increased taxation and more generous transfer payments, and (ii) increased inequality, caused by the regressive nature of transfers to high-skilled workers (blue solid lines, panels 1b-c).

The red dash-dotted lines examine the effect of non-targeted subsidies when the human capital channel is active, i.e., part of the additional revenue from the increase in the labor tax is allocated to basic education spending. The joint effect of education subsidies, which encourage skill acquisition, and increased spending on the basic tier of the hierarchical education system is to augment the human capital of both low- and high-skilled workers. Compared to the case in which the human capital channel is not active, we therefore observe higher labor productivity and higher production growth (red dash-dotted line, panel 1b). Interestingly, we also observe reduced inequality (red dash-dotted line, panel 1c). This effect materializes despite the fact that the human capital channel itself actually works to accentuate inequality (cf. Proposition 2.3.2 and panel 1a of Figure 2.3). But the underlying fiscal system assumed in the experiment at hand builds on a fixed share ω of (non-educational) transfers going to low-skilled workers and hence responds to the increased number of high-skilled workers with a substantially increased progressivity of (non-educational) transfer payments that ultimately leads to lower inequality. Taken together, these effects on production growth and inequality give rise to an increase in welfare, with a maximum effect for an increase in the labor tax of 11.4 percentage points (red dash-dotted line, panel 1a).[33]

Although education subsidies financed by the labor tax can lead to an increase in aggregate welfare when the human capital channel is active, an untargeted policy is sub-optimal since it also rewards inframarginal individuals who would have acquired higher education also in the absence of additional transfers. Education subsidies targeted at ex-ante unskilled individuals who can actually be induced to take up higher education, indeed, lead to lower inequality and higher production growth and welfare for any change in the labor tax (panels 1a-c, yellow dashed lines). For the targeted policy, the increase in welfare reaches its peak for an increase in the labor tax of 11.9 percentage points, which is similar in terms of magnitude to the non-targeted education subsidy case.[34]

Robot tax-financed education subsidies When the funding for additional transfers comes from increases in the robot tax, all considered policy scenarios generally entail negative welfare effects, where the induced reduction in inequality is not sufficient to compensate for the lost production growth. Higher robot taxes, indeed, have strong negative implications on production growth as they reduce the incentives for automation which is the driver of economic growth. Only under targeted education subsidies a marginal increase in the robot tax can induce a slightly positive effect on welfare. However, the effect appears negligible (at least for the considered welfare weight of $\zeta = 0.5$).[35] At any rate, and despite the hierarchical

[33]The increase in the labor tax by 11.4 percentage points is welfare-maximizing, but still involves the trade-off between production and equality, as it leads to a decline in production by 1.5 percent, combined with a decline in inequality by 1.2 percent.

[34]Targeted education subsidies facilitate higher welfare gains and are also able to break the production-equality trade-off. An increase of the labor tax by 11.9 percent leads to an increase in production by 2.8 percent, combined with a decline in inequality by 5.1 percent.

[35]Results for different levels of ζ are presented in Figure 2.11 and Table 2.6 in Appendix 2.E.

nature of the education system, the labor tax robustly emerges as the preferred alternative for the financing of education subsidies, whereas raising the robot tax generally has adverse welfare consequences.

2.7 Private education spending

In the US, private spending for college education accounts for an important fraction of total spending.[36] Under such co-funding for higher education from substitutable sources, changes in tax-funded public input can have important repercussions on the private spending component. To take this channel into account, we augment our model with an endogenous decision on how much individuals want to privately invest in higher education. We, therefore, rewrite the individual budget constraint of agent $j = \{L, H\}$ as:

$$(1 - \tau_{W,t})(1 - \eta_j - z_{j,t})w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]}\, \theta_t = c_{j,t} + s_{j,t}, \tag{2.33}$$

where θ_t represents private spending in higher education, which equals zero if the individual does not acquire higher education ($j = L$) and is otherwise optimally chosen when the individual undertakes higher education ($j = H$).[37] The substitutability of private and public spending on higher education is captured via the process of human capital formation of high-skilled workers:

$$h_{H,t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \left(\epsilon \cdot (\theta_t)^{\frac{\nu-1}{\nu}} + (1-\epsilon) \cdot \left(\hat{E}_{H,t} \right)^{\frac{\nu-1}{\nu}} \right)^{\frac{\nu}{\nu-1} \cdot \mu_H}, \tag{2.34}$$

where $\nu \in (0, \infty)$ governs the elasticity of substitution between private and public spending and $\epsilon \in (0, 1)$ is the associated share parameter of the CES aggregate.[38]

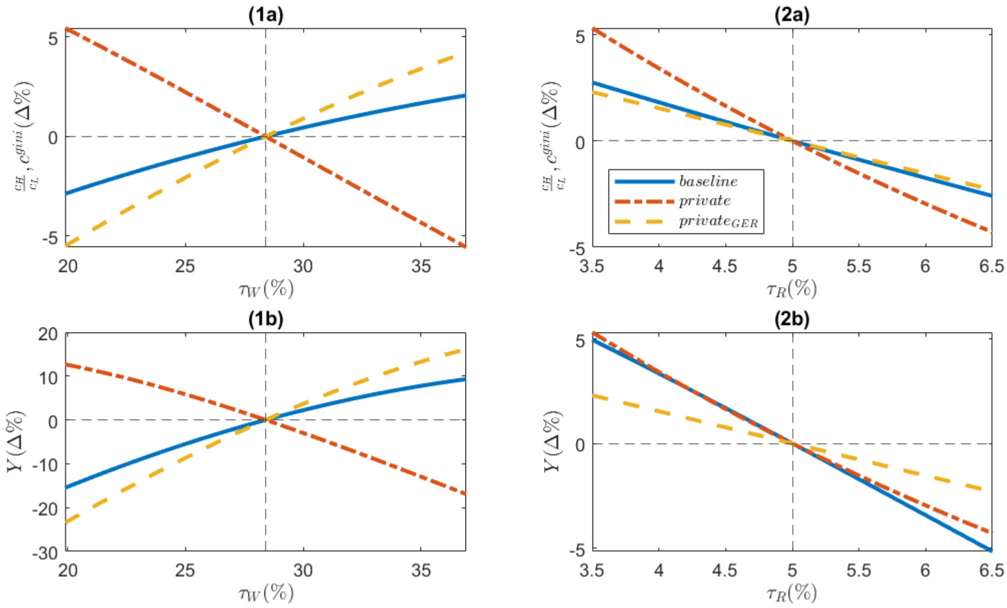
Calibration Integrating private education spending on higher education into the model necessitates modifications to the calibration strategy. The external parameters as well as the parameter A_0, which governs the technological frontier in the initial model period, remain unchanged at their baseline values. From (2.34), there are then two additional parameters to calibrate in the extended model, ϵ and ν.

[36] In 2019, private spending on college education accounted for 64.3 percent of the total (private and public) expenditure on higher education in the US (OECD, 2023f).

[37] See Appendix 2.F for details.

[38] When $\epsilon = 0$ and $\nu \to \infty$, (2.34) collapses back to our baseline specification in (2.21) without private spending on higher education.

Figure 2.8: One-dimensional tax policy interventions with private education spending.



Note: Percentage deviations of inequality (first row) and production (second row) in 2045 from the baseline situation for a variation in either the labor tax (first column) or the robot tax (second column). Blue solid lines: baseline model without private education spending; red dash-dotted lines: private spending model calibrated to the US; yellow dashed lines: private spending model for the German counterfactual.

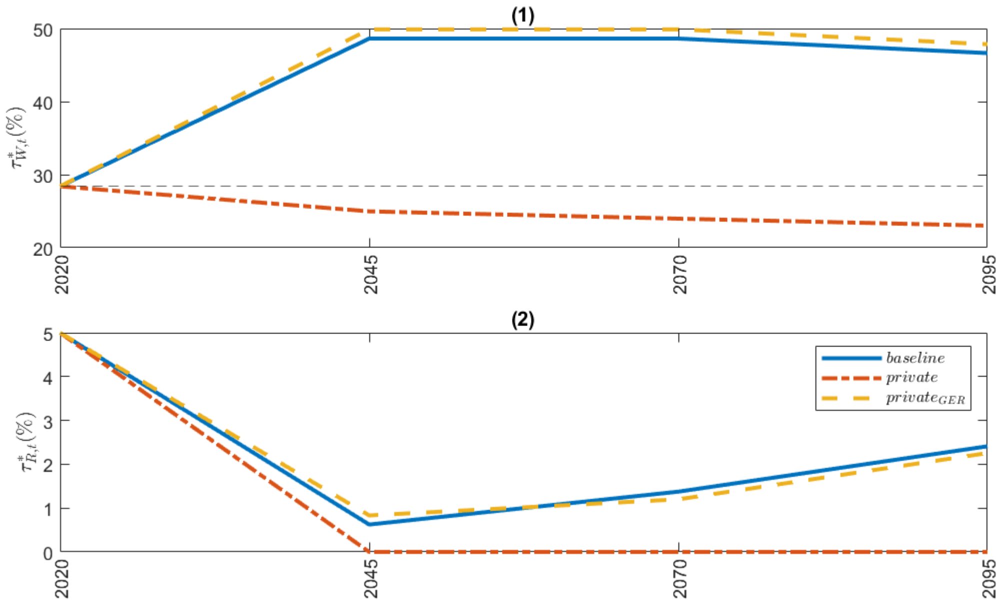
Given the relatively constant private spending share on higher education over time, we set the elasticity parameter ν to unity. The value of ϵ is then determined via internal calibration, whereby we target the average ratio of private to public higher education spending observed in the US for 2000-2019. At a value of 1.54, this ratio is significantly higher than what is observed in most European countries (OECD, 2023f).[39] To assess the implications of the different funding composition for higher education (public versus private), we, therefore, complement the US calibration with a counterfactual scenario based on a private-to-public ratio for higher education spending set in line with German data.[40]

Exogenous tax policy Including private spending for college education has important implications for the effects of tax policies. In particular, while the effects on growth and inequality remain similar when considering changes in the robot tax, results are qualitatively different when considering a change in the labor tax. Indeed,

[39] Italy, France, and Germany have average values for 2000-2019 of 0.43, 0.24, and 0.17, respectively.

[40] The calibration of the private spending model and its counterfactual version are detailed in Appendix 2.C.

Figure 2.9: Dynamic optimal tax policy with private education spending.



Note: Panels 1 and 2 show the welfare-optimizing labor tax and robot tax, respectively. Blue solid lines: baseline model without private education spending; red dash-dotted lines: private spending model calibrated to the US; yellow dashed lines: private spending model for the German counterfactual.

in the model with private spending, an increase in the labor tax now reduces both inequality and production growth (Figure 2.8, panels 1a and 1b, red dash-dotted lines). Hence, the findings from the baseline model (blue solid lines), where the (intensive margin) human capital channel dominates the redistribution channel for the labor tax, are overturned. This is because private and public college education spending are now substitutes so that additional public spending on higher education financed through the labor tax crowds out private spending.[41] This diminishes the magnitude of the human capital channel and leads to a reduction in inequality and production growth, i.e., the redistribution channel now dominates the human capital channel. However, when considering the counterfactual scenario based on a reduced role for private spending as in Germany (yellow dashed lines), the original result from the baseline model (dominant human capital channel) is reinstated for variations in the labor tax.

Optimal tax policy In analogy to the optimal tax analysis from Figure 2.5, panels 1 and 2 in Figure 2.9 show the optimal tax policy for a welfare weight $\zeta = 0.5$ when private education spending is included in the model. We again contrast

[41] See Figure 2.12 in Appendix 2.F for details illustrating the importance of the underlying crowding out mechanism.

alternative scenarios in which the importance of private spending corresponds to the US (red dash-dotted lines) or German (yellow dashed lines) system of funding higher education. When college education is predominantly publicly funded, the pattern of optimal labor and robot taxes remains almost unchanged relative the baseline model without private spending (blue solid lines). When college education spending is mostly privately financed, instead, the optimal tax policy significantly differs from the baseline. In particular, the labor tax immediately declines from its starting rate at $\tau_W = 0.28$, while the robot tax drops to zero.

The general reduction in the level of taxation can be accounted for by the reduced need for public education spending when a significant contribution comes from private funds. The specific dynamics of optimal tax rates over time again reflect the interaction of their effects on human capital and redistribution. As discussed above, the weaker human capital channel implies that both taxes are predominantly redistributive when private spending on higher education is sufficiently important. Hence, it becomes optimal to rely exclusively on the labor tax since this is the less distortionary source of revenue. Moreover, as the economy grows over time, private contributions towards higher education rise and can increasingly substitute for public spending. In consequence, optimal labor taxes are decreasing over time.

As a final point, notice that the comparison of the alternative model versions under the utilitarian welfare function with $\zeta = 0.5$ suggests a pattern of optimal robot taxes that are positive whenever the human capital channel effects of the labor tax dominate its redistributive effects. Accordingly, there is a normative case for the robot tax when higher education is mostly publicly funded. High-skilled workers then do not pay for their education and it becomes optimal to tax them indirectly through a positive robot tax. By contrast, when there are sufficiently important private contributions to college education, this indirect taxation is no longer justified. However, this clear taxonomy is complicated by the welfare weight that the social planner attaches to low-skilled workers. Indeed, for a sufficiently high weight on the low-skilled workers, it becomes eventually optimal to have a positive robot tax, which increases over time along with the dynamics of the state of automation.[42]

[42] See e.g. the case of $\zeta = 0.7$ depicted in Figure 2.13 in Appendix 2.F.

2.8 Conclusion

In this paper, we highlight the role of tax policy and education spending for economic growth and inequality in a dynamic growth model with automation, endogenous education choice, and endogenous human capital. Although beneficial for economic growth, automation contributes to wage inequality by replacing low-skilled workers. While direct redistribution mitigates inequality at the cost of lower economic growth, education spending boosts production growth and increases inequality as it favors the human capital accumulation of high-skilled workers.

Higher government spending that increases both redistributive transfers and education spending, therefore, has an ambiguous effect on economic growth and inequality. We show that the tax composition (labor versus robot tax) financing government spending is key to determining the effect on production and inequality as the robot tax is relatively more redistributive than the labor tax. In particular, we observe that, in a model accounting for the intensive margin of human capital formation, a combined increase in labor and robot taxes can reduce inequality without harming production growth. We determine the welfare-maximizing tax policy over time, showing that the robot tax should be initially reduced relative to the status quo to boost economic growth and then progressively increased to mitigate the increase in inequality.

We further show that education subsidies in the form of higher transfers to agents undertaking higher education can lead to an increase in welfare if the following conditions are satisfied: (i) per-capita spending on higher education is not compromised, (ii) per-capita spending on basic education spending is allowed to adjust to the policy (so that the human capital channel is active), and (iii) the increase in transfers is financed through an increase in the labor tax. In particular, we observe that the increase in welfare is maximized by an increase in the labor tax of around 11 percentage points.

Extending the model to encompass also private spending on higher education, we finally show that the desirability of robot taxes crucially depends on the extent of private contributions. For European countries in which the higher education system is mostly financed through public funds, the optimal robot tax is significantly positive; but in countries like the US which rely heavily on private spending, the robot tax is optimally zero. In contrast to education subsidies, which should be financed via the labor tax, there is thus an important role for the robot tax in financing quality-enhancing spending on higher education.

Appendix to Chapter 2

2.A Model

Equilibrium conditions Type-specific aggregate labor supply can be calculated as the type-specific individual labor supply multiplied with the mass of type-specific agents:

$$\tilde{H}_{Y,t} = (1 - \eta - z_{H,t})\, H_{Y,t}, \tag{2.35}$$

$$\tilde{H}_{A,t} = (1 - \eta - z_{H,t})\, H_{A,t}, \tag{2.36}$$

and

$$\tilde{L}_t = (1 - z_{L,t})\, L_t. \tag{2.37}$$

Aggregate high-skilled labor supply is defined as the sum of aggregate high-skilled labor supplied in the final production and R&D sector

$$\tilde{H}_t = \tilde{H}_{Y,t} + \tilde{H}_{A,t}, \tag{2.38}$$

and aggregate labor supply in the economy as

$$\tilde{N}_t = \tilde{H}_t + \tilde{L}_t. \tag{2.39}$$

The total number of high-skilled individuals is the sum of high-skilled individuals working in the final production sector and the researchers (the high-skilled individuals working in the R&D sector):

$$H_t = H_{Y,t} + H_{A,t}. \tag{2.40}$$

Overall, the number of high- and low-skilled individuals needs to sum up to (the constant population size) N in all model periods:

$$N = H_t + L_t. \tag{2.41}$$

To close the model economy, we impose a no-arbitrage condition on high-skilled wage rates in both final production and R&D sector:

$$w_{H,t} = w_{A,t}. \tag{2.42}$$

2.B Partial equilibrium analysis

Proof of Proposition 2.3.1: Redistribution channel Consider a change in the labor tax, τ_W:

$$\begin{aligned}\left.\frac{d\ c_H/c_L}{d\ \tau_W}\right|_{\text{RE}} &= \underbrace{\frac{\partial\ c_H/c_L}{\partial\ \tau_W}}_{\text{RE}_W(1)} + \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \mathcal{G}}\frac{\partial \mathcal{G}}{\partial \tau_W}}_{\text{RE}_W(2)} \\ &+ \underbrace{\sum_{j\in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j'\in H,L}\frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j''\in H,L}\frac{\partial w_{j'}}{\partial h_{j''}}\frac{\partial h_{j''}}{\partial \tau_W}}_{\text{RE}_W(3)}\end{aligned} \tag{2.43}$$

where:

$$\text{RE}_W(1) = \frac{-(1-\eta)w_H\left[(1-\tau_W)w_L + \hat{T}_L\right] + w_L\left[(1-\tau_W)(1-\eta)w_H + \hat{T}_H\right]}{\left[(1-\tau_W)w_L + \hat{T}_L\right]^2}, \tag{2.44}$$

which is positive if $\omega < \frac{w_L L}{(1-\eta)w_H H + w_L L} \equiv \tilde{\omega}$;

$$\text{RE}_W(2) = \frac{\partial c_H/c_L}{\partial \hat{T}_H}\frac{\partial \hat{T}_H}{\partial \mathcal{G}}\frac{\partial \mathcal{G}}{\partial \tau_W} + \frac{\partial c_H/c_L}{\partial \hat{T}_L}\frac{\partial \hat{T}_L}{\partial \mathcal{G}}\frac{\partial \mathcal{G}}{\partial \tau_W} \tag{2.45}$$

where $\frac{\partial \mathcal{G}}{\partial \tau_W}$ is always positive. This implies that $\text{RE}_W(2) > 0$ if:

$$\frac{\partial c_H/c_L}{\partial \hat{T}_H}\frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L}\frac{\partial \hat{T}_L}{\partial \mathcal{G}} > 0 \tag{2.46}$$

where:

$$\frac{\partial c_H/c_L}{\partial \hat{T}_H}\frac{\partial \hat{T}_H}{\partial \mathcal{G}} = \frac{1}{(1-\tau_W)w_L + \hat{T}_L}\cdot\frac{(1-\omega)(1-\phi)}{H} \tag{2.47}$$

and

$$\frac{\partial c_H/c_L}{\partial \hat{T}_L}\frac{\partial \hat{T}_L}{\partial \mathcal{G}} = -\frac{(1-\tau_W)(1-\eta)w_H + \hat{T}_H}{[(1-\tau_W)w_L + \hat{T}_L]^2}\cdot\frac{\omega(1-\phi)}{L}. \tag{2.48}$$

Substituting $\hat{T}_H = \frac{(1-\omega)(1-\phi)}{H}\mathcal{G}$ and $\hat{T}_L = \frac{\omega(1-\phi)}{L}\mathcal{G}$, we obtain that $\text{RE}_W(2) > 0$ if $\omega < \tilde{\omega}$;

$$\text{RE}_W(3) = \left(\frac{\partial c_H/c_L}{\partial \hat{T}_H}\frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L}\frac{\partial \hat{T}_L}{\partial \mathcal{G}}\right) \underbrace{\sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_W}}_{D}. \tag{2.49}$$

Since $D > 0$, $\text{RE}_W(3) > 0$ if $\frac{\partial c_H/c_L}{\partial \hat{T}_H}\frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L}\frac{\partial \hat{T}_L}{\partial \mathcal{G}} > 0$ which is the same condition that implies $\text{RE}_W(2) > 0$. Therefore, $\text{RE}_W(3) > 0$ if $\omega < \tilde{\omega}$. From the above, we obtain that: $\left.\frac{d\ c_H/c_L}{d\ \tau_W}\right|_{\text{RE}} < 0$ iff $\omega > \tilde{\omega}$.

Consider a change in the robot tax (τ_R):

$$\left.\frac{d\ c_H/c_L}{d\ \tau_R}\right|_{\text{RE}} = \underbrace{\frac{\partial\ c_H/c_L}{\partial\ w_H}\frac{\partial\ w_H}{\partial\ \tau_R}}_{\text{RE}_R(1)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \mathcal{G}}\frac{\partial \mathcal{G}}{\partial \tau_R}}_{\text{RE}_R(2)}$$
$$+ \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j}\frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_R}}_{\text{RE}_R(3)}. \tag{2.50}$$

Following the same steps as for the labor tax, we find that $\text{RE}_R(2)$ and $\text{RE}_R(3)$ are negative if $\omega > \tilde{\omega}$. $\text{RE}_R(1)$ is instead always negative. This implies that a sufficient condition for $\left.\frac{d\ c_H/c_L}{d\ \tau_R}\right|_{\text{RE}}$ to be negative is $\omega > \tilde{\omega}$.

Proof of Proposition 2.3.2: Human capital channel Consider a change in either the labor or the robot tax, i.e., $g \in \{W, R\}$:

$$\left.\frac{d\ w_H/w_L}{d\ \tau_g}\right|_{\text{HC}} = \underbrace{\frac{\partial w_H/w_L}{\partial h_H/h_L}\frac{\partial h_H/h_L}{\partial \tau_g}}_{\text{HC}_g(1)} + \underbrace{\frac{\partial w_H/w_L}{\partial \tilde{A}}\frac{\partial \tilde{A}}{\partial h_H}\frac{\partial h_H}{\partial \tau_g}}_{\text{HC}_g(2)}. \tag{2.51}$$

We can write the wage and human capital ratios as:

$$\frac{w_H}{w_L} = \frac{1-\alpha}{\alpha}\frac{L}{H}\left[1 + \tilde{A}\left(\frac{\alpha^2}{\bar{R}(1+\tau_R)}\right)^{\frac{\alpha}{1-\alpha}}\left(\frac{h_H H}{h_L L}\right)^{\alpha}\right], \tag{2.52}$$

$$\frac{h_H}{h_L} = \frac{B_H}{B^{\mu_H}}\left(\frac{\phi_B \cdot \phi}{N}\right)^{-\mu_B \mu_H}\left(\frac{(1-\phi_B)\phi}{H}\right)^{\mu_H}\mathcal{G}^{\mu_H(1-\mu_B)} \tag{2.53}$$

Table 2.3: Parameters across all model versions.

External*		Internal				Policy*	
Parameter	Value	Parameter	Baseline	Private	$Private_{GER}$	Parameter	Value
β	0.55	δ	0.584	0.599	0.570	τ_W	0.284
γ	1.44	ψ_1	0.479	0.497	0.403	τ_R	0.050
α	0.80	ψ_2	17.09	16.31	18.99	ϕ	0.269
μ_a	100	μ_B	0.354	0.338	0.357	ϕ_B	0.783
σ_a	15	μ_H	0.223	0.514	0.481	ρ	0.181
$\underline{a}$	100	B	1.720	1.628	1.669		
η	0.11	B_H	6.236	14.02	18.05		
N	1000	A_0	87.3	87.3	87.3		
λ_1	0.67	ϵ	-	0.921	0.099		
λ_2	0.44	ν	-	1	1		
$\bar{R}$	2.32						

Note: External, internal and policy parameters across all model versions. *Identical parameters across all model versions.

Since $\frac{\partial \mathcal{G}}{\partial \tau_g} > 0$, then $\frac{\partial h_H/h_L}{\partial \tau_g} > 0$. Therefore, since also $\frac{\partial w_H/w_L}{\partial h_H/h_L} > 0$, $\text{HC}_g(1) > 0$. Moreover, since all the three terms in the second term of (2.51) are positive, $\text{HC}_g(2)$ and $\left.\frac{d\ w_H/w_L}{d\ \tau_g}\right|_{\text{HC}}$ are positive.

2.C Calibration

Table 2.3 presents parameters for the baseline and the private education spending model, both for the US calibration and the German counterfactual. The goodness of fit of the baseline model and both private spending exercises is given in Table 2.4. External and policy parameters are kept at their baseline values. Internal parameters are re-calibrated by minimizing the squared difference between model moments and data. The inclusion of private spending on higher education requires the internal calibration of two additional parameters (ν and ϵ). We assume a unitary elasticity of substitution between private and public education spending on higher education, i.e. (2.34) simplifies to $h_{H,t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \left((\theta_t)^{\epsilon} \cdot \left(\hat{E}_{H,t}\right)^{1-\epsilon}\right)^{\mu_H}$. The share parameter ϵ adjusts such that the model replicates the observed ratio of private to public education spending on higher education in the US of 1.54 (or Germany of 0.17 for the German counterfactual). A better fit of the model-implied college share to its real world counterpart for both, the US calibration and the German counterfactual, would require an adjustment of the technological frontier in the initial model period (A_0). We decided to keep the initial technology level from our baseline calibration to remain comparability of the technology levels across all versions.

Table 2.4: Goodness of fit across all model versions.

Target	Data	Baseline	*Priv.*	$Priv._{GER}$
high-skilled human capital (normalization)	1.00	1.00	1.00	1.00
college share (%)	34.7	34.7	31.2	35.6
R&D employment share (%)	1.00	1.69	0.90	1.20
college wage premium	1.86	1.86	1.86	1.86
elast. of college attendance wrt. its overall price	1.20	1.20	1.20	1.20
elast. of low-sk. wages wrt. p.-c. spend. on low. educ.	0.54	0.54	0.58	0.55
TFP growth (annual, %)	0.91	0.91	0.91	0.91
ratio of private to pub. educ. spending on higher educ.	1.54/0.17	-	1.54	0.17

Note: Goodness of fit across all model versions. For the inclusion of private education spending into the model structure, we have an additional target, namely the ratio of private to public education spending on higher education. See text for details.

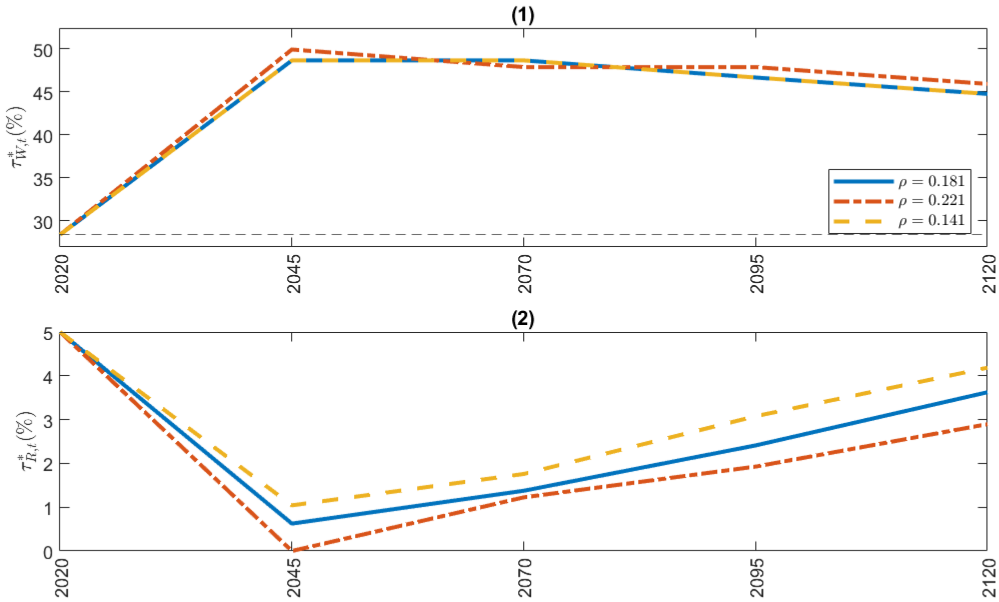
2.D Tax policy

Table 2.5: Dynamic optimal tax policy.

t	2045	2070	2095	2120	2045	2070	2095	2120	2045	2070	2095	2120
	$\zeta = 0.5$				$\zeta = 0.3$				$\zeta = 0.7$			
$\tau^*_{W,t}(\%)$	48.6	48.6	46.6	44.7	49.9	50.3	50.3	48.2	47.4	45.4	43.6	41.8
$\tau^*_{R,t}(\%)$	0.6	1.4	2.4	3.6	0	0	0	1.0	2.7	3.9	5.1	6.3
$CEV_t(\%)$	8.8	11.3	13.5	15.1	9.9	13.6	16.8	19.2	8.3	9.5	10.4	11.1
$\Delta Y_t(\%)$	37.2	42.6	44.0	42.6	41.0	52.5	62.5	65.1	24.5	24.5	21.9	18.3
$\Delta \frac{c_{H,t}}{c_{L,t}}(\%)$	14.8	21.1	25.1	25.9	16.9	27.0	38.1	42.2	9.0	10.8	11.0	9.5

Note: Optimal tax policy mix over time and its effects on production and inequality (relative to the baseline model) dependent on welfare weights in the welfare function, $\zeta \in \{0.3, 0.5, 0.7\}$.

Figure 2.10: Dynamic optimal tax policy for different progressivity levels of the tax-and-transfer system.



Note: $\rho \in \{0.181, 0.221, 0.141\}$, $\zeta = 0.5$, panels 1 and 2 show the dynamic optimal labor tax and robot tax, respectively. Compared to the baseline with $\rho = 0.181$ (blue solid line), higher progressivity requires less redistribution through the robot tax (red dash-dotted line), whereas lower progressivity calls for stronger redistribution through the robot tax (yellow dashed line).

2.E Education policies

We allow the government to increase either of its taxes to raise additional tax revenues that can be used for education policies. These education policies can either be education subsidies paid to all young high-skilled individuals in the economy or targeted education subsidies paid only to young individuals close to the ability threshold (marginal individuals, M_t). (Targeted) education subsidies realize as additional per-capita transfer payments to high-skilled (marginal) individuals, $T^{add.}_{H,t}$ ($T^{add.}_{M,t}$). The education policy experiments work as follows: we fix per-capita spending on higher education and the transfer share determining the amount of total (per-capita) transfers paid to low-skilled individuals to their respective time paths from the baseline model ($\hat{E}_{H,t} = \bar{\hat{E}}_{H,t}$ and $\omega_t = \bar{\omega}_t$,). We then calculate aggregate higher education spending that is required to maintain this per-capita level. The government can increase one of the two tax rates (either $\tau_{W,t}$ or $\tau_{R,t}$). Additional tax revenues are then used to finance (targeted) education subsidies.

2.E.1 Education subsidies

In this education policy version, additional tax revenues from higher labor or robot taxation are used as additional per-capita transfer payments to high-killed individuals $\hat{T}^{add}_{H,t}$, calculated as

$$\hat{T}^{add}_{H,t} = \frac{T^{add.}_{H,t}}{H_t} = \frac{(1-\phi_{B,t}) \cdot E_t - \bar{\hat{E}}_{H,t} \cdot H_t}{H_t}, \tag{2.54}$$

providing additional incentives for low-skilled individuals to become high-skilled and leading to an adjustment in the young-age budget constraint of high-skilled individuals, such that

$$(1-\tau_{W,t})(1-\eta-z_{H,t})w_{H,t} + \hat{T}_{H,t} + \hat{T}^{add}_{H,t} = c_{H,t} + s_{H,t}. \tag{2.55}$$

As a consequence, high-skilled individual's optimal consumption, savings and leisure decisions are then of the following form

$$c_{H,t} = \left(\frac{1}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta)w_{H,t} + \hat{T}_{H,t} + \hat{T}^{add}_{H,t}\right), \tag{2.56}$$

$$s_{H,t} = \left(\frac{\beta}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta)w_{H,t} + \hat{T}_{H,t} + \hat{T}^{add}_{H,t}\right), \tag{2.57}$$

$$z_{H,t} = \left(\frac{\gamma}{(1+\beta+\gamma)(1-\tau_{W,t})w_{H,t}}\right)\left((1-\tau_{W,t})(1-\eta)w_{H,t} + \hat{T}_{H,t} + \hat{T}^{add}_{H,t}\right). \tag{2.58}$$

For the specific version of this education policy in which we fix the human capital channel, we assume in addition that per-capita spending on basic education is also fixed at its baseline model time path ($\hat{E}_{B,t} = \bar{\hat{E}}_{B,t}$). Additional per-capita transfer payments to high-skilled individuals are then calculated as

$$\hat{T}^{add}_{H,t} = \frac{T^{add.}_{H,t}}{H_t} = \frac{E_t - \bar{\hat{E}}_{H,t} \cdot H_t - \bar{\hat{E}}_{B,t} \cdot N}{H_t}. \tag{2.59}$$

2.E.2 Targeted education subsidies

In this education policy version, additional tax revenues from higher labor or robot taxation are used as additional per-capita transfer payments $\hat{T}^{add.}_{M,t}$, but explicitly targeted to marginal individuals (M_t, individuals close to the ability threshold). This idea creates a three-type economy of high-skilled (H_t), low-skilled (L_t) and marginal individuals (M_t). Marginal individuals are high-skilled but receive additional transfer payments from the government, calculated as

$$\hat{T}^{add}_{M,t} = \frac{T^{add.}_{M,t}}{M_t} = \frac{(1-\phi_{B,t}) \cdot E_t - \bar{\hat{E}}_{H,t} \cdot (H_t + M_t)}{M_t}. \tag{2.60}$$

Households Lifetime utility for an agent of type $j \in \{H, M, L\}$ becomes

$$\mathcal{U}_{j,t} = \log(c_{j,t}) + \beta \log(\bar{R}s_{j,t}) + \gamma \log(z_{j,t}) - \mathbb{1}_{[j=H,M]}\ v(a), \tag{2.61}$$

and the respective budget constraint changes to

$$(1-\tau_{W,t})(1-\eta_j - z_{j,t})w_{j,t} + \hat{T}_{j,t} + \mathbb{1}_{[j=M]}\ \hat{T}^{add}_{j,t} = c_{j,t} + s_{j,t}. \tag{2.62}$$

Marginal agents have to spend the same amount of time in higher education as (non-marginal) high-skilled individuals ($\eta_H = \eta_M = \eta$). Optimal decisions follow as

$$c_{j,t} = \left(\frac{1}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} + \mathbb{1}_{[j=M]}\ \hat{T}^{add}_{j,t}\right), \tag{2.63}$$

$$s_{j,t} = \left(\frac{\beta}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} + \mathbb{1}_{[j=M]}\ \hat{T}^{add}_{j,t}\right), \tag{2.64}$$

$$z_{j,t} = \left(\frac{\gamma}{(1+\beta+\gamma)(1-\tau_{W,t})w_{j,t}}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} + \mathbb{1}_{[j=M]}\ \hat{T}^{add}_{j,t}\right). \tag{2.65}$$

Instead of ending up with one ability threshold

$$a^*_t = \psi_2 \left(\frac{c_{H,t}}{c_{L,t}}\right)^{-\frac{1+\beta+\gamma}{\psi_1}} \left(\frac{w_{H,t}}{w_{L,t}}\right)^{\frac{\gamma}{\psi_1}} + \underline{a}. \tag{2.66}$$

from $\mathcal{U}_{H,t}(a) \geqslant \mathcal{U}_{L,t}$, we get an additional threshold level

$$a^{**}_t = \psi_2 \left(\frac{c_{M,t}}{c_{L,t}}\right)^{-\frac{1+\beta+\gamma}{\psi_1}} \left(\frac{w_{M,t}}{w_{L,t}}\right)^{\frac{\gamma}{\psi_1}} + \underline{a}. \tag{2.67}$$

from $\mathcal{U}_{M,t}(a) \geqslant \mathcal{U}_{L,t}$. As marginal individuals are high-skilled individuals, both receive the same wage rate ($w_{H,t} = w_{M,t}$). General per-capita transfers for marginal and non-marginal high-skilled individuals are equivalent ($\hat{T}_{M,t} = \hat{T}_{H,t}$). As both high-skilled types (marginal and non-marginal) also receive the same wage rate, it holds true that $a_t^{**} \leqslant a_t^*$, as long as $\hat{T}^{add}_{M,t} \geqslant 0$ (which is true by assumption). The mass of (non-marginal) high-skilled individuals is therefore given by $H_t = (1 - \mathcal{F}(a_t^*)) \cdot N$, the mass of marginal individuals by $M_t = (\mathcal{F}(a_t^*) - \mathcal{F}(a_t^{**})) \cdot N$ and the mass of low-skilled individuals by $L_t = \mathcal{F}(a_t^{**}) \cdot N$.

Final production sector Aggregate output is produced as

$$Y_t = \left(h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}\right)^{1-\alpha} \left(\left(h_{L,t}\tilde{L}_t\right)^{\alpha} + \sum_{i=1}^{A_t} (x_{i,t})^{\alpha}\right), \tag{2.68}$$

inducing the following maximization problem

$$\max_{\left\{\tilde{H}_{Y,t}, \tilde{M}_{Y,t}, \tilde{L}_t, \{x_{i,t}\}_{i=1}^{A_t}\right\}} Y_t - w_{H,t}\tilde{H}_{Y,t} - w_{M,t}\tilde{M}_{Y,t} - w_{L,t}\tilde{L}_t - (1 + \tau_{R,t}) \sum_{i=1}^{A_t} p_{i,t}x_{i,t}. \tag{2.69}$$

Factor prices are obtained as

$$w_{H,t} = (1-\alpha)\left(h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}\right)^{-\alpha} h_{H,t} \left((h_{L,t}\tilde{L}_t)^{\alpha} + \sum_{i=1}^{A_t} (x_{i,t})^{\alpha}\right), \tag{2.70}$$

$$w_{M,t} = (1-\alpha)\left(h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}\right)^{-\alpha} h_{M,t} \left((h_{L,t}\tilde{L}_t)^{\alpha} + \sum_{i=1}^{A_t} (x_{i,t})^{\alpha}\right), \tag{2.71}$$

$$w_{L,t} = \alpha \left(\frac{h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}}{h_{L,t}\tilde{L}_t}\right)^{1-\alpha} h_{L,t}, \tag{2.72}$$

$$p_{i,t} = \left(\frac{\alpha}{(1+\tau_{R,t})}\right)\left(\frac{h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}}{x_{i,t}}\right)^{1-\alpha}, \tag{2.73}$$

from which we find that $w_{H,t} = w_{M,t}$.

R&D sector Blueprints for new machines are produced as

$$A_t - A_{t-1} = \bar{\delta}_t \left(h_{H,t}\tilde{H}_{A,t} + h_{M,t}\tilde{M}_{A,t}\right) \tag{2.74}$$

with

$$\bar{\delta}_t = \delta \cdot \frac{(A_{t-1})^{\lambda_1}}{(h_{H,t}\tilde{H}_{A,t} + h_{M,t}\tilde{M}_{A,t})^{1-\lambda_2}}. \tag{2.75}$$

R&D profits are given as

$$\max_{\left\{\tilde{H}_{A,t}, \tilde{M}_{A,t}\right\}} p_{A,t}\bar{\delta}_t \left(h_{H,t}\tilde{H}_{A,t} + h_{M,t}\tilde{M}_{A,t}\right) - w_{HA,t}\tilde{H}_{A,t} - w_{MA,t}\tilde{M}_{A,t}. \tag{2.76}$$

Optimality requires

$$w_{HA,t} = p_{A,t}\bar{\delta}_t h_{H,t}, \tag{2.77}$$

and

$$w_{MA,t} = p_{A,t}\bar{\delta}_t h_{M,t}. \tag{2.78}$$

Intermediate goods sector The supply of machines of the latest vintage is obtained as

$$x_t \equiv x_{n,t} = \left(\frac{\alpha^2}{\bar{R}(1+\tau_{R,t})}\right)^{\frac{1}{1-\alpha}} \cdot (h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}), \tag{2.79}$$

and the supply of machines of older vintage is given by

$$x_{m,t} = \left(\frac{\alpha}{\bar{R}(1+\tau_{R,t})}\right)^{\frac{1}{1-\alpha}} \cdot (h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}). \tag{2.80}$$

It holds that

$$x_{m,t} = \alpha^{\frac{1}{\alpha-1}} x_{n,t} \tag{2.81}$$

and the final production function can be rewritten as

$$Y_t = \left(h_{H,t}\tilde{H}_{Y,t} + h_{M,t}\tilde{M}_{Y,t}\right)^{1-\alpha} \left(\left(h_{L,t}\tilde{L}_t\right)^{\alpha} + \tilde{A}_t (x_t)^{\alpha}\right), \tag{2.82}$$

with

$$\tilde{A}_t \equiv \left(\alpha^{\frac{\alpha}{\alpha-1}} - 1\right) A_{t-1} + A_t. \tag{2.83}$$

Human capital Total public spending is still the sum of the expenditures across basic and higher education spending

$$E_t = E_{B,t} + E_{H,t}. \tag{2.84}$$

Basic (and low-skilled) human capital is given as

$$h_{B,t} = h_{L,t} = B \cdot \left(\hat{E}_{B,t}\right)^{\mu_B}, \tag{2.85}$$

with

$$\hat{E}_{B,t} \equiv \frac{E_{B,t}}{N}. \tag{2.86}$$

High-skilled human capital follows (2.21) with

$$\hat{E}_{H,t} \equiv \frac{E_{H,t}}{H_t + M_t}. \tag{2.87}$$

Human capital of marginal individuals is equal to high-skilled human capital

$$h_{M,t} = h_{H,t}. \tag{2.88}$$

Fiscal policy The government still runs a balanced budget

$$\mathcal{G}_t = \mathcal{G}_{W,t} + \mathcal{G}_{R,t}, \tag{2.89}$$

with revenues from taxing labor income and machines as

$$\mathcal{G}_{W,t} = \tau_{W,t} \cdot (w_{H,t}\tilde{H}_{Y,t} + w_{M,t}\tilde{M}_{Y,t} + w_{HA,t}\tilde{H}_{A,t} + w_{MA,t}\tilde{M}_{A,t} + w_{L,t}\tilde{L}_t), \tag{2.90}$$

$$\mathcal{G}_{R,t} = \tau_{R,t} \cdot \sum_{i=1}^{A_t} p_{i,t}x_{i,t} = \tau_{R,t}\hat{A}_t\bar{R}x_t, \tag{2.91}$$

with

$$\hat{A}_t \equiv \alpha^{\frac{1}{\alpha-1}} A_{t-1} + \alpha^{-1}(A_t - A_{t-1}). \tag{2.92}$$

Government budget balance implies

$$\mathcal{G}_t = E_t + T_t, \tag{2.93}$$

with

$$E_t = \phi_t \cdot \mathcal{G}_t \tag{2.94}$$

and

$$T_t = (1 - \phi_t) \cdot \mathcal{G}_t. \tag{2.95}$$

Public spending on basic education is given as

$$E_{B,t} = \phi_{B,t} \cdot E_t, \tag{2.96}$$

and public spending on higher education as

$$E_{H,t} = (1 - \phi_{B,t}) \cdot E_t. \tag{2.97}$$

The share of total transfers to low-skilled individuals is given as

$$T_{L,t} = \omega_t \cdot T_t \tag{2.98}$$

and to high-skilled (and marginal) individuals as

$$T_{H,t} = (1 - \omega_t) \cdot T_t, \tag{2.99}$$

leading to general per-capita transfer payments of

$$\hat{T}_{L,t} = \frac{T_{L,t}}{L_t} \tag{2.100}$$

and

$$\hat{T}_{H,t} = \hat{T}_{M,t} = \frac{T_{H,t}}{(H_t + M_t)} \tag{2.101}$$

Market clearing and equilibrium conditions The population constraint

$$N = H_t + M_t + L_t \tag{2.102}$$

holds, with the number of high-skilled individuals as

$$H_t = H_{Y,t} + H_{A,t}, \tag{2.103}$$

and the number of marginal individuals as

$$M_t = M_{Y,t} + M_{A,t}. \tag{2.104}$$

We impose two no-arbitrage conditions on wages in form of

$$w_{H,t} = w_{HA,t} \tag{2.105}$$

and

$$w_{M,t} = w_{MA,t}. \tag{2.106}$$

Type-specific aggregate labor supply is given as

$$\tilde{H}_{Y,t} = (1 - \eta - z_{H,t}) \cdot H_{Y,t}, \tag{2.107}$$

$$\tilde{H}_{A,t} = (1 - \eta - z_{H,t}) \cdot H_{A,t}, \tag{2.108}$$

$$\tilde{M}_{Y,t} = (1 - \eta - z_{M,t}) \cdot M_{Y,t}, \tag{2.109}$$

$$\tilde{M}_{A,t} = (1 - \eta - z_{M,t}) \cdot M_{A,t}, \tag{2.110}$$

and

$$\tilde{L}_t = (1 - z_{L,t}) \cdot L_t. \tag{2.111}$$

Type-specific individual labor supply follows

$$\tilde{h}_t = 1 - \eta - z_{H,t}, \tag{2.112}$$

$$\tilde{m}_t = 1 - \eta - z_{M,t}, \tag{2.113}$$

and

$$\tilde{l}_t = 1 - z_{L,t}. \tag{2.114}$$

Aggregate high-skilled labor supply is given as

$$\tilde{H}_t = \tilde{H}_{Y,t} + \tilde{H}_{A,t}, \tag{2.115}$$

aggregate marginal labor supply as

$$\tilde{M}_t = \tilde{M}_{Y,t} + \tilde{M}_{A,t} \tag{2.116}$$

and aggregate labor supply follows

$$\tilde{N}_t = \tilde{H}_t + \tilde{M}_t + \tilde{L}_t. \tag{2.117}$$

Welfare function The modified welfare function for the three-type economy is of the following form

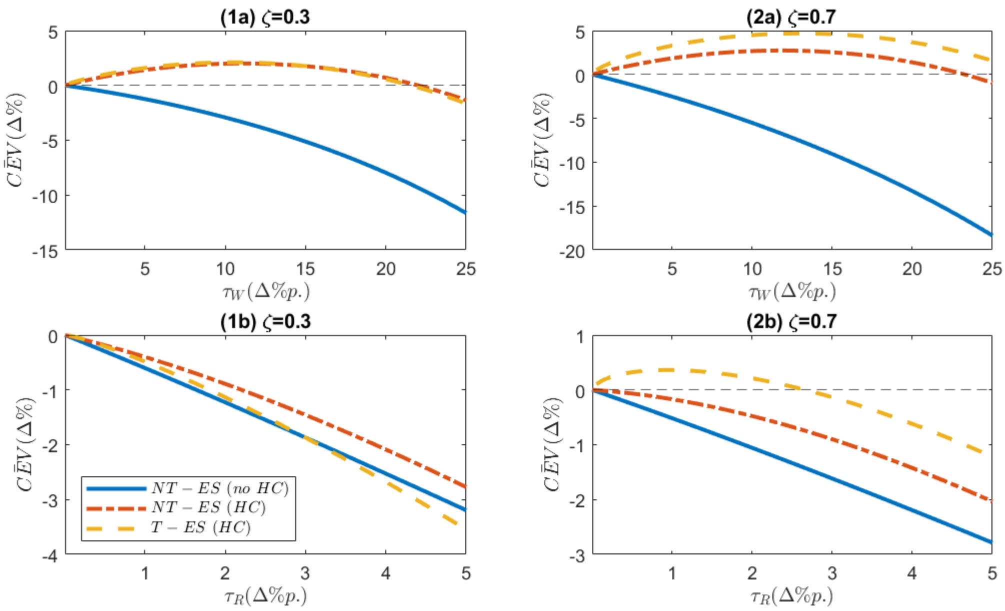
$$\Omega_t = \zeta \cdot \underbrace{\mathcal{F}(a_t^{**}) \cdot N}_{=L_t} \cdot \mathcal{U}_{L,t} + (1-\zeta) \cdot \left(\underbrace{(\mathcal{F}(a_t^{*}) - \mathcal{F}(a_t^{**})) \cdot N}_{=M_t} \cdot \mathcal{U}_{M,t} + \underbrace{(1 - \mathcal{F}(a_t^{*})) \cdot N}_{=H_t} \cdot \mathcal{U}_{H,t} \right). \tag{2.118}$$

2.F Private education spending

Household optimality FOC:

$$1 = (1 - \tau_{W,t})(1 - \eta - z_{H,t}) \frac{\partial w_{H,t}}{\partial \theta_t}, \tag{2.119}$$

Figure 2.11: Education subsidies.



Note: Percentage deviations of aggregate welfare (measured as the average consumption equivalent variation) in 2045 from the baseline situation for a tax increase in either the linear income tax rate (first row) or the robot tax (second row) for a lower weight on low-skilled individuals in the aggregate welfare function ($\zeta = 0.3$, first column) and a higher weight on low-skilled individuals in the aggregate welfare function ($\zeta = 0.7$, second column) for education subsidies without intensive margin human capital formation (blue solid line), education subsidies (red dash-dotted line) and targeted education subsidies (yellow dashed line).

Table 2.6: Education subsidies.

Education policy	τ_g^*	$\Omega \uparrow$	$\Delta\tau_g(\%p.)$	$C\bar{E}V(\%)$	$\Delta Y(\%)$	$\Delta\frac{c_H}{c_L}(\%)$
$\zeta = 0.5$						
Education subsidies	τ_W	✓	11.4	2.4	-1.5	-1.2
	τ_R	✗				
Targ. education subsidies	τ_W	✓	11.9	3.4	2.8	-5.1
	τ_R	✓	0.3	0.1	-0.5	-0.9
$\zeta = 0.3$						
Education subsidies	τ_W	✓	11.1	2.0	-1.4	-1.2
	τ_R	✗				
Targ. education subsidies	τ_W	✓	10.6	2.1	3.2	-4.8
	τ_R	✗				
$\zeta = 0.7$						
Education subsidies	τ_W	✓	11.9	2.7	-1.7	-1.3
	τ_R	✗				
Targ. education subsidies	τ_W	✓	13.1	4.7	2.4	-5.4
	τ_R	✓	1.0	0.4	-2.7	-2.7

Note: Welfare optimal tax increases for 2045 for different education subsidies and their effects on production and inequality. Tax adjustments (specified as percentage-point increases) refer to the initial calibration for the labor income tax rate of 28.4% and the robot tax of 5%. ($^*g = \{W, R\}$)

where:

$$\frac{\partial w_{H,t}}{\partial \theta_t} = (1-\alpha)^2 \frac{\left((h_{L,t}\tilde{L}_t)^{\alpha} + \tilde{A}_t x_t^{\alpha}\right)}{(h_{H,t}\tilde{H}_{Y,t})^{\alpha}} \cdot \frac{\partial h_{H,t}}{\partial \theta_t}, \tag{2.120}$$

and

$$\frac{\partial h_{H,t}}{\partial \theta_t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \mu_H \cdot \epsilon \cdot (\theta_t)^{-\frac{1}{\nu}} \cdot \left(\epsilon \cdot (\theta_t)^{\frac{\nu-1}{\nu}} + (1-\epsilon) \cdot \left(\hat{E}_{H,t}\right)^{\frac{\nu-1}{\nu}}\right)^{\frac{\nu}{\nu-1}\cdot\mu_H - 1}. \tag{2.121}$$

(2.56), (2.57) and (2.58), therefore, become:

$$c_{j,t} = \left(\frac{1}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]}\ \theta_t\right), \tag{2.122}$$

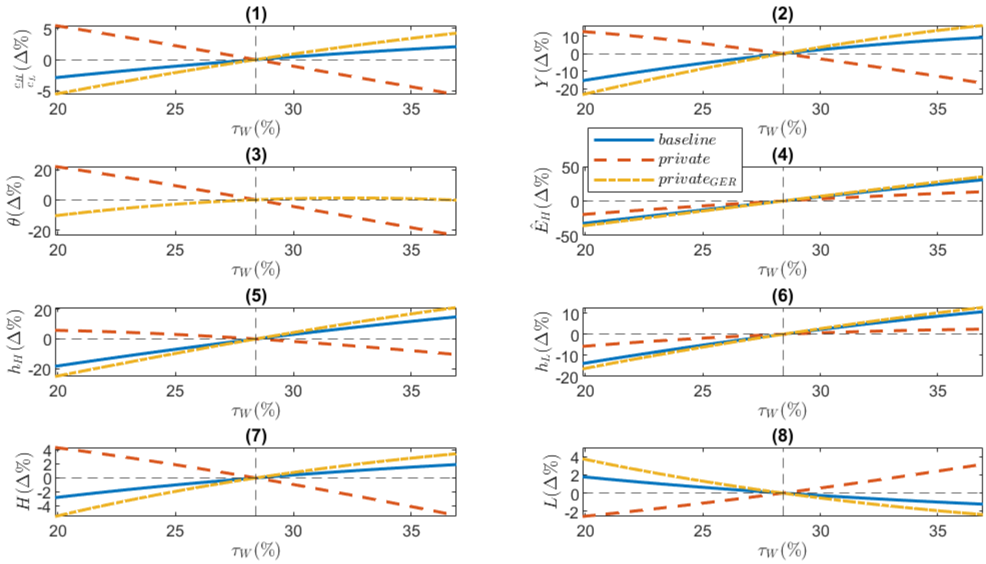
$$s_{j,t} = \left(\frac{\beta}{1+\beta+\gamma}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]}\ \theta_t\right), \tag{2.123}$$

and

$$z_{j,t} = \left(\frac{\gamma}{(1+\beta+\gamma)(1-\tau_{W,t})w_{j,t}}\right)\left((1-\tau_{W,t})(1-\eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]}\ \theta_t\right). \tag{2.124}$$

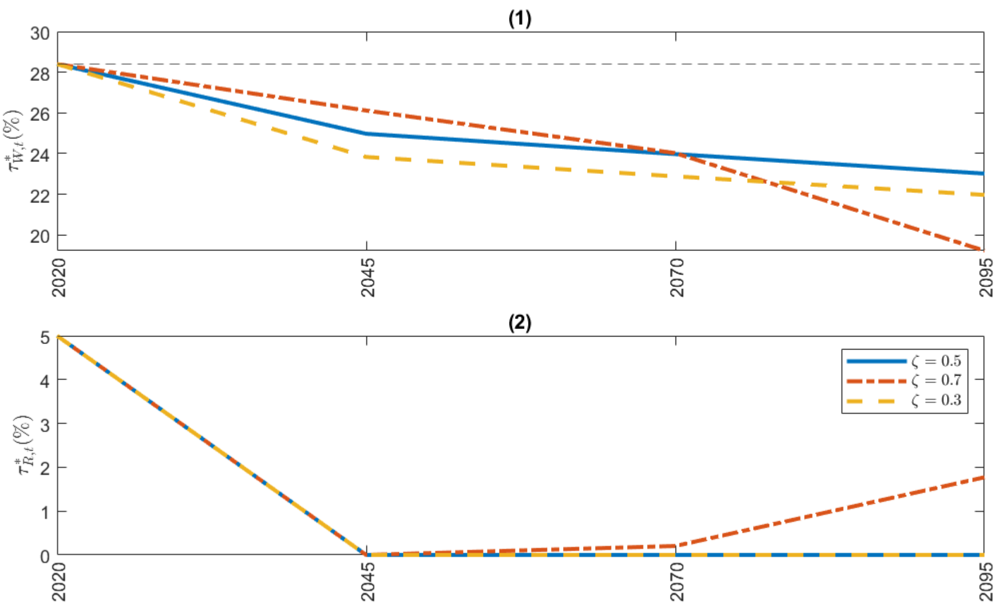
From solving the indifference condition ($\mathcal{U}_{H,t} = \mathcal{U}_{L,t}$), we obtain the same functional form as in (2.67).

Figure 2.12: One-dimensional tax policy interventions with private education spending.



Note: Percentage deviations of different model variables in 2045 from the baseline situation for a variation in the labor tax. Blue solid lines: baseline model without private education spending; red dash-dotted lines: private spending model calibrated to the US; yellow dashed lines: private spending model for the German counterfactual.

Figure 2.13: Dynamic optimal tax policy with private education spending.



Note: Panels 1 and 2 show the dynamic optimal labor tax and robot tax, respectively, for the private education model calibrated to the US and different levels of the welfare weight, $\zeta \in \{0.3, 0.5, 0.7\}$.

Chapter 3

Population aging and fiscal multipliers*

Abstract

This paper examines the consequences of population aging for the magnitude of fiscal multipliers. Using structural vector autoregressions (SVARs) for a broad cross-section of countries, we find that fiscal multipliers following a positive government spending shock are, on average, positive, larger in economies with a younger age structure, and negatively correlated with the old-age dependency ratio – a key measure of population aging. To explain these empirical findings, we develop a medium-scale overlapping generations model with heterogeneous households, calibrated to several developed economies and incorporating country-specific demographic variables. The central mechanism is that older economies exhibit a weaker labor supply response from working-age households, which dampens the output effect of fiscal expansions. This is because households in aging societies tend to save more intensively over the life cycle and respond less strongly to increases in non-distortionary taxation. Quantitatively, we find that a one standard deviation increase in the old-age dependency ratio – equivalent to a 6.3 percentage point rise – reduces the fiscal multiplier by an average of 17.7 percent across countries. After controlling for cross-country differences unrelated to the demographic structure of the economies, the reduction remains economically meaningful, though smaller, at 3.6 percent. The model predicts that continued population aging will reduce the size of fiscal multipliers by an average of 11.3 percent by 2070.

*For helpful discussions and pointed comments, I am grateful to Stefan Niemann.

3.1 Introduction

One of the most important measures for evaluating the effectiveness of fiscal policy is the fiscal multiplier, which captures how strongly output responds to changes in government spending. The economic literature has converged on the view that the fiscal multiplier is not a universal constant, but varies across countries and over time, depending on structural and cyclical factors. This paper explores how a key structural feature – the age structure of the population – affects the size of the fiscal multiplier across countries. Specifically, we investigate whether and how aging populations reduce the effectiveness of fiscal expansions, and what this implies for the effectiveness of fiscal policy in the context of future population aging.

Starting from our empirical analysis, based on a structural vector autoregression (SVAR) exercise using quarterly data from 35 countries between 1995 and 2019, we derive three stylized facts. Following the identification strategies of Blanchard and Perotti (2002) and Ilzetzki et al. (2013), we estimate impulse response functions to a positive government spending shock and use these to compute fiscal multipliers. Our *first stylized fact*, consistent with the existing empirical literature, is that a positive government spending shock generally produces a significant positive output response. To examine how this effect varies with the demographic structure, we divide countries into *young* and *old* age structure groups based on the median value of their old-age dependency ratios in 2020. We find that the output response is significantly larger in countries with a *young* age structure than in those with an *old* one – our *second stylized fact*. Finally, we estimate SVARs for each country individually and regress the resulting multipliers on their respective old-age dependency ratios. This yields our *third stylized fact*: across countries, there is a significant negative correlation between the size of the fiscal multiplier and the old-age dependency ratio, suggesting that older populations dampen the effectiveness of fiscal expansions.

In order to explain these three stylized facts, quantify the impact of the demographic change on fiscal multipliers, and assess how future population aging may affect fiscal policy effectiveness, we develop a medium-scale overlapping generations model, similar to Brinca et al. (2016) and Brinca et al. (2021). The model features endogenous labor supply and idiosyncratic income risk at the household level. The population structure is determined exogenously by time-varying demographics and, importantly, is country-specific. Firms produce with a constant returns-to-scale production function in a competitive environment. Households pay consumption and capital taxes, and contribute a share of their labor income to the social security system. Their labor income is progressively taxed. In return, they receive lump-sum transfers from the government. The government runs a balanced-budget pension system and allocates tax revenues to government consumption, pension benefits, and interest payments on outstanding debt.

We calibrate the baseline version of the model to the United States in 2020. Then, we repeat this process for another seventeen countries, enabling us to make cross-country comparisons. These countries differ not only in terms of the age structure of the population but also along various other dimensions.

The fiscal expansion in the model follows a standard approach in the literature: the government increases its (wasteful) consumption and finances this additional spending through non-distortionary, lump-sum taxation (Baxter and King, 1993). All other policy variables remain at their stationary equilibrium values. The immediate positive output response in the model, resulting from an increase in government consumption, stems from a negative wealth effect for households, induced by an increase in lump-sum taxation to fund additional government spending. In order to make up for at least part of the resulting drop in available income, households work more. Overall, aggregate labor increases and boosts production.

Consistent with our *first stylized fact*, the model generates positive impact multipliers across all countries in the sample. While these multipliers are smaller than their empirical counterparts, the model still exhibits substantial cross-country variation. The model-implied impact multiplier for the United States is 0.102, close to the unweighted sample mean of 0.104. The model predicts the largest multiplier of 0.154 for the Netherlands and the weakest output reaction to a positive government spending shock for Japan, with an impact multiplier of 0.021.

Mirroring our empirical results, the model confirms our *second stylized fact*: on average, countries with a *young* age structure exhibit significantly larger impact multipliers than those with an *old* one. Specifically, the average impact multiplier in countries with a *young* age structure is approximately 25 percent higher than in countries with an *old* age structure.

Relating the model-implied country-specific impact multipliers to the respective old-age dependency ratios reveals a significant negative relationship, consistent with our *third stylized fact*. The raw correlation coefficient is –0.526, indicating that higher dependency ratios are associated with smaller fiscal multipliers. A simple linear *cross-country regression* suggests that a one standard deviation increase in the old-age dependency ratio, equivalent to 6.3 percentage points, leads to a 0.018 unit decline in the impact multiplier. This decline corresponds to a 17.7 percent reduction in the unweighted sample average impact multiplier.

By comparing the impact multipliers in our benchmark economy, the United States, a country with a relatively young population, and Japan, the country with the oldest population in the model sample, we find that the United States' impact multiplier is around five times larger than the Japanese one. This disparity stems from weaker labor supply responses in Japan: households there save more intensively over the life cycle in anticipation of longer life expectancy, making them less sensitive to the negative wealth shock caused by higher lump-sum taxes. As a result, aggregate labor and output respond less strongly to the fiscal expansion.

While the age structure plays a central role, countries in the model sample also differ along many other dimensions. To disentangle the specific drivers of variation in impact multipliers, we conduct a detailed comparison between the United States and Japan. Holding all else constant, we adjust each parameter that differs between the two countries individually to assess its impact on the United States benchmark multiplier. Several adjustments significantly increase the impact multiplier – such as a higher social-security contribution rate, a lower labor income tax progressivity, and a higher debt-output ratio. In contrast, a lower average age-dependent productivity level and a higher old-age dependency ratio reduce the impact multiplier. Specifically, adjusting the United States' age structure to match that of Japan – implicitly raising the old-age dependency ratio from 24.5 to 49.1 percent – lowers the United States' impact multiplier by approximately 14.2 percent.

To isolate the pure effect of population aging on the fiscal multiplier – separate from other country-specific parameters – we simulate counterfactual scenarios in which the United States' age structure in 2020 is replaced with those of the other countries in the model sample, holding all other parameters constant. We then relate the resulting hypothetical multipliers to the corresponding old-age dependency ratios. This exercise yields a highly significant raw correlation of -0.949, indicating a strong negative relationship. A *within-country regression* for the United States suggests that a one standard deviation increase in the old-age dependency ratio reduces the hypothetical average impact multiplier by 0.004 units – equivalent to a 4.4 percent decline. Repeating the same counterfactual exercise across all countries in the sample yields an average decline of 3.6 percent, confirming that while the pure effect of population aging is smaller than the combined effect, it remains economically meaningful.

Finally, using old-age dependency ratio projections from United Nations (2022b), we project the effects of population aging on impact multipliers through 2070. When adjusting the age structure of the model-sample countries accordingly, we find that population aging leads to an average decline in the impact multipliers of approximately 11.3 percent. The magnitude of this effect varies across countries – from a minimum reduction of 7.1 percent in the United Kingdom to a maximum decline of 16.3 percent in Spain. For the United States, the model predicts a 10.3 percent drop in the impact multiplier by 2070, attributable solely to population aging.

Related literature This paper relates to several strands of the literature. First, and more broadly, it contributes to research on the macroeconomic consequences of population aging. Prior work has examined its effects on long-run trends – such as its consequences for the rates of return on capital (Krueger and Ludwig, 2007; Carvalho et al., 2016), for economic growth, for the ability to innovate, for employment and for labor productivity (Aksoy et al., 2019; Jones, 2022b; Maestas et al., 2023) and for the adaptation of automated technologies (Acemoglu and Restrepo, 2017; Angelini, 2023). Other studies highlight the impact of the demographic change on short-run fluctuations – such as the effect of the demographic structure on the impact of monetary policy (Leahy and Thapar, 2019) or the consequences of the demographic change on business cycle volatility (Jaimovich and Siu, 2009).

Second, the paper is closely related to research on the implications of population aging for the aggregate effects of fiscal policy. For instance, Janiak and Monteiro (2016) examine how the size of the government interacts with business cycle volatility when employment volatility varies across age groups, and high tax rates lead to a reduced supply of hours worked by young and old workers. Ferraro and Fiori (2020) study how population aging shapes the unemployment response to marginal tax rate shocks, while Miyamoto and Naoyuki (2017) find that fiscal and monetary policy effectiveness is weakened as the share of retirees in an economy increases.

Third, our paper contributes to the literature on state-dependent fiscal multipliers. Earlier studies show that the size of the fiscal multiplier varies across the business cycle (Auerbach and Gorodnichenko, 2012, 2013; Blanchard and Leigh, 2013), and also across structural characteristics, such as income levels (Kraay, 2012; Ilzetzki et al., 2013), the trade openness of an economy (Ilzetzki et al., 2013; Koh, 2017), the exchange rate regimes (Corsetti et al., 2012; Ilzetzki et al., 2013), and the public debt levels (Auerbach and Gorodnichenko, 2013; Nickel and Tudyka, 2014; Koh, 2017; Huidrom et al., 2020). More closely related to our work, recent research has examined how fiscal multipliers vary with the demographic structure (Basso and Rachedi, 2021; Kopecky, 2022; Miyamoto and Naoyuki, 2022), or with the interaction between demographics and public debt levels (Cho and Rhee, 2024). In addition, work by Brinca et al. (2016), on which this paper builds mainly in terms of the quantitative set-up, has focused on the impact of wealth inequality on the size of the fiscal multiplier.

Our contribution is twofold. First, we provide empirical evidence that population aging is associated with smaller fiscal multipliers, supporting existing findings in the literature. Second, we quantify this relationship in a structural model that captures differences in the demographic structure across countries, thereby extending the previous empirical and quantitative results in Basso and Rachedi (2021), who focus on a single country, the United States, and the military multiplier, and offering forward-looking estimates of how fiscal policy effectiveness will be affected by ongoing population aging.

The rest of the paper is structured as follows. Section 3.2 provides the three stylized facts that motivate us to set up the quantitative model, outlined in Section 3.3. Section 3.4 discusses the calibration strategy for the benchmark economy, the United States. Section 3.5 presents quantitative results. Finally, Section 3.6 concludes.

3.2 Stylized facts

In this section, we document the three stylized facts that motivate our analysis of the interaction between the size of fiscal multipliers and the age structure of an economy. We perform an empirical exercise based on structural vector autoregressions (SVARs) similar to Brinca et al. (2016) and Ilzetzki et al. (2013), building on Blanchard and Perotti (2002). We measure the size of fiscal multipliers across 35 different countries, based on data starting in the first quarter of 1995 and ranging until the last quarter of 2019.[1] Then, we relate the size of the fiscal multipliers to the age structures of the economies.

We estimate the following system of equations

$$A \cdot X_{i,t} = \sum_{h=1}^{H} C_h \cdot X_{i,t-h} + B \cdot \varepsilon_{i,t}, \tag{3.1}$$

[1]For some countries, the data series start in later quarters. Table 3.9 in Appendix 3.A provides an overview of the countries and quarters covered in our dataset.

where $X_{i,t}$ is a vector of variables in country i at quarter t. This vector is given as

$$X_{i,t} = \begin{pmatrix} g_{i,t} \\ y_{i,t} \\ ca_{i,t} \\ \Delta reer_{i,t} \end{pmatrix}, \tag{3.2}$$

and includes $g_{i,t}$ as the natural logarithm of real government consumption (IMF, 2025a), $y_{i,t}$ as the natural logarithm of real gross domestic product (GDP) (IMF, 2025b), $ca_{i,t}$ as the ratio of the current account to real GDP (FRED, 2025), and $\Delta reer_{i,t}$ as the change in the natural logarithm of the real effective exchange rate (BIS, 2025b,a).[2] Following Ilzetzki et al. (2013), the matrix C_h includes own- and cross-effects of the h-th lag of the variables on their current observations. The matrix B is diagonal. This means that the vector $\varepsilon_{i,t}$ is a vector of orthogonal i.i.d. shocks to government consumption and output, such that $\mathbb{E}[\varepsilon_{i,t}] = 0$, and $\mathbb{E}[\varepsilon_{i,t}\varepsilon'_{i,t}]$ defines the identity matrix. The matrix A allows for the possibility of simultaneous effects among the endogenous variables $X_{i,t}$. We impose the assumption that matrices A, B, and C_h are invariant across time and countries. We use panel OLS regressions with country- and time-fixed effects to estimate the system of equations given in (3.1). We follow Blanchard and Leigh (2013) and Ilzetzki et al. (2013) and assume that changes in government consumption require at least one quarter to respond to innovations in other macroeconomic variables. We apply a Cholesky decomposition and order the variables as follows: first, the natural logarithm of government consumption; second, the natural logarithm of real GDP; third, the current account to real GDP ratio; and lastly, the change in the natural logarithm of the real effective exchange rate. We further set the number of lags included in the system of equations from (3.1) to $H = 4$.[3]

We define two different fiscal multipliers. An *impact multiplier (IM)*, measuring the ratio of the change in output to a change in government consumption at the moment at which the impulse to government consumption occurs,

$$IM = \frac{\Delta y_0}{\Delta g_0}, \tag{3.3}$$

[2]We use the *narrow* real effective exchange rate if available and the *broad* real effective exchange rate otherwise. Real effective exchange rates are reported on a monthly basis. We convert these monthly values to quarterly values by averaging the values of the corresponding three months of a specific quarter. Table 3.9 in Appendix 3.A provides an overview of the countries for which we use the *narrow* and the *broad* time series of the real effective exchange rates.

[3]The empirical results are qualitatively robust to changes in H.

Table 3.1: Empirical multipliers.

		Median		*Average*	
	(1) *Total*	(2) *Young*	(3) *Old*	(4) *Young*	(5) *Old*
IM	0.5247	0.8110	0.4122	0.7964	0.4274
SRM	1.0824	1.1636	1.0256	1.1464	1.0394
# cntr.	35	17	18	14	21
# obs.	3,019	1,408	1,611	1,108	1,911

Note: This table reports the IMs and SRMs for the total sample in column (1), for the subsamples with the *young* and the *old* age structure with the median old-age dependency ratio in 2020 as the splitting-criterion in columns (2) and (3) and with the average old-age dependency ratio in 2020 as the splitting-criterion in columns (4) and (5). Robustness with respect to the splitting-criterion and the choice of the number of lags can be found in Table 3.10 in Appendix 3.A. For details, see text.

and a *short-run multiplier (SRM)*, measuring the ratio of the change in output to a change in government consumption until after one year at which the impulse to government consumption occurred,

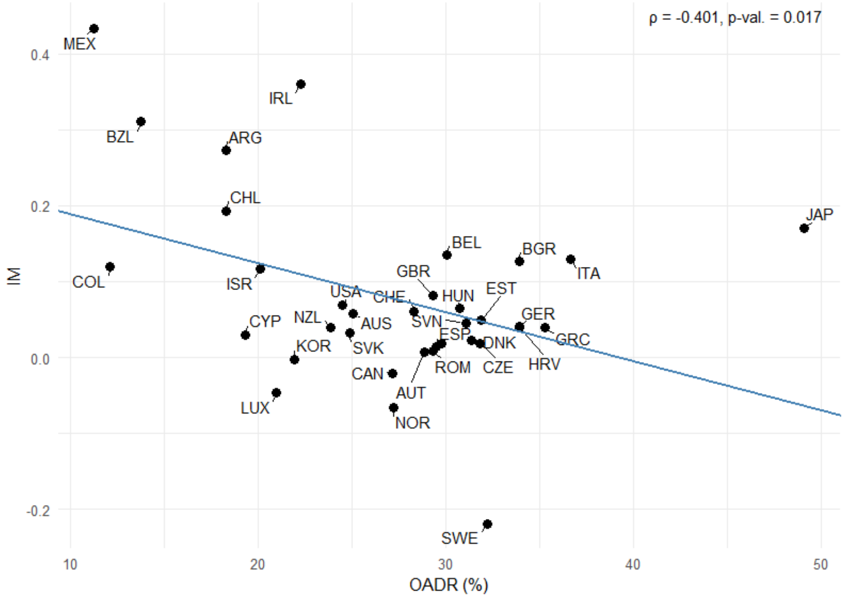
$$SRM = \frac{\sum_{t=0}^{3}(1+r)^{-t}\Delta y_t}{\sum_{t=0}^{3}(1+r)^{-t}\Delta g_t}. \tag{3.4}$$

We use a real interest rate, r, that corresponds to two percent on a yearly basis across all the countries in the sample to calculate the SRM.

We estimate impulse response functions and calculate the IMs and SRMs according to (3.3) and (3.4), respectively. The corresponding results are reported in Table 3.1. For our total sample (including all 35 countries and all 3,019 observations), we find an IM of 0.525 and a SRM of 1.082, and therefore a significant positive production effect induced by an increase in government consumption, both directly in the quarter in which the spending shock occurs and after one year. This finding describes our *first stylized fact*: A positive government spending shock creates a significant positive output effect, on average.

Then, we split the sample into countries with a *young* and an *old* age structure. The proxy for the age structure of the economies is the old-age dependency ratio, relating individuals older than 64 to individuals between 15-64 years old (World Bank, 2024a). We use the median old-age dependency ratio of the sample in the year 2020, corresponding to 28.9 percent, as the splitting-criterion and produce a subsample of 17 countries with a *young* age structure (including 1,408 observations) and a subsample of 18 countries with an *old* age structure (including 1,611 observations). We find an IM for the countries with a *young* age structure of 0.811 and a SRM of 1.164 relative to an IM of 0.412 and a SRM of 1.026 for the countries with

Figure 3.1: Empirical relationship of the multipliers and the old-age dependency ratios.



Note: This figure displays the relationship of the empirically estimated IMs and the old-age dependency ratios in 2020. For details, see text.

an *old* age structure. The IM in countries with a *young* age structure is therefore almost twice as large as in countries with an *old* age structure. The SRM is also 13.5 percent larger. These findings describe our *second stylized fact*: The positive output effect induced by a positive government spending shock is significantly stronger in countries with a *young* age structure than in countries with an *old* age structure. Using the average instead of the median old-age dependency ratio of the sample in the year 2020 as the splitting-criterion (corresponding to 27.1 percent) does not alter the results significantly.[4]

As the next step, we estimate the model from (3.1) for single countries at a time and relate the empirically estimated multipliers to the age structure of the economies. The relationship of the IMs and the old-age dependency ratio of 2020 is graphically represented in Figure 3.1. The raw correlation between the two variables across the countries is -0.401 ($p - val. = 0.017$). Therefore, we observe a significant negative correlation between the IMs and the old-age dependency ratios in 2020.[5]

[4]Additional robustness on the splitting-criterion (using the old-age dependency ratios of 2008 and 1995 and median versus average instead) is reported in Table 3.10 in Appendix 3.A. In addition, we present robustness on the choice of the lags (using $H = 2$ and $H = 6$ instead). Qualitatively, results are unchanged.

[5]Figure 3.8 in Appendix 3.A displays robustness with respect to both types of the multipliers (IMs and SRMs) and with respect to the year of the old-age dependency ratios (2020, 2008, and 1995). All the corresponding correlation coefficients are significantly negative, ranging from -0.401 to -0.538. Figure 3.9 in Appendix 3.A displays robustness with respect to the number of

Table 3.2: OLS regression results for regressing the empirically estimated multipliers on the old-age dependency ratio.

	(1) IM	(2) SRM
$\tilde{\alpha}$	0.25324***	0.63906***
	(0.07212)	(0.21651)
$\tilde{\beta}$	-0.00644**	-0.01935**
	(0.00257)	(0.00770)
R^2	0.161	0.161

Note: This table reports the coefficients from regressing the empirically estimated IMs and SRMs on the old-age dependency ratio in 2020 and a constant, following (3.5). Standard errors are reported in parentheses. It holds: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. For details, see text.

We further proceed by regressing the empirically estimated multipliers in country i on the respective old-age dependency ratio in 2020, according to

$$IM_i = \tilde{\alpha} + \tilde{\beta} \cdot OADR_i + \tilde{\varepsilon}_i. \tag{3.5}$$

The regression results are reported in Table 3.2. We observe that the regression coefficient on the old-age dependency ratio, $\tilde{\beta}$, is negative and statistically significant. This result holds for both types of empirically estimated multipliers and gives us the *third stylized fact*: The positive output effect induced by a positive government spending shock is, across countries, significantly negatively related to the age structure of an economy.[6]

To provide an economic reasoning for these stylized facts and a quantification of the effect of population aging on the size of fiscal multipliers, we build and analyse a quantitative model in the following sections.

3.3 Model

The quantitative model employed in this paper is a medium-scale overlapping generations model in the spirit of Auerbach and Kotlikoff (1987) with endogenous labor supply and idiosyncratic income risk on the household side, as in Conesa et al. (2009). The model is a slightly adjusted version of the set-ups used in Brinca et al. (2016) and Brinca et al. (2021). The population structure is exogenously determined

lags included into the system of equations in (3.1), $H = 2$, $H = 4$, and $H = 6$, for both types of multipliers (IM and SRM). Again, all multipliers are significantly negatively correlated with the old-age dependency ratios, with raw correlation coefficients ranging from -0.326 to -0.401.

[6] Table 3.11 and Table 3.12 in Appendix 3.A report robustness with respect to different old-age dependency ratios (2008 and 1995) and to a different number of lags ($H = 2$ and $H = 6$), respectively. The regression coefficient, $\tilde{\beta}$, is significant across all specifications.

by time-varying demographic processes for population growth and longevity. In a perfectly competitive environment, firms produce with a constant returns to scale production function, and pay a share of the social security contributions. Agents pay consumption taxes, capital taxes, and contribute a share of their labor income to the social security system. Their labor income is progressively taxed. The government runs a balanced-budget pension system and finances government consumption as well as interest payments on outstanding debt obligations by taxing household consumption and interest payments on capital holdings linearly, and labor income progressively. In addition, the government pays lump-sum transfers to households.[7]

3.3.1 Demographics and timing

One model period, t, corresponds to five years. In each model period, a continuum of new households is born. Newborns start with a real-life age of 20, denoted as $j = 1$. All generations retire at the age of 65, $j = J_r = 10$, and live up to a maximum age of 100, $j = J = 17$. In period t, all agents of age j survive until age $j + 1$ with probability $\psi_{j+1,t+j-1}$, where $\psi_{1,t} = 1$ and $\psi_{J+1,t+J-1} = 0$. The size of a cohort of age j in period $s = t + j - 1$ is therefore given by

$$N_{j,s} = \psi_{j,s} \cdot N_{j-1,s-1}. \tag{3.6}$$

The size of a new generation in period t follows

$$N_{1,t} = (1 + n_t) \cdot N_{1,t-1}, \tag{3.7}$$

with $n_t > -1$ as the population growth rate. The total population size is given by $N_t = \sum_{j=1}^{J} N_{j,t}$. There exist no annuity markets. A fraction of households leave unintended bequests, which are lump-sum and uniformly distributed to all currently alive households, denoted by beq_t. Age-specific cohort weights are given by

$$m_{j,t} = \begin{cases} 1, & if\ j = 1, \\ \left(\frac{\psi_{j,t}}{1+n_t}\right) \cdot m_{j-1,t-1}, & else, \end{cases} \tag{3.8}$$

[7] These transfers can also be interpreted as lump-sum taxes as soon as they become negative.

and the old age dependency ratio implied by the model has the following form

$$OADR_t = \frac{N_{r,t}}{N_{w,t}} = \frac{\sum_{j=J_r}^{J} m_{j,t}}{\sum_{j=1}^{J_r-1} m_{j,t}}, \tag{3.9}$$

with $N_{r,t}$ as the size of the retired population and with $N_{w,t}$ as the size of the working population.

3.3.2 Households

All households are endowed with one unit of time in each period and enter the economy with zero wealth, $a_{1,t} = 0$, except for accidental bequests, beq_t, and lump-sum transfers from the government, τ_t. They spend their time supplying labor to a competitive market or consuming leisure. Individual preferences are given by

$$\mathbb{E}\left[\sum_{j=1}^{J} \beta^{j-1} \cdot \left(\Pi_{i=1}^{j} \psi_{i,o}\right) \cdot u(c_{j,s}, \ell_{j,s})\right], \tag{3.10}$$

with $o = t + i - 1$, β as the discount factor and per-period utility

$$u(c_{j,s}, \ell_{j,s}) = \frac{\left((c_{j,s})^{\nu} \cdot (1 - \ell_{j,s})^{1-\nu}\right)^{1-\frac{1}{\gamma}}}{1 - \frac{1}{\gamma}}, \tag{3.11}$$

as a function of age j consumption, $c_{j,s}$, and labor supply, $\ell_{j,s}$, with $\gamma > 0$ as the intertemporal elasticity of substitution and $\nu \in [0, 1]$ as the taste parameter for consumption.

The expectation is formed from an ex-ante perspective, i.e., before any information about labor productivity, $\varepsilon(e(j), \theta, \eta)$, has been revealed to the household. Labor productivity depends on a deterministic and time-independent age-profile of earnings, $e(j) = \iota_1 \cdot j + \iota_2 \cdot j^2 + \iota_3 \cdot j^3$, a group-specific permanent productivity effect, $\theta \in \mathcal{I} \equiv \{\theta^1, ..., \theta^I\}$, which is drawn at the beginning of the life-cycle, and an idiosyncratic shock component, that follows a time-invariant AR(1) process given by

$$\log(\eta') = \rho \cdot \log(\eta) + \epsilon, \quad \epsilon \sim \mathcal{N}(0, \sigma_\epsilon^2), \tag{3.12}$$

with the discrete approximation by a Markov chain with states $\eta \in \mathcal{M} \equiv \{\eta^1, ..., \eta^M\}$ and transition probabilities $\pi(\eta'|\eta) > 0$.[8] The unique invariant distribution associ-

[8] The functional form for the deterministic and time-independent age-profile of earnings, $e(j)$, follows Brinca et al. (2016) and Brinca et al. (2021). The group-specific permanent productivity

ated with π is denoted by Π. Given these shocks, a household's individual labor productivity is given by

$$\varepsilon(e(j), \theta, \eta) = \begin{cases} e(j) \cdot \theta \cdot \eta, & if\ j < J_r \\ 0, & if\ j \geqslant J_r. \end{cases} \tag{3.13}$$

At the mandatory retirement age, individual labor productivity drops to zero, and households stop working and start receiving pension payments, pen_t, provided by the government. Individual public pension payments to households are not type- or earnings history-dependent. Households maximize the expected lifetime utility of (3.10) subject to the periodic budget constraints

$$(1+\tau_t^c)\cdot c_{j,t}+a_{j+1,t+1} = (1+r_t^n)\cdot a_{j,t}+beq_t+\tau_t+\begin{cases} \bar{y}_{j,t} \cdot \left(1 - \tau_t^{p,h} - \tau^\ell(\bar{y}_{j,t})\right), & if\ j < J_r \\ pen_t, & if\ j \geqslant J_r \end{cases} \tag{3.14}$$

and a borrowing constraint, $a_{j,t} \geqslant 0$. Individual variables further satisfy $c_{j,t} > 0$ and $\ell_{j,t} \in [0, 1]$. Individuals pay consumption taxes, $\tau_t^c \in [0, 1]$, capital taxes, $\tau_t^k \in [0, 1]$, and progressive labor income taxes. The net interest rate is given as $r_t^n = (1-\tau_t^k)\cdot r_t$. In addition, households contribute to the social security system. They pay a fixed share $\chi^p \in [0, 1]$ of the social security contributions, such that $\tau_t^{p,h} = \chi^p \cdot \tau_t^p$ holds, with $\tau_t^p \in [0, 1]$. The non-linear labor income tax is modelled in line with the functional form proposed in Heathcote et al. (2017), following

$$\tau^\ell(\bar{y}_{j,t}) = 1 - \lambda_1 \cdot (\bar{y}_{j,t})^{-\lambda_2}, \tag{3.15}$$

with $\bar{y}_{j,t} = \frac{y_{j,t}}{1+\tau_t^{p,f}}$ as the pre-tax labor income normalized by social security contributions paid by the representative firm, $\tau_t^{p,f}$. Pre-tax labor income is given as $y_{j,t} = \varepsilon(e(j), \theta, \eta) \cdot w_t \cdot \ell_{j,t}$ and social security contributions paid by the representative firm follow $\tau_t^{p,f} = (1 - \chi^p) \cdot \tau_t^p$. The parameters $\lambda_1 \in [0, 1]$ and λ_2 govern the level and progressivity of the tax system, respectively. The labor income tax system is progressive if $\lambda_2 > 0$ holds, regressive, if $\lambda_2 < 0$ holds, and flat at the rate of $1 - \lambda_1$, if $\lambda_2 = 0$ holds.

effect is included to capture differences in education and ability.

3.3.3 Firms

A continuum of competitive firms transforms capital, K_t, and labor, L_t, into output by means of a Cobb-Douglas production technology,

$$Y_t = \Omega \cdot (K_t)^{\alpha} \cdot (L_t)^{1-\alpha}, \tag{3.16}$$

with $\Omega > 0$ as the productivity parameter and $\alpha \in (0,1)$ as the capital share. The evolution of capital is given by

$$K_{t+1} = I_t + (1-\delta) \cdot K_t, \tag{3.17}$$

with I_t as gross investment and $\delta \in [0,1]$ as the depreciation rate. The representative firm maximizes profits by choosing the amount of capital and labor used in the production process. The maximization problem has the following standard form

$$\max_{\{K_t, L_t\}} Y_t - w_t \cdot L_t - (r_t + \delta) \cdot K_t, \tag{3.18}$$

subject to (3.16). Solving the maximization problem yields

$$r_t = \Omega \cdot \alpha \cdot \left(\frac{K_t}{L_t}\right)^{\alpha-1} - \delta \tag{3.19}$$

for the interest rate and

$$w_t = \Omega \cdot (1-\alpha) \cdot \left(\frac{K_t}{L_t}\right)^{\alpha} \tag{3.20}$$

for the wage rate. The factor prices are equal to their marginal products.

3.3.4 Government

The government runs a balanced social security system,

$$Pen_t = N_{r,t} \cdot pen_t = \mathcal{R}_t^p. \tag{3.21}$$

It raises social security revenues, $\mathcal{R}_t^p$, from taxing employees and employers at the rates $\tau_t^{p,h}$ and $\tau_t^{p,f}$ respectively, and pays uniform pensions to all retirees in the economy, given as

$$pen_t = \frac{\mathcal{R}_t^p}{N_{r,t}}. \tag{3.22}$$

All other tax revenues resulting from taxing consumption, $\mathcal{R}_t^c$, capital, $\mathcal{R}_t^k$, and labor income, $\mathcal{R}_t^\ell$, finance expenditures on pure public consumption goods, G_t, interest payments on national debt obligations, $r_t \cdot D_t$, and total lump-sum redistribution payments to households, $\mathcal{T}_t$.[9] The budget constraint of the government is given by

$$G_t + (1 + r_t) \cdot D_t + \mathcal{T}_t = \mathcal{R}_t^c + \mathcal{R}_t^k + \mathcal{R}_t^\ell + D_{t+1}. \tag{3.23}$$

3.3.5 Competitive equilibrium

A the beginning of period t, as long as they are workers ($j = \{1, ..., J_r - 1\}$), households are indexed by their age, j, their deterministic productivity type, θ, their idiosyncratic productivity shock, η, and their asset holdings, a. Thus, their maximization problem (in recursive form) is

$$V_t(j, \theta, \eta, a) = \max_{c, a', \ell} \left\{ u(c, \ell) + \beta \cdot \psi_{j,t} \cdot \sum_{\eta'} \pi(\eta' | \eta) \cdot V_{t+1}(j + 1, \theta, \eta', a') \right\} \tag{3.24}$$

$$\text{s.t} \quad (3.13), \quad (3.14), \quad (3.15), \quad a' \geqslant 0, \quad c > 0, \quad \ell \in [0, 1].$$

The maximization problem of retired households ($j = \{J_r, ..., J\}$) is simplified since they do not supply labor, and their deterministic productivity type, as well as the realization of the idiosyncratic shock, become irrelevant. Their maximization problem (in recursive form) is

$$V_t(j, a) = \max_{c, a'} \{u(c, \ell) + \beta \cdot \psi_{j,t} \cdot V_{t+1}(j + 1, a')\} \tag{3.25}$$

$$\text{s.t} \quad (3.14), \quad a' \geqslant 0, \quad c > 0, \quad \ell = 0.$$

Additionally, I define the cross-sectional measure of households at time t by Φ_t.

Definition 3.3.1 (Competitive equilibrium)**.** *Given an initial stock of physical capital, K_0, an initial population size, $N_{1,0}$, an initial cross-sectional measure of households, Φ_0, a sequence of population growth rates, $\{n_t\}_{t=0}^{\infty}$, and a sequence of survival probabilities, $\{\{\psi_{j,t}\}_{j=1}^{J+1}\}_{t=0}^{\infty}$, a competitive equilibrium are sequences of individual functions for the households,*
$\{V_t(j, \theta, \eta, a), c_t(j, \theta, \eta, a), \ell_t(j, \theta, \eta, a), a_t'(j, \theta, \eta, a)\}_{t=0}^{\infty}$, sequences of production plans,

[9] Individual lump-sum redistribution payments to households follow as $\tau_t = \frac{\mathcal{T}_t}{N_t}$.

$\{L_t, K_t\}_{t=0}^{\infty}$, *prices*, $\{w_t, r_t\}_{t=0}^{\infty}$, *accidental bequests*, $\{beq_t\}_{t=0}^{\infty}$, *government policies*, $\{\tau_t^p, \tau_t^c, \tau_t^k, \tau_t, G_t, D_{t+1}\}_{t=0}^{\infty}$, *and the cross-sectional measure of households*, $\{\Phi_t\}_{t=0}^{\infty}$, *such that*

1. *Given prices, policies, accidental bequests, and initial conditions,* $V_t(j, \theta, \eta, a)$ *solves (3.24),* $V_t(j, a)$ *solves (3.25),* $c_t(j, \theta, \eta, a), \ell_t(j, \theta, \eta, a)$ *and* $a_t'(j, \theta, \eta, a)$ *are the associated policy functions.*

2. *The population size of the newborn generation evolves according to (3.7).*

3. *The interest rate and the wage rate satisfy (3.19) and (3.20).*

4. *Total accidental bequests are given by*

$$Beq_{t+1} = \int beq_t \cdot \Phi_{t+1}(dj \times d\theta \times d\eta \times da) \tag{3.26}$$

$$= \int (1 - \psi_{j,t}) \cdot (1 + r_{t+1}^n) \cdot a_t'(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da). \tag{3.27}$$

5. *Government policies satisfy (3.21) and (3.23) in every period, with*

   - *aggregate social-security contributions as*

$$\mathcal{R}_t^p = \int_{j<J_r} \left(\tau_t^{p,f} + \tau_t^{p,h}\right) \cdot \underbrace{\left(\frac{\varepsilon(p(j), \theta, \eta) \cdot \ell_t(j, \theta, \eta, a) \cdot w_t}{1 + \tau_t^{p,f}}\right)}_{= \bar{y}_t(j,\theta,\eta,a)} \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.28}$$

   - *aggregate consumption tax revenues as*

$$\mathcal{R}_t^c = \int \tau_t^c \cdot c_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.29}$$

   - *aggregate capital tax revenues as*

$$\mathcal{R}_t^k = \int \tau_t^k \cdot r_t \cdot a_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.30}$$

   - *aggregate labor income tax revenues as*

$$\mathcal{R}_t^\ell = \int_{j<J_r} \tau_t^\ell \left(\bar{y}_t(j, \theta, \eta, a)\right) \cdot \bar{y}_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.31}$$

- *and total lump-sum redistribution payments to households as*

$$\mathcal{T}_t = \int \tau_t \cdot \Phi_t(dj \times d\theta \times d\eta \times da). \tag{3.32}$$

6. *Markets clear in all periods t,*

- *the labor market,*

$$L_t = L_t^s = \int \varepsilon(e(j), \theta, \eta) \cdot \ell_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.33}$$

- *the capital market,*

$$K_{t+1} + D_{t+1} = A_{t+1} = \int a_t'(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.34}$$

- *and the goods market,*

$$Y_t = C_t + I_t + G_t, \tag{3.35}$$

with

$$C_t = \int c_t(j, \theta, \eta, a) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.36}$$

and investment following from (3.17).

7. *The cross-sectional measure of households evolves as*

$$\Phi_{t+1}(\mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) = \int P_t((j, \theta, \eta, a), \mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) \cdot \Phi_t(dj \times d\theta \times d\eta \times da), \tag{3.37}$$

for all sets, $\mathcal{J}, \mathcal{I}, \mathcal{M}, \mathcal{A}$, where the Markov transition function, P_t, is given by

$$P_t((j,\theta, \eta, a), \mathcal{J} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) = \begin{cases} \psi_{j,t} \cdot \pi(\eta'|\eta), & if\ a_t'(j, \theta, \eta, a) \in \mathcal{A}, for\ \theta \in \mathcal{I}, j+1 \in \mathcal{J}, \eta' \in \mathcal{M}, \\ 0, & else. \end{cases} \tag{3.38}$$

and for newborns as

$$\Phi_{t+1}(\{1\} \times \mathcal{I} \times \mathcal{M} \times \mathcal{A}) = N_{1,t+1} \cdot \begin{cases} \Pi_1(\theta, \eta), & if\ 0 \in \mathcal{A}, \\ 0, & else, \end{cases} \tag{3.39}$$

The initial distribution, $\Pi_1(\theta, \eta)$ of $\theta \in \mathcal{I} = \{\theta^1, ..., \theta^I\}$ and $\eta \in \mathcal{M} = \{\eta^1, ..., \eta^M\}$

among the one-year old households is chosen to be uniform.[10]

Definition 3.3.2 (Stationary competitive equilibrium)**.** *A stationary competitive equilibrium is a competitive equilibrium in which individual behaviour is consistent with the aggregate behaviour of the economy, and the population growth rate, and the survival probabilities are constant over time, i.e.* $n_t = n$ *and* $\{\psi_{j,t} = \psi_j\}_{j=1}^J$.

3.4 Calibration

The model is calibrated to 18 different countries for the stationary equilibrium in the year 2020. This allows for a cross-country analysis of the size of the fiscal multipliers and their dependence on the respective age structure.[11] This section presents the calibration strategy for the US economy, which serves as the baseline economy in our analysis. The calibration procedure for all other countries is identical. Table 3.3, Table 3.4 and Table 3.5 summarize the choice of the exogenously chosen parameters common across all countries, the country-specific and exogenously chosen parameters, and the endogenously calibrated and country-specific parameters. We calibrate seven parameters endogenously to match seven different targets. Table 3.6 summarizes the fit of the model with respect to the targeted moments.

3.4.1 Exogenously chosen parameters common across all countries

We set the capital share, α, to 0.33 across all countries, while the parameter governing the intertemporal elasticity of substitution, γ, is set to 0.5. These values are standard in the literature. The depreciation rate, δ, is set to a value of 0.266, which corresponds to an annualized depreciation rate of six percent. The persistence of the idiosyncratic shock, denoted by the parameter ρ, and the parameter governing the variance of the idiosyncratic shock, denoted by the parameter σ_ϵ, are taken from Brinca et al. (2021) and set to 0.335 and 0.307, respectively. The number of deterministic productivity types, denoted by $\mathcal{I}$, is set to 2, and the number of idiosyncratic productivity types, denoted by $\mathcal{M}$, to 7. The former decision is driven by the idea of accounting for tertiary versus non-tertiary educated individuals in the

[10] In detail, $\Pi_1(\theta^1, \eta^1) = \Pi_1(\theta^1, \eta^2) = \Pi_1(\theta^2, \eta^1) = ... = \Pi_1(\theta^I, \eta^M) = \frac{1}{I \cdot M}$.

[11] The countries of interest are Austria (AUT), Canada (CAN), the Czech Republic (CZE), Finland (FIN), France (FRA), Germany (GER), Greece (GRC), Iceland (ICL), Italy (ITA), Japan (JAP), the Netherlands (NLD), Portugal (PRT), Spain (ESP), Slovakia (SVK), Sweden (SWE), Switzerland (CHE), the United Kingdom (GBR), and the United States (USA).

Table 3.3: Exogenously chosen parameters common across all countries.

Parameter	Description	Value	Source
α	Capital share	0.330	Standard
γ	Intertemp. elasticity of substitution	0.500	Standard
δ	Depreciation rate*	0.266	Standard
ρ	Persistence of idiosyncratic shock	0.335	Brinca et al. (2021)
σ_ϵ	Variance of idiosyncratic productivity	0.307	Brinca et al. (2021)
I	No. of determ. productivity types	2	Tertiary vs. Non-Tertiary, $i = \{H, L\}$
M	No. of idiosync. productivity types	7	Standard

Note: This table reports the exogenously chosen parameters common across all countries for the stationary equilibrium in 2020. For details, see text. *The value corresponds to an annualized depreciation rate of 6 percent.

economy and matching the observed skill premium in the data. The latter decision is a standard assumption in the literature.

3.4.2 Country-specific and exogenously chosen parameters

The age-dependent survival probabilities, denoted by $\{\psi_j\}_{j=1}^{J+1}$, are derived from United Nations (2022b). The reported survival probabilities are converted to five-year values for the stationary equilibrium in 2020.[12] We then take the average values of the respective five consecutive years to align the data with the model.[13] The three parameters determining the shape of the age-dependent productivity profile of workers, ι_1, ι_2, and ι_3, are chosen based on values from Brinca et al. (2016) and set to 0.9556, -0.0183 and -0.0035, respectively.[14] We set the debt-output ratio, denoted by $\frac{D}{Y}$, to a value of 132.6 percent, in line with the data from IMF (2025c). Following Brinca et al. (2016), the consumption tax rate, τ^c, is set to a value of 4.7 percent, and the capital tax rate, τ^k, is set to a value of 36.4 percent. The parameters governing the average and the progressivity level of the income tax system, λ_1 and λ_2, follow Brinca et al. (2016) and are set to 0.888 and 0.137, respectively. The share of

[12]This conversion is required because the dataset reports survival probabilities on an annual basis. These annual survival probabilities are then multiplied in five-year increments to align with the age-group intervals in the model.

[13]The final survival probabilities used in the calibration are depicted in Figure 3.10 in Appendix 3.B.

[14]In detail, we convert the age profiles from Brinca et al. (2016) for a model in which one period corresponds to one year to an age-structure in which one period corresponds to five years. We use the values for the parameters reported in Brinca et al. (2016), $\hat{\iota}_1 = 0.26500$, $\hat{\iota}_2 = -0.00300$, and $\hat{\iota}_3 = 0.00004$, and calculate 5-year averages in accordance with $\hat{e}(\hat{j}) = \hat{\iota}_1 \cdot \hat{j} + \hat{\iota}_2 \cdot \hat{j}^2 + \hat{\iota}_3 \cdot \hat{j}^3$, $\hat{j} = \{1, 2, ..., \hat{J}_r - 1\}$, such that $e(1) = \frac{\hat{e}(1)+\hat{e}(2)+\hat{e}(3)+\hat{e}(4)+\hat{e}(5)}{5}$, $e(2) = \frac{\hat{e}(6)+\hat{e}(7)+\hat{e}(8)+\hat{e}(9)+\hat{e}(10)}{5}$, ..., $e(J_r - 1 = 9) = \frac{\hat{e}(41)+\hat{e}(42)+\hat{e}(43)+\hat{e}(44)+\hat{e}(\hat{J}_r - 1 = 45)}{5}$ hold. Then, we use $e(2)$, $e(5)$, and $e(7)$ to find the respective values for ι_1, ι_2 and ι_3 that solve a system of three equations and three unknowns, where $e(j) = \iota_1 \cdot j + \iota_2 \cdot j^2 + \iota_3 \cdot j^3$ holds, for $j = \{2, 5, 7\}$. The resulting age-dependent productivity profile is depicted in Figure 3.11 in Appendix 3.B.

Table 3.4: Country-specific and exogenously chosen parameters.

Parameter	Description	Value	Source
$\{\phi_j\}_{j=1}^{J+1}$	Survival probabilities	Figure 3.10	United Nations (2022b)
ι_1	Age-dependent productivity	0.9556	Brinca et al. (2016)
ι_2	Age-dependent productivity	-0.0183	Brinca et al. (2016)
ι_3	Age-dependent productivity	-0.0035	Brinca et al. (2016)
$\frac{D}{Y}$	Debt-output ratio*	132.6	IMF (2025c)
τ^c	Consumption tax rate*	4.7	Brinca et al. (2016)
τ^k	Capital tax rate*	36.4	Brinca et al. (2016)
λ_1	Labor income system, average	0.888	Brinca et al. (2016)
λ_2	Labor income system, progressivity	0.137	Brinca et al. (2016)
χ^p	Share of soc.-sec. contributions paid by workers*	47.2	ISSA (2025)

Note: This table reports country-specific and exogenously chosen parameters for the stationary equilibrium in 2020 for the United States. For details, see text. The respective parameters for all other countries are collected in Table 3.13 in Appendix 3.B. *Values are reported in percent.

social-security contributions paid by workers, denoted by χ^p, is set to 47.2 percent and derived from data reported by ISSA (2025).[15]

3.4.3 Endogenously calibrated and country-specific parameters

We calibrate the population growth rate, n, to an annualized value of 1.42 percent to match the old-age dependency ratio of 24.5 percent for the United States in 2020, in line with United Nations (2022b). We set the government consumption-output ratio, $\frac{G}{Y}$, to a value of 29.7 percent to prevent non-zero individual transfer payments in the stationary equilibrium in 2020. In fact, we normalize the transfer-output ratio, $\frac{T}{Y}$, to 0 percent. This normalization ensures comparability across countries. The production productivity parameter, Ω, is set to a value of 1.700: This choice ensures a unitary wage rate in the stationary equilibrium in 2020. The taste parameter for consumption, ν, is set to 0.478 and chosen so that the average individual labor supply of all workers is 29.8 percent of their total available time.[16] The parameter governing the variance of permanent productivity, σ_θ, is set to 0.265 so that the tertiary education premium, $\frac{\tilde{y}(\theta^H)}{\tilde{y}(\theta^L)}$, in the stationary equilibrium in 2020 lies at a

[15] The International Social Security Association (ISSA) reports total average social-security contribution rates, the average values for the insured person and the average values for the respective employer across all branches. The share of social-security contributions paid by the worker is calculated as their share of the total average social-security contribution rate. We use the most recent available values for each country, in the US case this is the year 2019.

[16] This number is calculated by dividing the average annual hours actually worked per worker reported by OECD (2025a) for the year 2020 by 6.024 available hours. Available hours are defined as the total number of hours in a year minus Saturdays, Sundays, and an average of ten public holidays, resulting in 251 available working days, multiplied by 24 hours per day.

Table 3.5: Endogenously calibrated and country-specific parameters.

Parameter	Description	Value
n	Population growth rate*	1.42
$\frac{G}{Y}$	Government consumption-output ratio*	29.7
Ω	Production productivity	1.700
ν	Taste parameter for consumption	0.478
σ_θ	Variance of permanent productivity	0.265
β	Subjective discount factor	1.015
τ^p	Social-security contribution rate*	10.2

Note: This table reports the endogenously calibrated and country-specific parameters for the stationary equilibrium in 2020 for the United States. The population growth rate reported in this table corresponds to the annualized growth rate. The discount factor corresponds to the annualized factor. For details, see text. The respective parameters for all other countries are collected in Table 3.14 in Appendix 3.B. *Values are reported in percent.

value of 1.81, based on OECD (2022b).[17] The annualized subjective discount factor, β, is calibrated to 1.015, to match the capital-output ratio of 224.3 percent in the data, based on IMF (2021).[18] The social-security contribution rate, τ^p, is set to 10.2 percent, which leads to an average gross pension replacement rate of 39.2 percent, based on OECD (2025b).[19] In the model, the average gross pensions replacement rate is measured as the individual pension payments relative to the average labor income from the previous period.[20] The model perfectly fits the targeted moments.

The model-implied annualized (after-tax) interest rate is 5.36 percent. The investment-output ratio is 15.21 percent, which understates the non-targeted real-world counterpart of 21.59 percent (World Bank, 2025b). The model's aggregate consumption expenditure to output ratio lies at 84.79 percent and therefore fairly close to its non-targeted real-world counterpart of 81.51 percent (World Bank, 2025a).[21] The public pensions to output ratio is 6.43 percent, one percentage point smaller than in the data (OECD, 2025c).

Table 3.7 collects model and data moments for the total income and wealth dis-

[17]The tertiary education premium is calculated as the ratio of the relative earnings of 25-64 year-old adults with tertiary educational attainment versus upper secondary or post-secondary non-tertiary educational attainment for the year 2020.

[18]The capital-output ratio is calculated as the sum of the general government capital stock, the private capital stock, and – if applicable – the public-private partnership capital stock in a specific year, divided by the respective gross domestic product. We use the data series that are reported in billions of constant 2017 international dollars. Then, we calculate the average value of the ratio from 1990 to 2019.

[19]The gross pension replacement rates are reported separately for men and women. We use the values for the year 2020 and calculate the simple average for men and women.

[20]In detail, we define the average gross pension replacement rate as follows: $\tilde{\kappa}_t = \frac{pen_t}{w_{t-1}L^s_{t-1}/N_{w,t-1}}$.

[21]Aggregate consumption expenditure is understood as the sum of aggregate private consumption and government consumption, in line with the definition in World Bank (2025a).

Table 3.6: Country-specific targeted moments and model fit.

Target	Description	Model	Data	Source
$OADR$	Old-age dependency ratio*	24.5	24.5	United Nations (2022b)
$\frac{T}{Y}$	Transfer-output ratio*	0	0	Normalization
w	Wage rate	1	1	Normalization
$\tilde{\ell}$	Average labor supply*	29.8	29.8	OECD (2025a)
$\frac{\tilde{y}(\theta^H)}{\tilde{y}(\theta^L)}$	Tertiary education premium	1.81	1.81	OECD (2022b)
$\frac{K}{Y}$	Capital-output ratio*	224.3	224.4	IMF (2021)
$\tilde{\kappa}$	Average gross pension replacement rate*	39.2	39.2	OECD (2025b)

Note: This table reports the country-specific targeted moments and the model fit for the stationary equilibrium in 2020 for the United States. For details, see text. The respective model fit for all other countries is reported in Table 3.15 in Appendix 3.B. *Values are reported in percent.

tributions. Total income measures are calculated before taxes.[22] The data counterparts for total income and wealth measures are based on World Inequality Database (2025). We focus on the Gini coefficients, the quintile shares (Q1-Q5), the Bottom50, the Top10, and the Top1 percent shares of the respective variable. Although the Gini coefficient for total income is a non-targeted moment, it is still matched. Most of the other non-targeted moments for the total income distribution are also close to their data counterparts. However, the model predicts an insufficiently high total income share for the Top1 percent. The Gini coefficient for wealth, at 0.686, is significantly below its data counterpart and therefore significantly understates wealth inequality. This difference in the Gini coefficient is mainly driven by insufficiently concentrated wealth holdings at the top of the wealth distribution, e.g., observable from the difference of the Top1 wealth share of 17.6 percentage points between the data and the model value. This observation is a caveat of standard Aiyagari (1994)-models.[23]

3.5 Quantitative results

This section reports the quantitative results. We follow the literature and perform the fiscal experiment to which most of the literature on fiscal multipliers relates to (Baxter and King, 1993). The government increases its consumption and finances

[22](Pre-tax) total income consists of labor income (if $j \leqslant J_r - 1$) and interest income, accidental bequests, lump-sum transfers, and pension payments (if $j \geqslant J_r$), such that: $y^{tot}_{j,t} = \begin{cases} y_{j,t} + r_t \cdot a_{j,t} + beq_t + \tau_t, if\ j \leqslant J_r - 1, \\ pen_t + r_t \cdot a_{j,t} + beq_t + \tau_t, if\ j \geqslant J_r. \end{cases}$

[23]The introduction of a bequest motive can help to bring the model-implied wealth distribution closer to the empirical observations (Brinca et al., 2021).

Table 3.7: Distributional measures.

	Gini	Q1	Q2	Q3	Q4	Q5	Bottom50	Top10	Top1
Total income, y^{tot}									
Model	0.578	1.5	4.1	12.2	23.1	59.0	10.6	39.3	7.8
Data	0.574	2.1	6.5	11.7	19.6	60.1	13.7	44.6	18.2
Wealth, a									
Model	0.686	0.0	0.2	6.6	26.0	67.1	1.9	42.5	16.6
Data	0.826	0.0	0.4	3.3	11.7	84.6	1.6	70.1	34.2

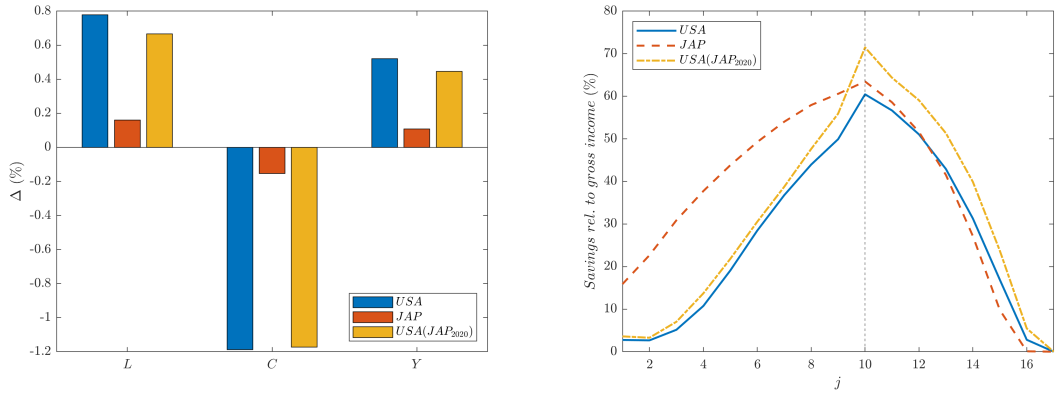
Note: This table reports Gini coefficients, the quintile shares (Q1-Q5), the Bottom50, the Top10, and the Top1 percent shares for the stationary equilibrium in 2020 for the United States. All values, except the Gini coefficients, are reported in percent. All data values are based on World Inequality Database (2025). For details, see text.

this additional spending by non-distortionary taxation. Specifically, this means that the government reduces lump-sum transfers or – as in the stationary equilibrium, the transfers to households are zero by assumption – imposes lump-sum taxes. The fiscal experiment can be understood as an *MIT shock*, an unexpected, one-time deviation from the stationary equilibrium value of government consumption. Government debt, as well as all other tax rates, are assumed to be constant across time. The specific assumption on the government spending shock is as follows: Government consumption in 2025 ($t = 1$) increases by 5.1 percent relative to its calibrated stationary equilibrium value in 2020 ($t = 0$), i.e. $G_1 = 1.051 \cdot G_0$.[24] From 2030 ($t = 2$) onward, government consumption returns back to the same relation to production as in the stationary equilibrium before the shock, i.e. $G_t = \frac{G_0}{Y_0} \cdot Y_t, \forall t \geqslant 2$. Consequently, lump-sum transfers to the households react to clear the government budget in every period. The multiplier of interest in the model is the impact multiplier, IM, defined as the ratio of the adjustment in production in 2025 ($t = 1$) relative to the government spending adjustment in the same period, i.e. $IM = \frac{\Delta Y_1}{\Delta G_1}$.

Figure 3.2, panel (a), depicts the reaction of aggregate labor, consumption, and production to the positive government spending shock in 2025, relative to the stationary equilibrium in 2020, and highlights the mechanism that drives the positive IM. The initial increase in government consumption creates a decline in the transfer-output ratio. This happens because lump-sum taxes (the same as negative lump-sum transfers) refinance additional government spending. Consequently, households suffer from a negative wealth effect. To make up for at least part of the drop in available income, households decide to work more, but they also consume less. In the aggregate, labor increases by 0.78 percent and consumption drops by

[24] The size of the government spending increase corresponds to an annual increase in government spending by 1 percent.

Figure 3.2: Economic mechanism behind the positive impact multiplier and comparison across different age structures.



(a) Changes rel. to stationary equilibrium.

(b) Savings rel. to gross income.

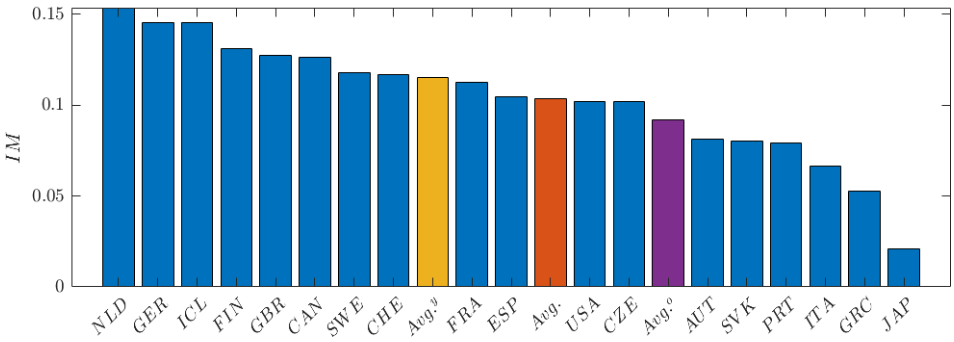
Note: Panel (a) in this figure depicts changes in aggregate labor, consumption, and production for 2025 relative to the stationary equilibrium in 2020 in percent. The blue bars display the adjustments for the benchmark US economy, the orange bars the adjustments for Japan, and the yellow bars the adjustments for the US economy with the age structure of the Japanese economy. Panel (b) displays individual average savings to gross income ratios across age groups in the stationary equilibrium in 2020 in percent for the same configurations as in panel (a). For details, see text.

1.19 percent in the United States, our benchmark economy (blue bars). As capital is predetermined and the drop in investment (induced by the households' consumption smoothing motive) realizes only in the subsequent periods, the increase in aggregate labor induces a positive output effect. Production increases by 0.52 percent. The production adjustment relative to the increase in government consumption creates a positive IM of 0.102.

The model-implied IMs across all countries in the sample are displayed in Figure 3.3. Generally, we observe that a positive government spending shock creates, on impact, a positive output effect in all the countries, in line with our *first stylized fact*. The unweighted sample average IM is 0.104 (orange bar). The model-implied IMs range from the maximum size of 0.154 in the Netherlands to the minimum size of 0.021 in Japan. The size of the IM in our benchmark economy, the United States, is close to the unweighted sample average IM. Although the absolute size of IMs is relatively small, we still observe significant variation in the size of the IMs across countries. The IM in the Netherlands is more than seven times larger than the IM in Japan. And, although the IM in the United States is close to the unweighted sample average IM, it is still around five times larger than the IM in Japan.

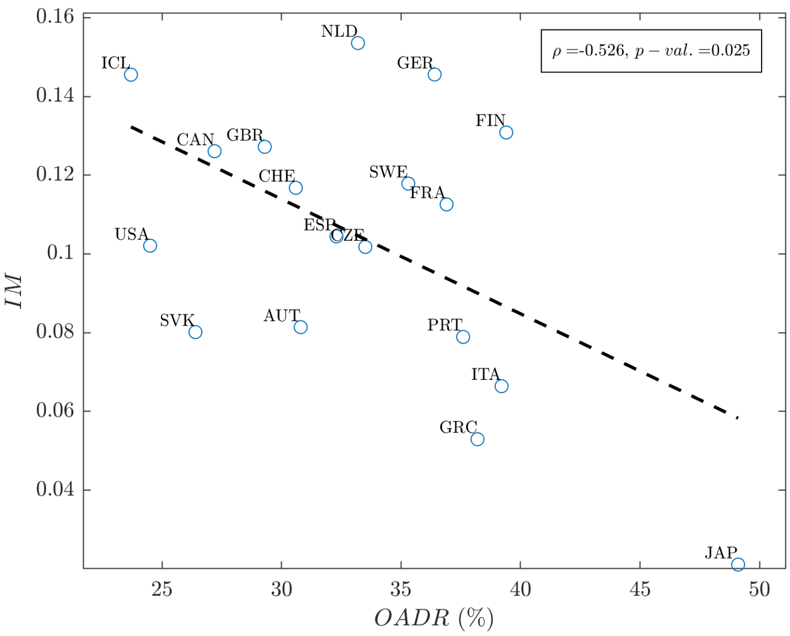
Grouping the sample similar to the empirical exercise into *young* and *old* age

Figure 3.3: Impact multipliers across countries.



Note: This figure depicts the model-implied IMs across all countries in the model sample. The orange bar represents the unweighted sample average IM. The yellow (purple) bar represents the average IM for the *young* (*old*) age structure country group. For details, see text.

Figure 3.4: Impact multipliers across countries relative to the old-age dependency ratios.



Note: This figure relates the model-implied IMs across all countries in the sample to the respective old-age dependency ratios (in percent) in 2020. For details, see text.

structure countries (either by the median or the average old-age dependency ratio in 2020 as the splitting-criterion), we also observe that the IM in *young* age structure countries is significantly larger than the IM in the *old* age structure countries, in line with our *second stylized fact*. The average IM for *young* age structure countries is with a value of 0.115 (yellow bar), around 25 percent larger than the average IM for *old* age structure countries, with a value of 0.092 (purple bar).

To be coherent with the *third stylized fact*, we should observe a negative correla-

Table 3.8: OLS regression results across and within countries.

	(1) CCR	(2) WCR
$\tilde{\alpha}^{Model}$	0.20126***	0.11901***
	(0.04012)	(0.00189)
$\tilde{\beta}^{Model}$	-0.00291**	-0.00067***
	(0.00118)	(0.00006)
R^2	0.277	0.901
Δ	-0.0184	-0.0042
Δ IM (%)	17.71	4.12

Note: This table reports the coefficients from regressing the model-implied IMs on the old-age dependency ratios and a constant, following (3.5). CCR in column (1) corresponds to a *cross-country regression*, where countries differ in terms of their age-structure, but also other country-specific parameters. WCR in column (2) corresponds to a *within-country regression* for the US, where we only vary the age structure of the US economy in line with all other countries in the sample. Standard errors are reported in parentheses. It holds: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$. For details, see text.

tion between the IM and the age structure of the economies, proxied by the old-age dependency ratio. Therefore, we relate our model-implied IMs to the respective old-age dependency ratios in 2020 in Figure 3.4. We observe a significant negative correlation with a raw correlation coefficient of the IM and the old-age dependency ratio of -0.526 (p-value = 0.025).

Similar to the empirical exercise, we then perform a simple linear *cross-country regression (CCR)* of the model-implied IMs on the old-age dependency ratios, following (3.5). Table 3.8, column (1), reports the results for this regression. Both the intercept and the coefficient on the old-age dependency ratio are statistically significant. The significant negative $\tilde{\beta}$ coefficient shows that the model predictions about the correlation of the size of the IM and the age structure of an economy are in line with the *third stylized fact*. The estimates suggest that a one standard deviation increase in the old-age dependency ratio (+6.3 percentage points) leads to a decline of 0.018 units in the size of the IM. This is a sizeable decline, as it corresponds to a 17.71 percent reduction of the unweighted sample average IM.

By comparing the blue and the orange bars in Figure 3.2, panel (a), we learn more about the difference in the size of the IMs between the United States, as a country with a relatively young age structure in 2020 ($OADR_{US,2020} = 24.5\%$), and Japan, as the country with the oldest age structure ($OADR_{JAP,2020} = 49.1\%$) in the model sample. As a consequence of the positive government spending shock, and the increase in the lump-sum taxes to refinance additional government spending, the labor adjustment in Japan, driven by the negative wealth effect, is significantly weaker (only +0.16 percent) in comparison to the United States. The same holds true for the consumption reduction (only -0.15 percent). The dampened increase in aggregate labor creates a less significant increase in production (only +0.11 percent) and therefore a much smaller IM for Japan. Individuals in the Japanese economy save more intensively over the life cycle as they live longer. The difference in the savings behaviour, especially among workers, is observable in Figure 3.2, panel (b), by comparing average saving to gross income ratios across age groups between the Japanese economy (broken orange line) and the United States (solid blue line). Japanese workers save significantly more, and the negative wealth effect induced by the increase in lump-sum taxation to refinance additional government consumption is therefore less severe, leading to a dampened labor supply response among the working households.[25]

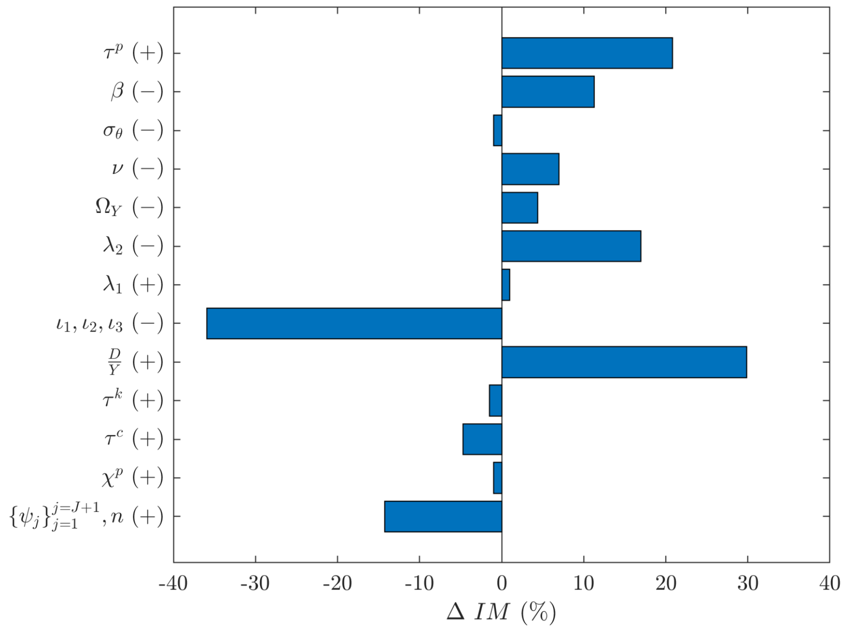
The countries in the model sample differ not only along the old-age dependency ratios but along many other dimensions: the social-security contribution rates, the subjective discount factors, the variances of the permanent productivity type, the taste parameters for consumption, the production productivity parameters, the parameters governing the average and the progressivity level of the tax system, the parameters governing the age-dependent productivity profile, the debt-output ratio, the consumption and capital tax rates, and the social-security contribution share paid by workers. Therefore, we break down the drivers of the difference in the IMs between the United States and Japan to highlight the importance of the differences in the age structures between the two countries. We adjust all the parameters that differ across the US and Japan one by one. For instance, we calculate the IM for the United States under the assumption that all country-specific parameters remain at their baseline calibration values, but the demographic parameters – the population growth rate and the survival probabilities – change to the Japanese values.[26]

Figure 3.5 displays the results of this exercise. Several parameter adjustments have significant effects on the size of the IM. An increase in the social security tax rate relative to the benchmark US calibration, a lower labor income tax progressivity, a higher debt-output ratio, and a lower discount factor lead to substantial increases in the IM by 20.84 percent, 16.97 percent, 29.87 percent, and 11.26 percent, respectively. The IM declines significantly by 35.95 percent if the parameters governing the age-dependent productivity profile are adjusted to the Japanese val-

[25] Higher individual savings also lead to a significantly higher aggregate capital in the Japanese economy of 366.9 percent relative to the US baseline value of 224.3 percent.

[26] This joint adjustment of the demographic parameters ensures that we compare the benchmark US economy to a hypothetical US economy with the exact same age structure as in the Japanese economy.

Figure 3.5: Differences in the impact multipliers in the United States for one by one adjustments in the calibration parameters to the Japanese values.

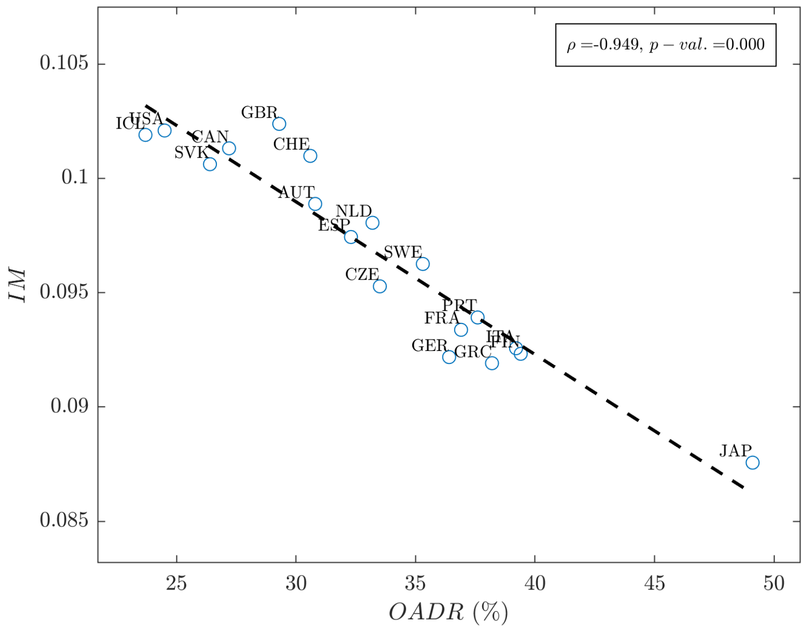


Note: This figure displays changes in the IM for the United States (in percent), when replacing the respective parameter one by one with the calibrated value of the Japanese economy. The signs in brackets behind each variable highlight whether the respective variable increases (+) or decreases (−) relative to the baseline US value. For details, see text.

ues. The change in the productivity profile parameters leads to a significant decline in the average age-dependent productivity level. When calculating the IM for the US economy with the Japanese age structure, we observe a strong reduction in the IM by 14.23 percent.

The explanation for the difference in the size of the IMs between the US economy and the hypothetical US economy with the Japanese age structure follows from comparing the blue and the yellow bars in Figure 3.2, panel (a). The increase in labor supply in the hypothetical US economy with the Japanese age structure (+0.67 percent) is less pronounced than in the benchmark economy with the younger age structure (+0.78 percent). As a result, we observe a mitigated production effect (+0.45 percent instead of +0.52 percent), and consequently a smaller IM. Changing the age structure from the baseline US case to the hypothetical US case with the Japanese age structure incentivizes individuals to save more over the life cycle, as individuals live longer. This adjustment is also observable from Figure 3.2, panel (b), by comparing the solid blue and the broken yellow line. The induced negative wealth effect, through lump-sum taxes to refinance additional government spending, is less severe for individuals with relatively higher wealth holdings, observable across

Figure 3.6: Hypothetical impact multipliers in the United States relative to the old-age dependency ratios across all countries in 2020.



Note: This figure relates the hypothetical model-implied IMs in the United States for the age structure calibrated across all countries in the sample to the respective old-age dependency ratios (in percent) in 2020. For details, see text.

all age groups in the hypothetical US economy with the Japanese age structure. The labor supply reaction of the workers is therefore less pronounced.[27]

The mechanism at play is further supported by the observation of a higher IM for the United States, if the social security tax rate is at the higher Japanese level. Higher expected pensions reduce the need for life cycle savings, leaving households with relatively less wealth holdings. Consequently, in response to a positive government spending shock financed by lump-sum taxes, the negative wealth effect is more severe, and workers respond with a stronger increase in labor supply, raising the IM. Furthermore, a smaller discount factor leads to an increase in the IM, again driven by reduced incentives to save over the life cycle and, therefore, stronger labor supply responses in the case of higher lump-sum taxes.[28]

Adjusting purely the age structure from the baseline US to the hypothetical US case with the Japanese values disentangles the pure effect of population aging

[27] Again, higher individual savings also lead to a significantly higher aggregate capital in the hypothetical US economy with the Japanese age structure of 301.3 percent relative to the US baseline value of 224.3 percent.

[28] The adjustments in the average savings relative to gross income for these two counterfactuals relative to the baseline US case and the hypothetical US case with the Japanese age structure are depicted in Figure 3.12 in Appendix 3.C.

on the IM from a combined effect of the age structure and other country-specific parameters. Therefore, to estimate the pure aging effect for the US economy, we calculate several hypothetical IMs for the US by adjusting the age structure to all the different countries included in the model sample.

Figure 3.6 displays the resulting hypothetical IMs from this exercise. We observe a significant negative relationship between the hypothetical US IMs and the old-age dependency ratios across all the countries with a highly significant raw correlation coefficient of -0.949. Then, we regress the model-implied hypothetical US IMs on the old-age dependency ratios, in line with (3.5). The resulting coefficients from this *within-country regression (WCR)* are reported in Table 3.8, column (2). Again, both the intercept and the coefficient on the old-age dependency ratio are statistically significant. We find that a hypothetical one standard deviation increase in the old-age dependency ratio (+6.3 percentage points) within the US leads to a decline of 0.004 units in the size of the hypothetical US IM. This decline corresponds to a reduction in the hypothetical average US IM by 4.36 percent. We perform the same exercise for all the countries included in the model sample.[29] The average decline in a country's hypothetical average IM across all the countries for a one standard deviation increase in the old-age dependency ratio is 3.61 percent, ranging from a maximum of 5.04 percent in Switzerland to a minimum of 1.62 percent in Slovakia. Although the pure effects of an adjustment in the age structure are significantly smaller than the effects from a change in the age structure interacted with differences in all other country-specific variables, they are still sizeable.

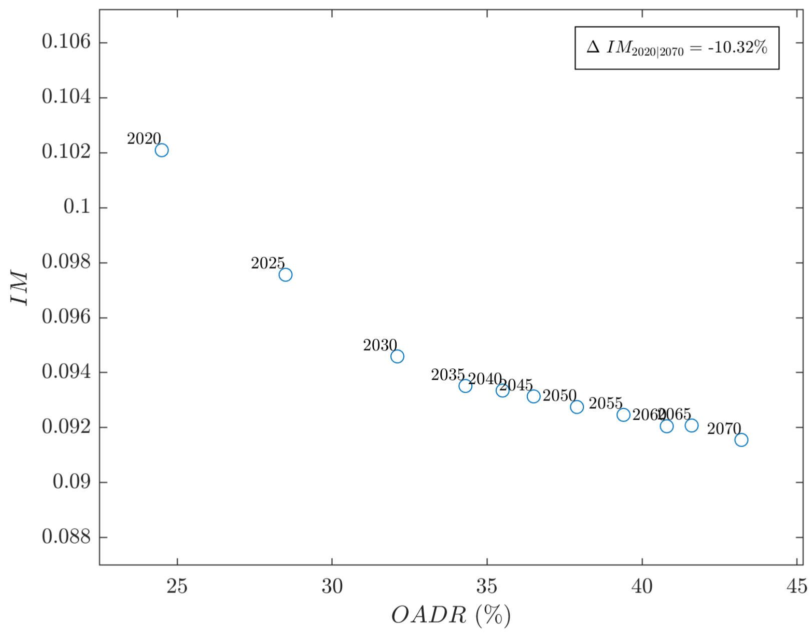
As a last exercise, we want to understand how the IMs will evolve in the future, depending on the projected age structures of the economies. To do this, we adjust the age structure of a specific country such that the model replicates the projected old-age dependency ratios by the United Nations (2022b) until the year 2070. In line with these projections, the old-age dependency ratio in the US will increase to 37.9 percent by 2050 and even further to 43.2 percent by 2070.

Figure 3.7 presents the IMs dependent on the predicted old-age dependency ratios in five-year steps until 2070. We observe that the IMs will drop quite significantly in future years. Population aging leads to a decline in the US IM by 9.15 percent until 2050, and to a decline by even 10.32 percent until 2070. We also perform this exercise for all the countries included in the model sample.[30] Across

[29] Figure 3.13 in Appendix 3.C presents IMs within countries for old-age dependency variations of 2020 across countries, while Table 3.16 in Appendix 3.C displays the corresponding regression results.

[30] Figure 3.14 in Appendix 3.C displays the corresponding results for all the countries.

Figure 3.7: Impact multipliers in the United States relative to predicted old-age dependency ratios.



Note: This figure relates the model-implied IMs for the United States to the predicted old-age dependency ratios. The old-age dependency ratios are reported in percent. Predictions until 2070 are taken from United Nations (2022b). Model-implied multipliers from the same exercise for all other countries are displayed in Figure 3.14 in Appendix 3.C. For details, see text.

all the countries, on average, the IMs will drop by 11.26 percent until 2070, and the country-specific decline in the IM varies from a maximum of 16.29 percent for Spain to a minimum of 7.05 percent in the United Kingdom.

3.6 Conclusion

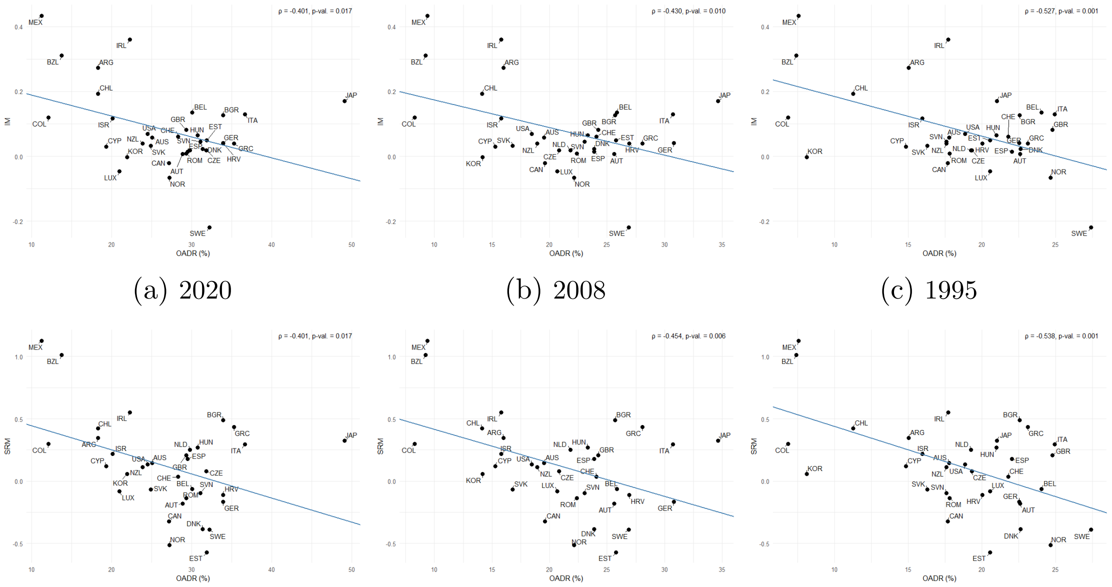
This paper shows that the age structure of an economy's population is a critical determinant of the effectiveness of fiscal policy. Empirically, we establish three stylized facts: fiscal expansions in the form of a positive government spending shock generally raise output; this effect is stronger in younger economies; and the fiscal multiplier is significantly and negatively correlated with the old-age dependency ratio. Our theoretical model replicates these patterns and allows us to disentangle the specific contribution of demographic factors. The underlying mechanism is rooted in differences in household behaviour: in older economies, working-age households exhibit weaker labor supply responses to fiscal expansions, driven by higher saving rates and reduced sensitivity to negative wealth effects induced by higher lump-sum taxation. We find that a one standard deviation increase in the old-age dependency ratio reduces the fiscal multiplier by roughly 17.7 percent on average, and that even after holding other country characteristics constant, the pure effect of population aging remains substantial. Looking ahead, demographic projections suggest that continued population aging will reduce the power of fiscal policy to support the economy. Our model predicts an average decline in the fiscal multiplier of 11.3 percent by 2070, with variation across countries depending on the severity of the demographic change.

Our findings suggest that as populations age, governments may need to reconsider the design and anticipated effects of fiscal policy, opening at least two promising avenues for future research. First, our analysis has focused exclusively on financing increased government spending through non-distortionary taxation. It would be valuable to explore how demographic changes influence the economic impact of other fiscal instruments, such as labor income, consumption, and capital taxes. Second, in light of rising debt levels across many countries, a decline in fiscal multipliers due to population aging could be seen as a silver lining. If reducing public debt becomes a pressing priority, understanding how optimal fiscal consolidation strategies vary with the demographic structure of an economy could offer important insights to policymakers.

Appendix to Chapter 3

3.A Stylized facts

Figure 3.8: Empirical relationship of the multipliers and different old-age dependency ratios.



(a) 2020 (b) 2008 (c) 1995

(d) 2020 (e) 2008 (f) 1995

Note: This figure displays the relationship of the empirically estimated IMs and SRMs and the old-age dependency ratios in 2020, 2008, and 1995. We observe significant negative raw correlations for all specifications, ranging from -0.401 to -0.538.

Table 3.9: Data coverage and age structure groups.

Country	First obs.	# of obs.	$OADR_{2020}$ *Med.*	$OADR_{2020}$ *Avg.*	$OADR_{2008}$ *Med.*	$OADR_{2008}$ *Avg.*	$OADR_{1995}$ *Med.*	$OADR_{1995}$ *Avg.*
Argentina‡	2006:Q1	56	y	y	y	y	y	y
Australia†	1995:Q1	100	y	y	y	y	y	y
Austria†	1995:Q1	100	o	o	o	o	o	o
Belgium†	2003:Q1	68	o	o	o	o	o	o
Brazil‡	1996:Q1	96	y	y	y	y	y	y
Bulgaria‡	1998:Q1	88	o	o	o	o	o	o
Canada†	1995:Q1	100	y	o	y	y	y	y
Chile‡	2003:Q1	68	y	y	y	y	y	y
Colombia‡	2005:Q1	60	y	y	y	y	y	y
Croatia‡	2000:Q1	80	o	o	o	o	o	o
Cyprus‡	2004:Q1	64	y	y	y	y	y	y
Czech Republic‡	1995:Q1	100	o	o	y	y	o	o
Denmark†	2005:Q1	60	o	o	o	o	o	o
Estonia‡	1995:Q1	100	o	o	o	o	o	o
Germany†	1995:Q1	100	o	o	o	o	o	o
Greece†	2002:Q1	72	o	o	o	o	o	o
Hungary‡	1995:Q1	100	o	o	o	o	o	o
Ireland†	2002:Q1	72	y	y	y	y	y	y
Israel‡	1995:Q1	100	y	y	y	y	y	y
Italy†	1996:Q1	96	o	o	o	o	o	o
Japan†	1996:Q1	96	o	o	o	o	o	o
South Korea†	1995:Q1	100	y	y	y	y	y	y
Luxembourg‡	1995:Q1	100	y	y	y	y	o	o
Mexico†	2006:Q1	56	y	y	y	y	y	y
Netherlands†	2003:Q2	67	o	o	y	o	y	o
New Zealand†	1995:Q1	100	y	y	y	y	y	y
Norway†	1995:Q1	100	y	o	o	o	o	o
Romania‡	1999:Q1	84	o	o	o	o	y	y
Slovakia‡	2004:Q1	64	y	y	y	y	y	y
Slovenia‡	1995:Q1	100	o	o	o	o	y	y
Spain†	1995:Q1	100	o	o	o	o	o	o
Sweden†	1995:Q1	100	o	o	o	o	o	o
Switzerland†	1995:Q1	100	y	o	o	o	o	o
United Kingdom†	1995:Q1	100	o	o	o	o	o	o
United States†	2002:Q1	72	y	y	y	y	y	o

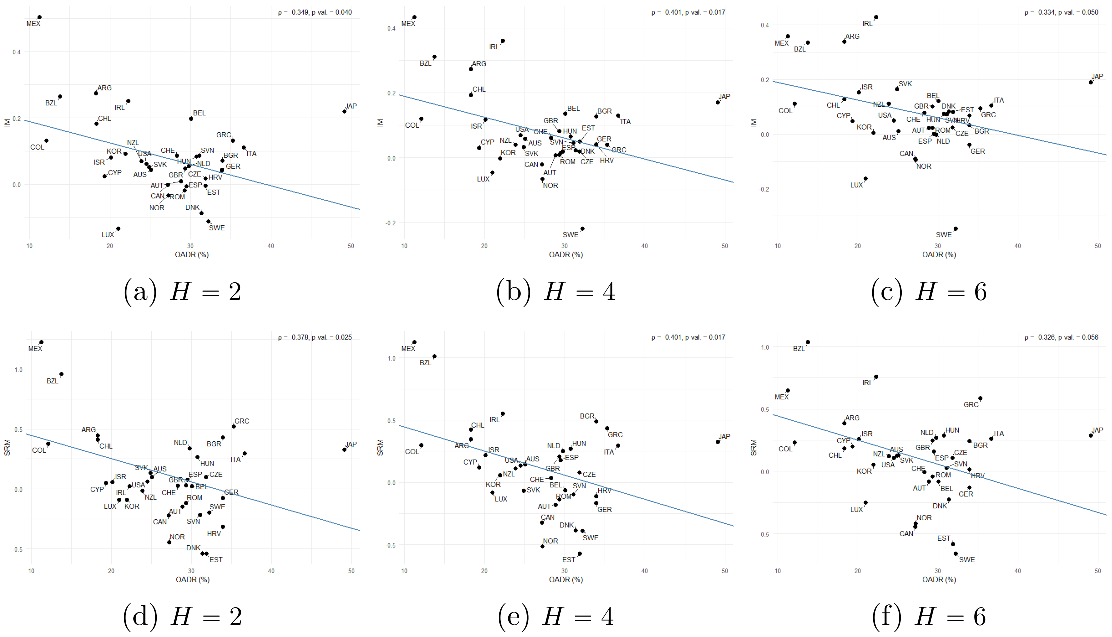
Note: This table reports the starting year:quarter combination of data availability for each country; final observation for all countries is 2019:Q4. Full coverage corresponds to 100 observations. The total sample includes 3,019 observations. If the country is marked with † (‡), we use the narrow (broad) real effective exchange rate from BIS (2025b) (BIS (2025a)). For y (o), the country is part of the *young* (*old*) age structure country group. A specific country belongs to y (o), if its own $OADR$ in a specific year (2020, 2008, or 1995) is below (above) the sample median or average $OADR$ in the respective year.

Table 3.10: Empirical multipliers across age structure groups dependent on different old-age dependency ratios or different lags.

			$OADR_{2020}$				$OADR_{2008}$				$OADR_{1995}$			
			$Median$		$Average$		$Median$		$Average$		$Median$		$Average$	
	$Lags$	(1) $Tot.$	(2) y	(3) o	(4) y	(5) o	(6) y	(7) o	(8) y	(9) o	(10) y	(11) o	(12) y	(13) o
	$H = 2$	0.4983	0.7642	0.4044	0.7493	0.4177								
IM	$H = 4$	0.5247	0.8110	0.4122	0.7964	0.4274	0.7681	0.4284	0.7706	0.4285	0.6647	0.4687	0.6560	0.4716
	$H = 6$	0.5318	0.8121	0.4260	0.7968	0.4416								
	$H = 2$	0.8500	1.0974	1.0120	1.0832	1.0102								
SRM	$H = 4$	1.0824	1.1636	1.0256	1.1464	1.0394	1.1134	1.0745	1.1194	1.0675	1.2283	1.0086	1.1730	1.0519
	$H = 6$	1.0161	1.1117	1.0799	1.0930	1.0907								
# $cntr.$		35	17	18	14	21	17	18	16	19	17	18	15	20
# $obs.$		3,019	1,408	1,611	1,108	1,911	1,375	1,644	1,308	1,711	1,359	1,660	1,220	1,799

Note: This table reports the IMs and SRMs for the total sample in column (1), for the subsamples with the *young* and the *old* age structure with the median old-age dependency ratio in 2020 as the splitting-criterion in columns (2) and (3), and with the average old-age dependency ratio in 2020 as the splitting-criterion in columns (4) and (5). Columns (6) and (7) are based on the median old-age dependency ratio in 2008 as the splitting-criterion, while columns (8) and (9) are based on the average instead of the median. Columns (10) and (11) are based on the median old-age dependency ratio in 1995 as the splitting-criterion, while columns (12) and (13) are based on the average instead of the median. We also perform robustness checks on the number of lags included into the system of equations in (3.1), $H = 2$ and $H = 6$. The results are robust across all different specifications.

Figure 3.9: Empirical relationship of the multipliers and the old-age dependency ratios in 2020 for different lags.



(a) $H = 2$ (b) $H = 4$ (c) $H = 6$

(d) $H = 2$ (e) $H = 4$ (f) $H = 6$

Note: This figure displays the relationship of the empirically estimated IMs and SRMs and the old-age dependency ratios in 2020 for a different number of lags included into the system of equations in (3.1), $H = 2$, $H = 4$, and $H = 6$. We observe significant negative raw correlations for all specifications, ranging from -0.326 to -0.401.

Table 3.11: OLS regression results for the empirical multipliers across all countries dependent on different old-age dependency ratios.

	$OADR_{2020}$		$OADR_{2008}$		$OADR_{1995}$	
	(1) IM	(2) SRM	(3) IM	(4) SRM	(5) IM	(6) SRM
$\tilde{\alpha}$	0.25324***	0.63906***	0.25876***	0.68540***	0.30704***	0.81510***
	(0.07212)	(0.21651)	(0.06846)	(0.20288)	(0.06656)	(0.19818)
$\tilde{\beta}$	-0.01935**	-0.00644**	-0.02690***	-0.00849***	-0.03754***	-0.01224***
	(0.00770)	(0.00257)	(0.00919)	(0.00310)	(0.01023)	(0.00344)
R^2	0.161	0.161	0.185	0.206	0.278	0.290

Note: This table reports the coefficients from regressing the empirically estimated IMs and SRMs on the old-age dependency ratios in 2020, 2008, and 1995, and a constant, following (3.5). Standard errors are reported in parentheses. It holds: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$. The $\tilde{\beta}$ coefficient is significantly negative across all specifications.

Table 3.12: OLS regression results for the empirical multipliers across all countries dependent on the old-age dependency ratio in 2020 with different lags.

	$H = 2$		$Baseline, H = 4$		$H = 6$	
	(1) IM	(2) SRM	(3) IM	(4) SRM	(5) IM	(6) SRM
$\tilde{\alpha}$	0.23244***	0.58907**	0.25324***	0.63906***	0.24863***	0.51494**
	(0.07342)	(0.21905)	(0.07212)	(0.21651)	(0.08774)	(0.21303)
$\tilde{\beta}$	-0.00559**	-0.01828**	-0.00644**	-0.01935**	-0.00636**	-0.01499*
	(0.00261)	(0.00779)	(0.00257)	(0.00770)	(0.00312)	(0.00758)
R^2	0.122	0.143	0.161	0.161	0.112	0.106

Note: This table reports the coefficients from regressing the empirically estimated IMs and SRMs on the old-age dependency ratios in 2020, for a different number of lags, and a constant, following (3.5). Standard errors are reported in parentheses. It holds: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$. The $\tilde{\beta}$ coefficient is significantly negative across all specifications.

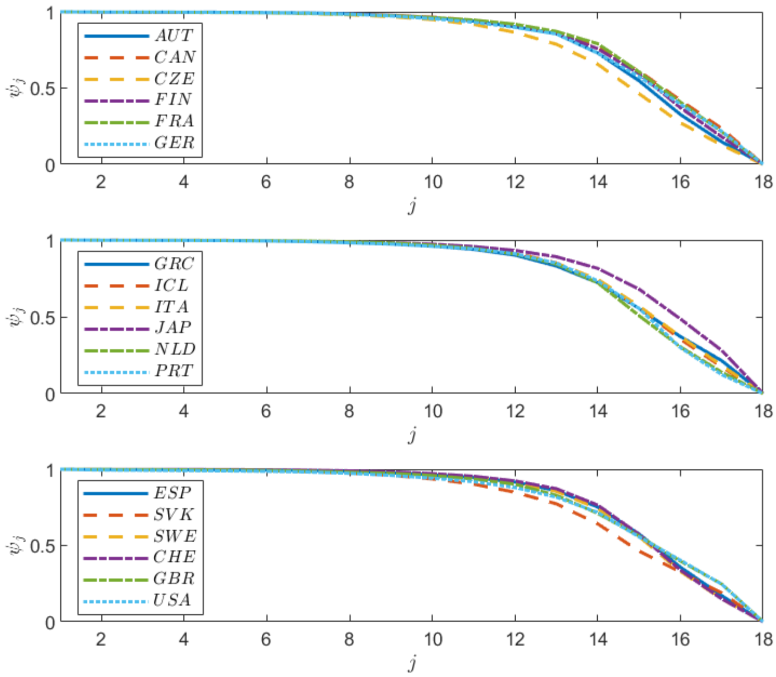
3.B Calibration

Table 3.13: Country-specific and exogenously chosen parameters across all countries.

Country	ι_1	ι_2	ι_3	$\frac{D}{Y}^*$	$\tau^{c,*}$	$\tau^{k,*}$	λ_1	λ_2	$\chi^{p,*}$
Austria‡	0.5757	-0.0376	-0.0010	83.0	19.6	24.0	0.939	0.187	40.9
Canada†	0.8127	-0.0346	-0.0030	118.2	11.8	42.7	0.900	0.193	47.7
Czech Republic‡	0.6401	-0.0329	0.0009	36.9	18.2	22.0	0.988	0.143	20.5
Finland†	0.6683	-0.0261	-0.0021	75.3	27.1	31.3	0.854	0.237	28.9
France‡	0.6983	-0.0228	-0.0021	114.9	18.3	35.5	0.915	0.142	24.0
Germany‡	0.6298	-0.0044	-0.0024	67.9	15.5	23.3	0.881	0.221	48.5
Greece‡	0.4286	-0.0015	-0.0020	213.2	15.4	16.0	1.062	0.201	25.1
Iceland‡	0.5798	-0.0098	-0.0025	77.5	25.3	20.0	0.868	0.204	20.7
Italy‡	0.4087	-0.0039	-0.0018	154.3	14.5	34.0	0.897	0.180	23.8
Japan†	0.1321	0.0111	-0.0014	258.4	6.6	37.4	0.948	0.101	48.6
Netherlands‡	1.1257	-0.0510	-0.0033	53.3	19.4	29.3	0.938	0.254	72.5
Portugal‡	0.6317	-0.0302	-0.0020	134.9	20.8	23.4	0.937	0.136	31.7
Spain‡	0.5082	0.0080	-0.0025	119.2	14.4	29.6	0.904	0.148	16.7
Slovakia‡	0.3493	-0.0117	-0.0008	58.8	18.1	15.1	0.974	0.105	31.8
Sweden‡	0.6241	-0.0179	-0.0023	40.3	25.5	40.9	0.796	0.223	25.0
Switzerland†	0.8991	-0.0246	-0.0034	43.2	8.7	29.6	0.929	0.133	49.7
United Kingdom‡	0.6679	-0.0252	-0.0028	105.8	16.3	45.6	0.920	0.200	47.2
United States†	0.9556	-0.0183	-0.0035	132.6	4.7	36.4	0.888	0.137	43.4

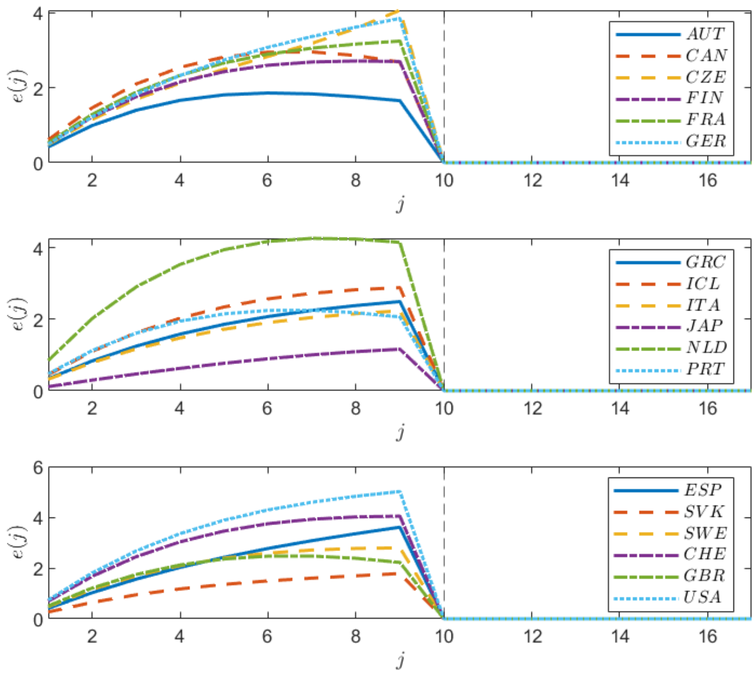
Note: This table reports the country-specific and exogenously chosen parameters across all countries in the model sample. The baseline values behind the three parameters shaping the age-dependent productivity profile of workers, ι_1, ι_2 and ι_3, and the values for the capital and consumption tax, τ^c and τ^k, as well as the values for the parameters for the labor income tax function, λ_1 and λ_2, are based on Brinca et al. (2016), if the country name is marked with †, or based on Brinca et al. (2021), if the country name is marked with ‡. The debt-output ratio, $\frac{D}{Y}$, is set in line with data from IMF (2025c) and the share of social security contributions paid by workers, χ^p, is based on data from ISSA (2025). *Values are reported in percent.

Figure 3.10: Age-dependent survival probabilities across all countries.



Note: This figure depicts the age-dependent survival probabilities for the stationary equilibrium in 2020 across all countries in the model sample. The values are based on data from United Nations (2022b) and adapted to the respective age structure.

Figure 3.11: Deterministic and age-dependent productivity profiles across all countries.



Note: This figure depicts the age-dependent productivity profiles for the stationary equilibrium in 2020 across all countries in the model sample. The age-dependent productivity profiles are based on values for the productivity parameters, $\iota_1, \iota_2, \iota_3$, in Brinca et al. (2016) and Brinca et al. (2021) and adapted to the respective age structure. Final values for the parameters are reported in Table 3.13. The respective productivity profile is then calculated from $e(j) = \iota_1 \cdot j + \iota_2 \cdot j^2 + \iota_3 \cdot j^3$. The vertical broken line in all panels signals the first retirement period ($j = J_r = 10$), in which the age-dependent productivity drops to zero, by assumption.

Table 3.14: Country-specific and endogenously calibrated parameters across all countries.

Country	n^*	$\frac{G}{Y}^*$	Ω_Y	ν	σ_θ	β	$\tau^{p,*}$
Austria	1.09	23.3	1.54	0.306	0.167	0.998	26.4
Canada	1.54	35.0	1.64	0.353	0.122	0.998	11.2
Czech Republic	0.49	30.1	1.55	0.375	0.200	1.014	18.9
Finland	0.49	37.5	1.53	0.342	0.167	1.016	26.5
France	0.72	29.2	1.57	0.302	0.187	1.044	26.7
Germany	0.59	37.4	1.60	0.320	0.207	1.007	16.4
Greece	0.44	7.4	1.70	0.405	0.158	0.984	35.0
Iceland	1.91	34.3	1.62	0.316	0.138	0.993	13.6
Italy	0.51	21.2	1.59	0.334	0.138	1.010	37.6
Japan	0.17	8.2	1.45	0.298	0.152	1.003	17.3
Netherlands	0.90	45.6	1.63	0.382	0.212	1.025	24.7
Portugal	0.51	21.9	1.62	0.360	0.237	0.992	34.9
Spain	1.04	28.6	1.60	0.348	0.161	1.011	20.0
Slovakia	1.01	16.3	1.65	0.328	0.210	0.974	22.5
Sweden	0.82	40.9	1.55	0.304	0.095	1.015	21.9
Switzerland	1.29	31.1	1.51	0.311	0.182	1.010	14.4
United Kingdom	1.41	32.5	1.67	0.296	0.190	0.988	15.5
United States	1.42	34.8	1.70	0.478	0.265	1.015	10.2

Note: This table reports the endogenously calibrated and country-specific parameters for the stationary equilibrium in 2020 for all countries in the model sample. The population growth rate reported in this table corresponds to the annualized growth rate. The discount factor corresponds to the annualized factor. *Values are reported in percent.

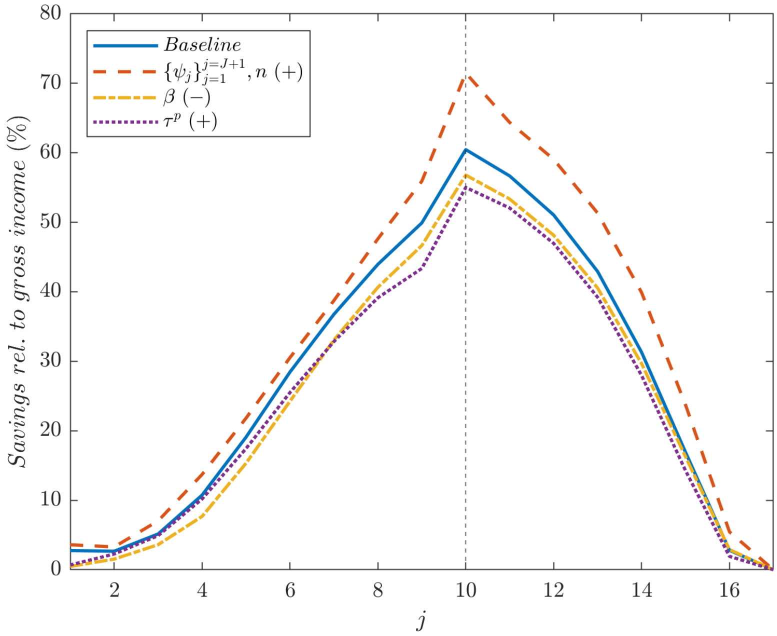
Table 3.15: Country-specific targeted moments and model fit across all countries.

	$OADR$*		$\frac{\mathcal{T}}{Y}$*		w		$\tilde{\ell}$*		$\frac{\bar{y}(\theta^H)}{\bar{y}(\theta^L)}$		$\frac{K}{Y}$*		$\tilde{\kappa}$*	
Country	Model	Data	Model	Norm.	Model	Norm.	Model	Data	Model	Data	Model	Data	Model	Data
Austria	30.8	30.8	0.0	0.0	1	1	23.3	23.3	1.45	1.45	304.8	304.8	74.1	74.1
Canada	27.2	27.2	0.0	0.0	1	1	27.6	27.6	1.30	1.30	250.4	250.4	38.8	38.8
Czech Republic	33.5	33.5	0.0	0.0	1	1	28.0	28.0	1.58	1.58	299.1	299.1	49.0	49.0
Finland	39.4	39.4	0.0	0.0	1	1	25.5	25.5	1.47	1.47	309.7	309.7	56.6	56.6
France	36.9	36.9	0.0	0.0	1	1	23.5	23.3	1.57	1.57	286.7	286.4	60.2	60.2
Germany	36.4	36.4	0.0	0.0	1	1	21.9	21.9	1.60	1.60	273.5	273.5	41.5	41.5
Greece	38.2	38.2	0.0	0.0	1	1	28.9	28.9	1.42	1.42	226.0	226.0	72.6	72.6
Iceland	23.7	23.7	0.0	0.0	1	1	24.4	24.4	1.35	1.35	262.2	262.3	51.8	51.8
Italy	39.2	39.2	0.0	0.0	1	1	25.8	25.7	1.38	1.38	277.9	277.9	74.6	74.6
Japan	49.1	49.1	0.0	0.0	1	1	26.6	26.6	1.40	1.40	366.9	366.9	32.4	32.4
Netherlands	33.2	33.2	0.0	0.0	1	1	23.6	23.4	1.55	1.55	255.2	255.2	69.7	69.7
Portugal	37.6	37.6	0.0	0.0	1	1	26.9	26.9	1.70	1.70	260.7	260.6	74.9	74.9
Spain	32.3	32.3	0.0	0.0	1	1	26.3	26.2	1.45	1.45	271.4	271.4	53.1	53.1
Slovakia	26.4	26.4	0.0	0.0	1	1	26.0	26.0	1.58	1.58	248.6	248.4	73.9	73.9
Sweden	35.3	35.3	0.0	0.0	1	1	23.7	23.8	1.24	1.24	299.8	299.5	53.3	53.3
Switzerland	30.6	30.6	0.0	0.0	1	1	24.7	25.0	1.51	1.51	322.0	322.1	43.8	43.8
United Kingdom	29.3	29.3	0.0	0.0	1	1	22.8	22.7	1.51	1.51	237.3	237.2	49.0	49.0
United States	24.5	24.5	0.0	0.0	1	1	29.8	29.8	1.81	1.81	224.3	224.4	39.2	39.2

Note: This table reports the country-specific targeted moments and the model fit for the stationary equilibrium in 2020 for all countries in the model sample. *Values are reported in percent.

3.C Quantitative results

Figure 3.12: Average savings relative to gross income for several counterfactuals across age groups.



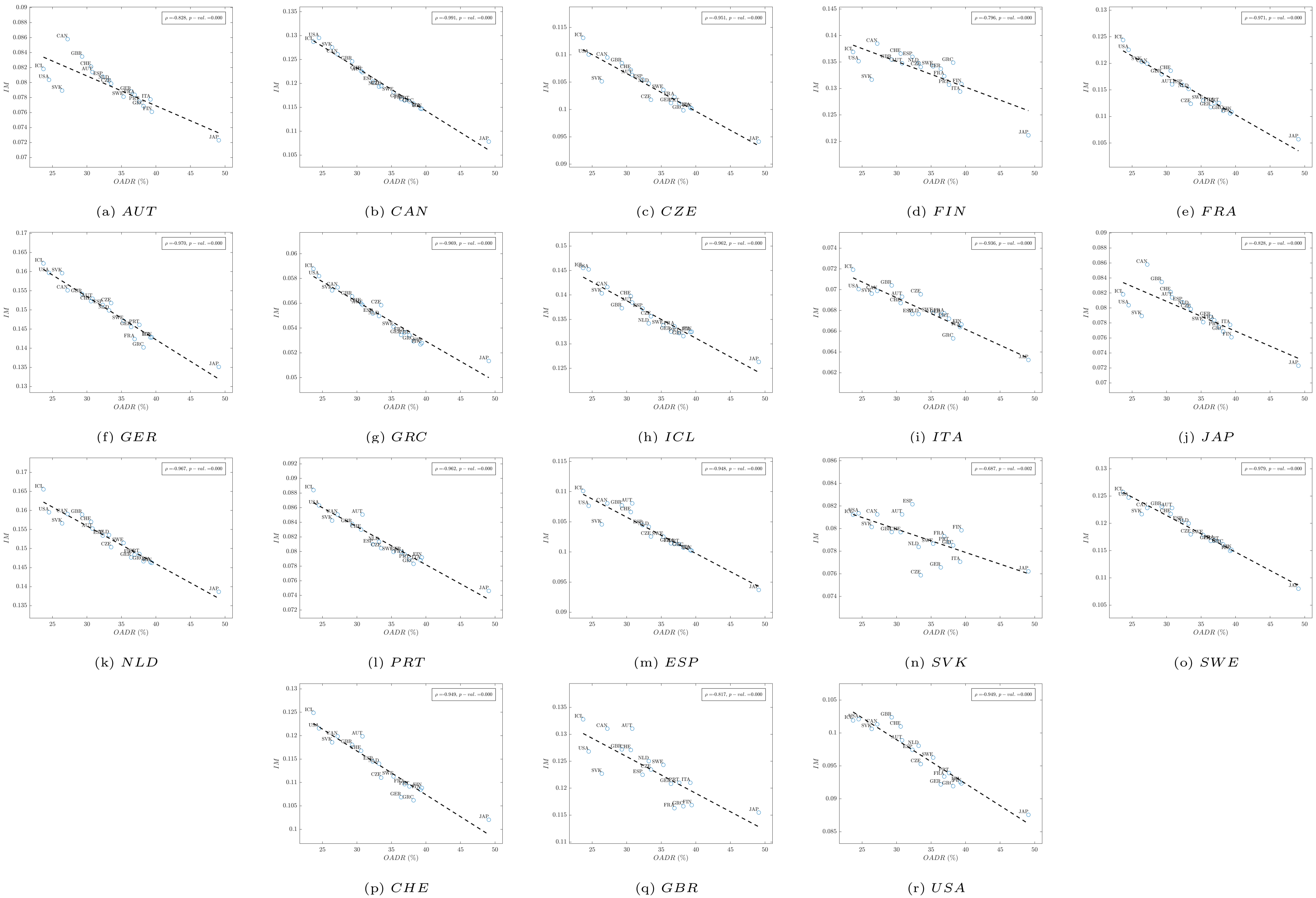
Note: This figure depicts the average savings relative to gross income (in percent) for several counterfactuals across age groups in the stationary equilibrium in 2020. Baseline (blue solid line) refers to the benchmark US case. The broken orange line refers to the counterfactual US case with the Japanese age structure, the broken yellow line to the counterfactual US case with the Japanese discount factor, and the dotted purple line to the counterfactual US case with the Japanese social security contribution rate. Individual variations in savings also create variation across capital-output ratios. While in the baseline case, the capital-output ratio is 224.3 percent, it increases to 301.3 percent in the age structure counterfactual, drops to 196.9 in the discount factor counterfactual and to 197.9 in the social security contribution rate counterfactual.

Table 3.16: Within-country regressions for all countries for variations in the old-age dependency ratio in 2020 across all countries.

	(1) AUT	(2) CAN	(3) CZE	(4) FIN	(5) FRA	(6) GER
$\tilde{\alpha}^{Model}$	0.09283***	0.15025***	0.12731***	0.14971***	0.13989***	0.18728***
	(0.00229)	(0.00104)	(0.00191)	(0.00315)	(0.00156)	(0.00241)
$\tilde{\beta}^{Model}$	-0.00040***	-0.00090***	-0.00069***	-0.00049***	-0.00074***	-0.00113***
	(0.00007)	(0.00003)	(0.00006)	(0.00009)	(0.00005)	(0.00007)
R^2	0.686	0.982	0.905	0.634	0.943	0.941
Δ	-0.0025	-0.0057	-0.0044	-0.0031	-0.0047	-0.0071
Δ IM (%)	-3.08	-4.50	-4.28	-2.34	-4.14	-4.88
	(7) GRC	(8) ICL	(9) ITA	(10) JAP	(11) NLD	(12) PRT
$\tilde{\alpha}^{Model}$	0.06578***	0.16180***	0.07835***	0.02376***	0.18577***	0.09900***
	(0.00070)	(0.00185)	(0.00097)	(0.00112)	(0.00222)	(0.00125)
$\tilde{\beta}^{Model}$	-0.00032***	-0.00077***	-0.00030***	-0.00007*	-0.00099***	-0.00052***
	(0.00002)	(0.00005)	(0.00003)	(0.00003)	(0.00007)	(0.00004)
R^2	0.939	0.926	0.877	0.216	0.936	0.926
Δ	-0.0020	-0.0048	-0.0019	-0.0004	-0.0063	-0.0033
Δ IM (%)	-3.83	-3.32	-2.89	-2.07	-4.08	-4.15
	(13) ESP	(14) SVK	(15) SWE	(16) CHE	(17) UK	(18) US
$\tilde{\alpha}^{Model}$	0.12383***	0.08613***	0.14159***	0.14477***	0.14630***	0.11901***
	(0.00172)	(0.00186)	(0.00119)	(0.00264)	(0.00409)	(0.00189)
$\tilde{\beta}^{Model}$	-0.00060***	-0.00021**	-0.00067***	-0.00093***	-0.00068**	-0.00067***
	(0.00005)	(0.00005)	(0.00003)	(0.00008)	(0.00012)	(0.00006)
R^2	0.899	0.473	0.958	0.901	0.668	0.901
Δ	-0.0038	-0.0013	-0.0042	-0.0059	-0.0043	-0.0042
Δ IM (%)	-3.63	-1.62	-3.59	-5.04	-3.38	-4.12

Note: This table reports the *within-country regressions (WCR)* for all the countries, where we only vary the age structure in one specific country in line with all other countries in the sample. Δ represents the change in the IM in a specific country if the old-age dependency ratio increases by one standard deviation (+6.3 percentage points). Δ IM represents the respective percent adjustment in the country-specific IM, reported in percent. The average adjustment across all countries is -3.61 percent. It holds: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

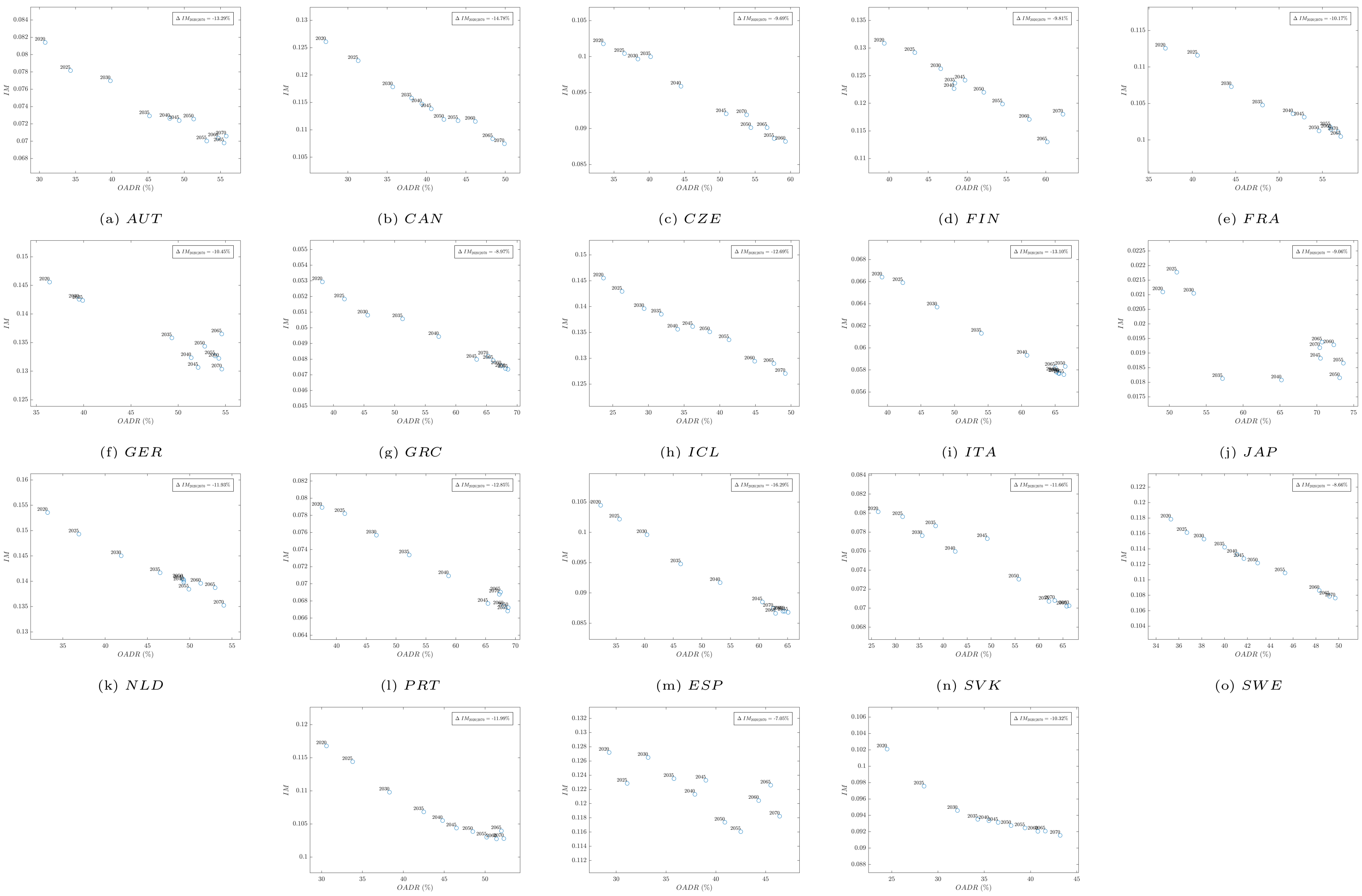
Figure 3.13: Hypothetical impact multipliers in all countries relative to the old-age dependency ratios across all countries in 2020.



(a) AUT (b) CAN (c) CZE (d) FIN (e) FRA (f) GER (g) GRC (h) ICL (i) ITA (j) JAP (k) NLD (l) PRT (m) ESP (n) SVK (o) SWE (p) CHE (q) GBR (r) USA

Note: This figure relates the hypothetical model-implied IMs in all countries for the age structure calibrated across all countries in the sample to the respective old-age dependency ratios (in percent) in 2020. The negative relationship is very robust across countries.

Figure 3.14: Impact multipliers in all countries relative to predicted old-age dependency ratios.



(a) *AUT* (b) *CAN* (c) *CZE* (d) *FIN* (e) *FRA*

(f) *GER* (g) *GRC* (h) *ICL* (i) *ITA* (j) *JAP*

(k) *NLD* (l) *PRT* (m) *ESP* (n) *SVK* (o) *SWE*

(p) *CHE* (q) *GBR* (r) *USA*

Note: This figure relates the model-implied IMs for all the countries to their predicted old-age dependency ratios. The old-age dependency ratios are reported in percent. Predictions until 2070 are taken from United Nations (2022b). The IMs in all countries will significantly drop.

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Bibliography

Acemoglu, D. et al. (2012). What does human capital do? A review of Goldin and Katz's The race between education and technology. *Journal of Economic Literature*, 50(2):426–63.

Acemoglu, D., Manera, A., and Restrepo, P. (2020). Does the US tax code favor automation? *Brooking Papers on Economic Activity*, 1:231–300.

Acemoglu, D. and Restrepo, P. (2017). Secular stagnation? The effect of aging on economic growth in the age of automation. *American Economic Review: Papers and Proceedings*, 107(5):174–179.

Acemoglu, D. and Restrepo, P. (2018). The race between man and machine: Implications of technology for growth, factor shares, and employment. *American Economic Review*, 108(6):1488–1542.

Acemoglu, D. and Restrepo, P. (2020). Robots and jobs: Evidence from US labor markets. *Journal of Political Economy*, 128(6):2188–2244.

Aiyagari, S. R. (1994). Uninsured idiosyncratic risk and aggregate saving. *Journal of Monetary Economics*, 109(3):659–684.

Aksoy, Y., Basso, H. S., Smith, R. P., and Grasl, T. (2019). Demographic structure and macroeconomic trends. *American Economic Journal: Macroeconomics*, 11(1):193–222.

Angelini, D. (2023). Aging population and technology adoption. *University of Konstanz, Department of Economics, Working Paper Series*, 1.

Arcalean, C. and Schiopu, I. (2010). Public versus private investment and growth in a hierarchical education system. *Journal of Economic Dynamics and Control*, 34(4):604–622.

Artige, L. and Cavenaile, L. (2023). Public education expenditures, growth and income inequality. *Journal of Economic Theory*, 209:1–27.

Attanasio, O., Kitao, S., and Violante, G. L. (2007). Global demographic trends and social security reform. *Journal of Monetary Economics*, 54(1):144–198.

Auerbach, A. and Gorodnichenko, Y. (2012). Measuring the output response to fiscal policy. *American Economic Journal: Economic Policy*, 4(2):1–27.

Auerbach, A. J. and Gorodnichenko, Y. (2013). *Fiscal policy after the financial crisis*. University of Chicago Press.

Auerbach, A. J. and Kotlikoff, L. J. (1987). *Dynamic fiscal policy*. Cambridge University Press.

Autor, D. H. (2019). Work of the past, work of the future. *AEA Papers and Proceedings*, 109:1–32.

Basso, H. and Rachedi, O. (2021). The young, the old, and the government: Demographics and fiscal multipliers. *American Economic Journal: Macroeconomics*, 13(4):110–141.

Baxter, M. and King, R. G. (1993). Fiscal policy in general equilibrium. *American Economic Review*, 83(3):315–334.

Beraja, M. and Zorzi, N. (2024). Inefficient automation. *Review of Economic Studies*, 92(1):69–96.

BIS (2025a). BIS data, real effective exchange rate, broad basket (M.R.B.), monthly.

BIS (2025b). BIS data, real effective exchange rate, narrow basket (M.R.N.), monthly.

Blanchard, O. and Perotti, R. (2002). An empirical characterization of the dynamic effects of changes in government spending and taxes on output. *Quarterly Journal of Economics*, 117:1329–1368.

Blanchard, O. T. and Leigh, D. (2013). Growth forecast errors and fiscal multipliers. *American Economic Review*, 103(3):117–120.

Blankenau, W. (2005). Public schooling, college subsidies and growth. *Journal of Economic Dynamics and Control*, 29(3):487–507.

Boldrin, M. and Montes, A. (2005). The intergenerational state education and pensions. *Review of Economic Studies*, 72:651–664.

Bottazzi, L. and Peri, G. (2007). The international dynamics of R&D and innovation in the long run and in the short run. *The Economic Journal*, 117:486–511.

Brinca, P., Ferreira, M. H., Franco, F., Holter, H. A., and Laurence, M. (2021). Fiscal consolidation programs and income inequality. *International Economic Review*, 62(1):405–460.

Brinca, P., Holter, H. A., Krusell, P., and Malafry, L. (2016). Fiscal multipliers in the 21st century. *Journal of Monetary Economics*, 77:53–69.

Brynjolfsson, E. and McAfee, A. (2011). *Race against the machine: How the digital revolution is accelerating innovation, driving productivity, and irreversibly transforming employment and the economy.* Brynjolfsson and McAfee.

Busemeyer, M. R., Garritzmann, J. L., Neimanns, E., and Nezi, R. (2018). Investing in education in Europe: Evidence from a new survey of public opinion. *Journal of European Social Policy*, 28(1):34–54.

Buyse, T., Heylen, F., and Van de Kerckhove, R. (2012). Pension reform, employment by age, and long-run growth. *Journal of Population Economics*, 26:769–809.

Bénabou, R. (2002). Tax and education policy in a heterogeneous-agent economy: What levels of redistribution maximize growth and efficiency? *Econometrica*, 70(2):481–517.

Börsch-Supan, A., Alexander, L., and Winter, J. (2006). Ageing, pension reform and capital flows: A multi-country simulation model. *Economica*, 73:625–648.

Carvalho, C., Ferrero, A., and Nechio, F. (2016). Demographics and real interest rates: Inspecting the mechanism. *European Economic Review*, 88:208–226.

Cho, D. and Rhee, D.-E. (2024). Government debt and fiscal multipliers in the era of population aging. *Macroeconomic Dynamics*, 28:1161–1181.

Coe, D. T. and Helpman, E. (1995). International R&D spillovers. *European Economic Review*, 39:859–887.

Conesa, J. C., Kitao, S., and Krueger, D. (2009). Taxing capital? Not a bad idea after all! *American Economic Review*, 99(1):25–48.

Corsetti, G., Meier, A., and Müller, G. (2012). Government spending multipliers. *Economic Policy*, 27(72):521–565.

Costinot, A. and Werning, I. (2022). Robots, trade, and luddism: A sufficient statistic approach to optimal technology regulation. *Review of Economic Studies*, 90(5):2261–2291.

De Nardi, M., İmrohoroglu, S., and Sargent, T. J. (1999). Projected U.S. demographics and social security. *Review of Economic Dynamics*, 2(3):575–615.

Diamond, P. A. and Mirrlees, J. A. (1971). Optimal taxation and public production I: Production efficiency. *American Economic Review*, 61(1):8–27.

Domeij, D. and Floden, M. (2006). Population aging and international capital flows. *International Economic Review*, 47(3):1013–1032.

Downs, A. (1957). An economic theory of political action in a democracy. *Journal of Political Economy*, 65(2):135–150.

Drechsel-Grau, M., Peichl, A., Schmieder, J., Schmid, K. D., Walz, H., and Wolter, S. (2022). Inequality and income dynamics in Germany. *Quantitative Economics*, 13(4):1593–1635.

Dynarski, S. M. (2003). Does aid matter? Measuring the effect of student aid on college attendance and completion. *American Economic Review*, 93(1):279–288.

Epper, T., Fehr, H., Fehr-Duda, H., Thustrup Kreiner, C., Dreyer Lassen, D., Leth-Petersen, S., and Nyftoft Rasmussen, G. (2020). Time discounting and wealth inequality. *American Economic Review*, 110(4):1177–1205.

European Social Survey (2023). European Social Survey 2002-2023, Online Edition.

Eurostat (2023a). Demographic balances and indicator by type of projection, old-age dependency ratio, 3rd variant (population 65 years or over to population 20 to 64 years), baseline projections.

Eurostat (2023b). General government expenditure by function (COFOG), percentage of gross domestic product (GDP), general government, education, total general government expenditure.

Eurostat (2023c). Pensions, old age pension, percentage of gross domestic product (GDP).

Ferraro, D. and Fiori, G. (2020). The aging of the baby boomers: Demographics and propagation of tax shocks. *Amercian Economic Journal: Macroeconomics*, 12(2):167–193.

Fougère, M. and Mérette, M. (1999). Population ageing and economic growth in seven OECD countries. *Economic Modelling*, 16(3):411–427.

FRED (2025). FRED data, balance of payments, current account, balance (revenue minus expenditure), percentage of GDP, seasonally adjusted, quarterly.

Frey, C. B. and Osborne, M. A. (2017). The future of employment: How susceptible are jobs to computerisation? *Technological forecasting and social change*, 114:254–280.

Fuster, L., İmrohoroglu, A., and İmrohoroglu, S. (2007). Elimination of social security in a dynastic framework. *Review of Economic Studies*, 74(1):113–145.

Glomm, G. and Kaganovich, M. (2008). Social security, public education and the growth-inequality relationship. *European Economic Review*, 52:1009–1034.

Goldin, C. and Katz, L. F. (2010). *The race between education and technology.* Harvard University Press.

Goldin, C., Katz, L. F., and Autor, D. (2020). Extending the race between education and technology. *National Bureau of Economic Research Working Paper Series*, No. 26705.

Gonzalez-Eiras, M. and Niepelt, D. (2008). The future of social-security. *Journal of Monetary Economics*, 55:197–218.

Gonzalez-Eiras, M. and Niepelt, D. (2012). Ageing, government budgets, retirement, and growth. *European Economic Review*, 56:97–115.

Graetz, G. and Michaels, G. (2018). Robots at work. *Review of Economics and Statistics*, 100(5):753–768.

Guerreiro, J., Rebelo, S., and Teles, P. (2022). Should robots be taxed? *Review of Economic Studies*, 89(1):279–311.

Guvenen, F., Kuruscu, B., and Ozkan, S. (2013). Taxation of human capital and wage inequality: A cross-country analysis. *Review of Economic Studies*, 81(2):818–850.

Hansen, G. (1993). The cyclical and secular behavior of the labour input: Comparing efficiency units and hours worked. *Journal of Applied Econometrics*, 8(1):71–80.

He, H. and Liu, Z. (2008). Investment-specific technological change, skill accumulation, and wage inequality. *Review of Economic Dynamics*, 11(2):314–334.

Heathcote, J., Storesletten, K., and Violante, G. L. (2017). Optimal tax progressivity: An analytical framework. *Quarterly Journal of Economics*, 132(4):1693–1754.

Heer, B. (2019). *Public economics - The macroeconomics perspective.* Springer Nature Switzerland AG.

Huang, H., Imrohoroglu, S., and Sargent, T. J. (1997). Two computations to fund social security. *Macroeconomic Dynamics*, 1(1):7–44.

Huidrom, R., Kose, M., Lim, J. J., and Ohnsorge, F. L. (2020). Why do fiscal multipliers depend on fiscal positions? *Journal of Monetary Economics*, 114:109–125.

Hémous, D. and Olsen, M. (2022). The rise of the machines: Automation, horizontal innovation, and income inequality. *American Economic Journal: Macroeconomics*, 14(1):179–223.

Ilzetzki, E., Mendoza, E. G., and A., V. C. (2013). How big (small?) are fiscal multipliers? *Journal of Monetary Economics*, 60(2):239–254.

IMF (2021). IMF investment and capital stock dataset, 1960-2019.

IMF (2025a). IMF data, final consumption expenditure, general government, constant prices, seasonally adjusted, domestic currency, quarterly.

IMF (2025b). IMF data, gross domestic product (GDP), constant prices, seasonally adjusted, domestic currency, quarterly.

IMF (2025c). IMF datamapper, general government gross debt (percent of GDP).

Imrohoroglu, A., Imrohoroglu, S., and Joines, D. H. (1995). A life cycle analysis of social security. *Economic Theory*, 6:83–114.

ISSA (2025). International Social Security Association, contribution rates, employee and employer contribution rates (percent).

Jackson, C. K., Johnson, R. C., and Persico, C. (2015). The effects of school spending on educational and economic outcomes: Evidence from school finance reforms. *The Quarterly Journal of Economics*, 131(1):157–218.

Jacobs, B. and Thuemmel, U. (2022). Optimal linear income taxation and education subsidies under skill-biased technical change. *International Tax and Public Finance*, 30:1529–1575.

Jaimovich, N. and Siu, H. E. (2009). The young, the old, and the restless: Demographics and business cycle volatility. *American Economic Review*, 99(3):804–826.

Janiak, A. and Monteiro, P. S. (2016). Towards a quantitative theory of automatic stabilizers: The role of demographics. *Journal of Monetary Economics*, 78:35–49.

Jones, C. I. (1995). R&D-based models of economic growth. *Journal of Political Economy*, 103(4):759–784.

Jones, C. I. (2022a). The past and future of economic growth: A semi-endogenous perspective. *Annual Review of Economics*, 14:125–152.

Jones, C. I. (2022b). The end of economic growth? Unintended consequences of a declining population. *American Economic Review*, 112(11):3489–3527.

Koh, W. C. (2017). Fiscal multipliers: New evidence from a large panel of countries. *Oxford Economic Papers*, 69(3):569–590.

Kopecky, J. (2022). The age for austerity? Population age structure and fiscal consolidation multipliers. *Journal of Macroeconomics*, 73.

Kraay, A. (2012). How large is the government spending multiplier? Evidence from World Bank lending. *The Quarterly Journal of Economics*, 127:829–887.

Krueger, D. and Ludwig, A. (2007). On the consequences of demographic change for rates of returns to capital, and the distribution of wealth and welfare. *Journal of Monetary Economics*, 54:49–87.

Krueger, D. and Ludwig, A. (2013). Optimal progressive labor income taxation and education subsidies when education decisions and intergenerational transfers are endogenous. *American Economic Review*, 103(3):496–501.

Krueger, D. and Ludwig, A. (2016). On the optimal provision of social insurance: Progressive taxation versus education subsidies in general equilibrium. *Journal of Monetary Economics*, 77:72–98.

Krusell, P., Ohanian, L. E., Ríos-Rull, J.-V., and Violante, G. L. (2000). Capital-skill complementarity and inequality: A macroeconomic analysis. *Econometrica*, 68(5):1029–1053.

Krusell, P. and Smith, A. A. (1999). On the welfare effects of eliminating business cycles. *Review of Economic Dynamics*, 2:245–272.

Lancia, F. and Russo, A. (2016). Public education and pensions in democracy: A political economy theory. *Journal of the European Economic Association*, 14(5):1038–1073.

Leahy, J. V. and Thapar, A. (2019). Demographic effects on the impact of monetary policy. *NBER Working Paper No. 26324*.

Leighley, J. E. and Nagler, J. (1992). Socioeconomic class bias in turnout, 1964–1988: The voters remain the same. *American Political Science Review*, 86(3):725–736.

Lindbeck, A. and Weibull, W. (1987). Balanced-budget redistribution as the outcome of political competition. *Public Choice*, 52:273–297.

Ludwig, A., Schelkle, T., and Vogel, E. (2012). Demographic change, human capital and welfare. *Review of Economic Dynamics*, 15:94–107.

Maestas, N., Mallen, K. J., and Powell, D. (2023). The effect of population aging and economic growth, the labor force, and productivity. *American Economic Journal: Macroeconomics*, 15(2):306–332.

Mann, K. and Püttmann, L. (2023). Benign effects of automation: New evidence from patent texts. *The Review of Economics and Statistics*, 105(3):562–579.

McMorrow, K. and Röger, W. (2009). R&D capital and economic growth: The empirical evidence. *EIB papers*, 14(1):94–118.

Mirrlees, J. A. (1971). An exploration in the theory of optimum income taxation. *Review of Economic Studies*, 38(2):175–208.

Miyamoto, H. and Naoyuki, Y. (2017). Declined effectiveness of fiscal and monetary policies faced with aging population in Japan. *Japan and the World Economy*, 42:32–44.

Miyamoto, H. and Naoyuki, Y. (2022). A note on population aging and effectiveness of fiscal policy. *Macroeconomic Dynamics*, 25:1679–1689.

Müller, C. (2024). World Robotics 2024, industrial robots, IFR statistical department, VDMA services GmbH, Frankfurt am Main, Germany.

Nickel, C. and Tudyka, A. (2014). Fiscal stimulus in times of high debt: Reconsidering multipliers and twin deficits. *Journal of Money, Credit and Banking*, 46(7):1313–1344.

OECD (2022a). Multifactor productivity, total, annual growth rate (in percent), 2005–2021. https://data.oecd.org/lprdty/multifactor-productivity.htm.

OECD (2022b). OECD education at a glance 2022: OECD indicators, indicator A4. what are the earnings advantages from education?, relative earnings of 25–64 year-old adults, by educational attainment.

OECD (2022c). Taxing wages 2022: Impact of COVID-19 on the tax wedge in OECD countries. https://www.oecd-ilibrary.org/sites/f7f1e68a-en/index.html?itemId=/content/publication/f7f1e68a-en.

OECD (2023a). Education at a glance 2023: OECD indicators, indicator A4, what are the earnings advantages from education?, relative earnings of 25–64 year-old adults, by educational attainment.

OECD (2023b). Pension spending, public, percent of GDP, 1980–2020. https://data.oecd.org/socialexp/pension-spending.htmindicator-chart.

OECD (2023c). Public spending on education, primary to post-secondary non-tertiary / tertiary / primary to tertiary, percent of GDP, 2000–2019. https://data.oecd.org/eduresource/public-spending-on-education.htm.

OECD (2023d). Researchers, total, per 1.000 employed, 1981–2020. https://data.oecd.org/rd/researchers.htm.

OECD (2023e). Social spending, public, percent of GDP, 1980–2021. https://data.oecd.org/socialexp/social-spending.htmindicator-chart.

OECD (2023f). Spending on tertiary education. https://data.oecd.org/eduresource/spending-on-tertiary-education.htm.

OECD (2025a). OECD data explorer, average annual hours actually worked per worker.

OECD (2025b). OECD data explorer, gross pension replacement rates, percent of pre-retirement earnings, men/women.

OECD (2025c). OECD data explorer, public and private social expenditures, public (percent of GDP).

Ono, T. and Uchida, Y. (2016). Pensions, education, and growth: A positive analysis. *Journal of Macroeconomics*, 48:127–143.

Persson, T. and Tabellini, G. (2002). *Political economics: Explaining economic policy*. MIT press.

Powell, G. B. (1986). American voter turnout in comparative perspective. *American Political Science Review*, 80(1):17–43.

Prettner, K. and Strulik, H. (2020). Innovation, automation, and inequality: Policy challenges in the race against the machine. *Journal of Monetary Economics*, 116:249–265.

Rauh, C. (2017). Voting, education, and the Great Gatsby curve. *Journal of Public Economics*, 146:1–14.

Restuccia, D. and Urrutia, C. (2004). Intergenerational persistence of earnings: The role of early and college education. *American Economic Review*, 94(5):1354–1378.

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98(5):71–102.

Sadahiro, A. and Shimasawa, M. (2003). The computable overlapping generations model with an endogenous growth mechanism. *Economic Modelling*, 20(1):1–24.

Slavik, C. and Yazici, H. (2014). Machines, buildings, and optimal dynamic taxes. *Journal of Monetary Economics*, 66:47–61.

Smets, K. and van Ham, C. (2013). The embarrassment of riches? A meta-analysis of individual-level research on voter turnout. *Electoral Studies*, 32(2):344–359.

Song, Z. (2011). The dynamics of inequality and social security in general equlibrium. *Review of Economic Dynamics*, 14:613–635.

Stiglitz, J. E. (1982). Self-selection and pareto efficient taxation. *Journal of Public Economics*, 17(2):213–240.

Storesletten, K. (2000). Sustaining fiscal policy through immigration. *Journal of Political Economy*, 108(2):300–323.

Thuemmel, U. (2022). Optimal taxation of robots. *Journal of the European Economic Association*, 21(3):1154–1190.

United Nations (2022a). Department of economic and social affairs, population division, world population prospects 2022, online edition, abridged lifetable, medium fertility variant, 2022–2100.

United Nations (2022b). Department of economic and social affairs, population division, world population prospects 2022, online edition, single age lifetable, estimates, 1980–2021.

United Nations (2024). Department of economic and social affairs, population division, rate of population change.

US Bureau of Economic Analysis (2023). Gross saving as a percentage of gross national income. https://fred.stlouisfed.org/series/W206RC1Q156SBEA.

US Census Bureau (2023a). Mean earnings of workers 18 years and over, by educational attainment, race, hispanic origin, and sex, 1975–2021. https://www.census.gov/data/tables/time-series/demo/educational-attainment/cps-historical-time-series.html.

US Census Bureau (2023b). Percent of people 25 years and over who have completed high school or college, by race, hispanic origin and sex, selected years 1940–2022. https://www.census.gov/data/tables/time-series/demo/educational-attainment/cps-historical-time-series.html.

US Patent and Trademark Office (2023). Patent term. https://www.uspto.gov/web/offices/pac/mpep/s2701.html.

Verba, S. and Nie, N. H. (1987). *Participation in America: Political Democracy and Social Equality*. University of Chicago Press.

Verba, S., Nie, N. H., and Kim, J. (1978). *Participation and Political Equality: A Seven-Nation Comparison*. Cambridge University Press.

Vogel, E., Ludwig, A., and Axel, B.-S. (2017). Aging and pension reform: Extending the retirement age and human capital formation. *PEF*, 16(1):81–107.

World Bank (2023). Real interest rate (percent), United States. https://data.worldbank.org/indicator/FR.INR.RINR?end=2021locations=US.

World Bank (2024a). World development indicators, age dependency ratio, old (percent of working-age population).

World Bank (2024b). World development indicators, gross capital formation (percent of GDP, formerly gross domestic investment).

World Bank (2025a). National accounts data, final consumption expenditure (percent of GDP).

World Bank (2025b). National accounts data, gross fixed capital formation (percent of GDP).

World Inequality Database (2025). World inequality database (WID), online edition.

Abgrenzung

Hiermit versichere ich, dass ich sowohl das erste Kapitel dieser Dissertation *"Population aging, inequality and public policy"* als auch das dritte Kapitel *"Population aging and fiscal multipliers"* eigenständig und ohne Zuhilfenahme anderer als der angegebenen Hilfsmittel erarbeitet habe.

Das zweite Kapitel *"Fiscal policy and human capital in the race against the machine"* stellt eine gemeinsame Forschungsarbeit mit Daniele Angelini (Universität Wien) und Stefan Niemann (Universität Konstanz) dar. Der Inhalt wurde gemeinschaftlich und zu gleichen Teilen verfasst.