CHARLES UNIVERSITY
FACULTY OF SOCIAL SCIENCES
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Essays on Labour Force and its Productivity

Doctoral Thesis

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Year of defense: 2019

Acknowledgments

The author is grateful especially to PhDr. Jaromír Baxa, Ph.D. for his support throughout the master and doctoral programmes at the Charles University. Without him, his advice, encouragement – and lending me the textbook that initially started it all – the baseline simulation model used throughout this thesis would have never been developed.

I would also like to thank Marco Hafner, Kaveh Jahanshahi, Francois Millard, and other collaborators at RAND Europe, RAND Corporation and Discovery Group for their help with the research partially presented in this study.

Lastly, I am grateful to participants at the Researcher Links Workshop 'Inequality or State Capacity' and the International Conference on Sustainable Development, as well as the three reviewers of this thesis for their comments.

This study received support from the Charles University, project GA UK No. 824218, in 2018 and 2019.

Declaration of Authorship

I hereby declare that I compiled this thesis using only the listed resources and literature. The thesis has not been used to obtain any other academic title.

Prague, November 17, 2019

Martin Stepanek

Bibliographic Record
Štěpánek, Martin: *Essays on Labour Force and its Productivity.* Doctoral Thesis. Charles University, Faculty of Social Sciences, Institute of Economic Studies, Prague. 2019, 137 pages. Advisor: PhDr. Jaromír Baxa, Ph.D.

Abstract

This doctoral thesis presents four articles analysing labour force and its productivity. It utilises simulation modelling to assess the impacts of demographic changes, migration or shifts in productivity determinants on public finances and the economies in the Czech Republic and the USA, as well as statistical modelling to evaluate determinants behind workplace productivity. The first three studies assess the topic from a high-level perspective, providing economy-wide projections for the future decades. They also utilise the same core simulation model, an overlapping generations (OLG) framework coded in MATLAB, which is further developed for the particular use in each study. The fourth study, on the other hand, approaches the topic from the opposite direction, analysing the individual-level factors affecting productivity.

Specifically, the first article deals with demographic changes – population ageing and shrinking – in the context of the Czech pension system. The findings show that the existing system can provide pensions increasing at the rate of change in nominal wages, be financially sustainable in the long term, or increase the default retirement age by only two years in the next decades – but only two of these three objectives can be achieved at the same time. On the contrary, a structural change towards an alternative, partially funded pension scheme may provide a better balance in the three outcomes without putting an excessive debt burden on the next generations.

The second article broadly builds on the previous one by analysing the economic impacts of demographic changes in the Czech Republic, yet it extends the scope of the analysis to (un)anticipated migration and sectoral effects. This is done by introducing a computable general equilibrium (CGE) side of the simulation model with a detailed representation of individuals of different ages, educational attainment and occupations, as well as interrelations among industrial sectors in producing intermediate and final outputs. The results show that the annual net immigration would need to increase by at least 8 thousand individuals on average in the 2020-2035 period and by 17 thousand individuals in the 2036-2050 period to offset the negative effects of the projected demographic changes in the long term.

The third study investigates the economic implications of later high school start times in the United States by assessing the effect on educational attainment and, in turn, on human capital accumulation on one hand and on car accidents, one of the leading causes of death among teenagers, on the other. The benefit–cost projections of this study suggest that delaying school start times would be a cost-effective population-level strategy with potentially a significant positive impact on public health and the US economy.

Finally, the last study analyses productivity determinants at the individual level by examining data on 31,950 employees in the UK using structural equation modelling. The analysed factors comprise socioeconomic characteristics, lifestyle, commuting, physical and mental health, well-being, and job and workplace environment. The study finds that, controlling for personal characteristics, mental and physical health cover more than 84% of the direct effects on productivity loss. In addition, 93% of the indirect influences are mediated through mental and/or physical health, meaning that even job or workplace factors, such as job satisfaction, support from managers or feeling isolated ultimately affect productivity through mental and/or physical health.

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Acronyms

AIC Akaike Information Criterion

BIC Bayesian Information Criterion

CFA Confirmatory Factor Analysis

CFI Comparative Fit Index

CGE Computable General Equilibrium Model

CSO Czech Statistical Office

EFA Exploratory Factor Analysis

EFTA European Free Trade Association

EU European Union

GDP Gross Domestic Product

GSP Gross State Product

GTAP Global Trade Analysis Project

MICZ Ministry of the Interior of the Czech Republic

MLSA Ministry of Labour and Social Affairs of the Czech Republic

OECD Organisation for Economic Co-operation and Development

OLG Overlapping Generations Model

PAY-GO Pay-As-You-Go Pension Funding Scheme

ROW Rest of the World

SAM Social Accounting Matrix

SEM Structural Equation Model

SST School Start Times

UK United Kingdom

UN United Nations

US United States of America

Chapter 1

Introduction

This thesis contains four studies linked by a focus on labour force – or, more generally, on individual and population dynamics – and its productivity, analysing the implications for the economy, from individual workplaces to the public finance systems. The first three studies are very close in their focus and methodologies; they use simulation modelling to the assess macroeconomic impact of demographic changes in the Czech Republic and the USA. The first study was published in the *Czech Journal of Economics and Finance*, the second study is waiting to be published, and the third study was published in *Sleep Health*. The fourth study, published in *Journal of Occupational and Environmental Medicine*, then complements the previous studies by providing individual-level insights into determinants of labour productivity.

While being gradually replaced by automation, human labour has always been an essential component of production and economic development globally. As the technological advancement progressed throughout the ages, it has continuously shifted from often hard, manual labour in agriculture, crafts and basic construction towards factory systems, mass production and services, requiring a diverse range of often highly specialised skills and intellectual engagement with modern technology. With it, the importance of labour quantity slowly decreased and the importance of labour productivity increased; the empirical data show that the average number of hours worked per employee in the OECD countries dropped by nearly 5% in the last two decades (and by nearly 17% since 1970 in the G7 countries), while labour productivity has grown by 21% and unit labour costs – the average cost of labour per unit of output – have grown by 22% over the same period (OECD, 2016). Indeed, nowadays more than ever, workers' health and physical fitness is but a component in a complex array of attributes determining their ability to produce an economic output, while the importance of education, experience, know-how and mental health has greatly increased as job functions became more complex. At the same time, factors such as the growth in mobility, freelancing and crowdsourcing freed workers from many traditional bounds and constraints, allowing many of them to work where they want and when they want without affecting the output of their work – or indeed making them more productive. It is only natural that human labour, productivity, their economic implications and determinants have become major points of interest for businessmen and researchers alike (see e.g. Culling and Skilling, 2018; Lisenkova et al., 2013; Xanthopoulou et al., 2009; Zhang and Lucey, 2017).

A collection of individuals working or willing to work constitutes a labour force. Just as the individuals in it, we can characterise labour force by a multitude of variables, particularly its size, gender or age composition, level of education, skills or health status. Labour force – and the broader population – are essential determinants of the economic situation in a country, affecting demand for goods and services, labour supply, production, wages or public finances. As such, prosperity of a nation is directly affected by its population size and structure, labour force mobility, productivity and human capital accumulation, the stock of habits, knowledge, social and personality attributes embodied in the ability to perform labour so as to produce economic value (Goldin, 2016). And the populations worldwide, which have collectively grown more than four-fold in the last century, are projected to dramatically change in the next decades.

As a result of changes in the migration patterns, improvements in healthcare leading to rising life expectancy, and sub-replacement fertility rates, populations in almost every country in the world have been gradually ageing and, in many, particularly developed countries, shrinking in the past decades. The data from United Nations (2017) show that the number of individuals aged 60+ in the population worldwide has increased from 202 million in 1950 to more than 900 million in 2015, with its share in the overall population increasing from 8% to 12%; crucially, these figures are expected to increase to 2.08 and 3.14 billion (21% and 28%) in 2050 and 2100, respectively. The changes have had – and are expected to have – profound effects on the economies and indeed the entire societies. For instance, the public finances will likely be affected by population ageing as older people have higher savings and consume less goods and services than the young, require higher health and social care expenditure from the state, and are less likely to work, needing other sources of income.

Similarly to human labour and its productivity, the topic of population ageing and broader demographic changes has received substantial attention in the past years (see e.g. Bloom et al., 2015; Broersma et al., 2017; Kanabar, 2015; Martinez et al., 2017; Temple and McDonald, 2017). There is now a good understanding of the means and magnitude of effects on the economy and society, yet this is often done at either a theoretical or insufficiently granular basis to enable evidence-based policy-making at the regional or national level. This is particularly the case of smaller countries such as the Czech Republic, which are only infrequently in the focus of research studies aimed at a single or a small group of countries, as opposed to large-scale studies such as European Commission (2019), OECD (2018) or OECD (2019), which generally follow a predefined framework for assessment of all countries in the studied sample.

Equally, the use of the standard, commonly utilised theoretical and statistical models have their limitations in providing projections of labour force changes and their implications, as they may not provide the necessary level of detail and/or have sufficient empirical data to work with. Like in other mathematically intensive sciences, the use of computers, programming and simulation processes is increasingly finding its way in economics, with the premise of moving from a simple computation – effectively a form of theory articulation – to utilising the underlying theoretical/mathematical model calibrated using appropriate data to deliver results where traditional analytical solutions cannot be derived and statistical solutions lack information to work with. As argued by Lehtinen and Kuorikoski (2007), the choice behaviour of agents in the economy – individuals, firms, institutions – is often described in the economic theory by relatively simple rules. Computer simulations thus appear as a natural tool for exploring the aggregate effects of changes in parametrisation of the studied environment or behavioural assumptions; in this case: demographic changes or age-related behavioural shifts. In particular, computer simulations provide one way of overcoming difficulties with evaluation of heterogeneous populations and distributional effects using traditional analytical models.

It was the velocity and magnitude of changes in the world around us, particularly the way that people live, work and interact with modern technologies, population changes, and the lack of timely response to such changes from individuals, organisations and policy-makers, that sparked my interest in the research discussed in this thesis. And it is with a hope that by providing concrete, understandable assessment of these issues, yet based on the latest data, research findings and methodologies, we, as a society, can better appreciate the need for a constant improvement.

This thesis utilises computer-based simulation modelling to explore the potential impacts of changes in the population and labour force – its size, demographic structure and productivity – in the Czech Republic and the United States, as well as a statistical assessment of factors behind labour productivity, with the aim to highlight the potential/need for policy reforms in order to maintain and further improve the economic situation in the countries considered. The use of micro-simulation models, which allow assessment of autonomous individuals (both individual or collective entities) and interactions between them, is particularly useful for the intended purpose as the demographic and productivity dynamics discussed above vary across the different agents in the economy. One can therefore explicitly assume that the behaviour a highly-educated professional at the end of their career will substantially differ from a young, unskilled worker, or that the progressive ageing of the population will have different implications for high-earning individuals able to save enough financial resources for their retirement, as opposed to the low-earning classes that are more reliant on the state support. Consequently, such a research approach can deliver a more detailed assessment of the situation than the standard analytical methods.

Specifically, Chapter 2 looks at the projected demographic changes in the Czech Republic, how they may affect pensions and long-term financial sustainability of the Czech pension system, and feasibility of various parametric and structural reforms addressing such changes. To do so, it develops a bespoke overlapping generations (OLG) model with heterogeneous agents, bequests, productivity shocks, market imperfections, and realistic representation of three distinct types of pension systems calibrated using real-world data, with numerical results obtained through computer simulations. The use of micro-simulation modelling not only allows us to evaluate a variety of counter-factual scenarios differing only in a single assumption or parameter value, but, importantly, highlight the implications on intra- and inter-generational solidarity, i.e. whether, and to what extent, the contrasting pension system reforms affect individual population subgroups and generations. What is more, all factors in the model – economic growth, demographic changes, tax regulations, consumption behaviour, etc. – are modelled explicitly and can be adjusted in a sensitivity analysis, which is particularly useful given the uncertainty inherent to future projections.

The baseline OLG model used in the study and inspired by the works of Börsch-Supan et al. (2006), Deger (2008), Heer and Maussner (2009), Ihori (1996) and Zodrow et al. (2013), explicitly distinguishes between 60 cohorts of economically active agents differing in their age, where the youngest cohort is born and the oldest cohort dies each period (year), with the other cohorts facing a positive probability of death throughout their lives. Moreover, agents within a single cohort are heterogeneous in their skills and income, leading to a range of specific consumption or saving behaviours despite all agents following the same baseline choice behaviour function.

The model is implemented in a MATLAB script and since each interaction in the modelled economy and the optimisation procedures are distinctly defined in the script, as opposed to use of a preexisting commercial economic modelling software allowing only a limited specification (and type) of the assumed model (Dellink et al., 2015; Lofgren et al., 2013; Roos et al., 2015), the model could be completely tailored for the particular case of the Czech pension system, including factors such as degressive income replacement rates or structural reforms.

Customisability of the baseline simulation model is capitalised on in the study on impacts of demographic changes on the Czech economy as a whole, presented in Chapter 3. The study develops the model further by adding a computable general equilibrium (CGE) element allowing assessment of individual sectors in the economy. Concretely, the model replicates in detail the distribution of individuals in the Czech Republic in terms of age, educational attainment, industrial sector and occupation, as well as the interrelations among industrial sectors in producing intermediate and final outputs, resulting in a comprehensive evaluation of the projected changes in labour supply or demand for goods and services on population welfare, production and public finances. Again, using a micro-simulation model is particularly useful in this case as it provides a thorough overview of the sector- and subgroup-specific implications with the ability to precisely pinpoint the source of the effects.

Chapter 4 is broadly aligned with the previous two studies in terms of the analytical method, using again an adjusted version of the baseline OLG model from Chapter 2, yet this time it differs more substantially in terms of its research focus, analysing the potential economic impacts of delaying school starting times for high school students in the US. The study was inspired by my previous publication with colleagues at RAND Europe (Hafner et al., 2016), which was well received by both the academic and non-academic community and shown a substantial demand for further economic quantification of insufficient sleep, an elephant in the room practically disregarded by individuals, organisations and the state despite its evident impacts on physical and mental health. Indeed, numerous studies have shown that later school start times (SST) are associated with positive student outcomes, including improvements in academic performance, mental and physical health, and public safety. While the benefits of later SST are well documented in the literature, in practice there is opposition against delaying SST due to the associated costs. The presented study investigates economic implications of a statewide universal shift in SST to 8.30 a.m., including the benefits of higher academic performance of students and reduced car crash rates, which, in turn, result in a larger and more productive labour force. Unlike Chapter 2, the models in Chapters 3 and 4 do not consider bequests to be a part of the decision-making processes of households. This is done to lower the computational demands of the simulation models as the bequest motive is not essential for analysis in the two models.

Finally, Chapter 5 complements the previous economy-wide studies by looking at the productivity determinants at the individual level by examining data on 31,950 employees in the UK, their workplace productivity (loss) and what influences it. The variables of interest, comprising socioeconomic characteristics, lifestyle, commuting, physical and mental health, well-being, and job and workplace environment, are assessed using structural equation models, which allow systematic decomposition of the complex network of influences and lead to new, deeper insights than the prior studies. While the modelling principally highlights the importance of a comprehensive approach to human health and productivity, as a wide range of factors across both the individual and organisational dimensions appear as significant determinants of workplace productivity, it also shows the potential issues with using only a small subset of variables in the analysis, as some of the factors with an initially estimated high impact on productivity show reduced – or effectively non-existent – effects once other factors are considered, suggesting that the initially observed effect is affected by the omitted variable bias, which may affect results of earlier studies.

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Chapter 2

Pension reforms and adverse demographics: options for the Czech Republic

Abstract[1]

This study estimates changes in pensions and long-term financial sustainability of the Czech pension system in the light of population ageing, market imperfections or a potential economic downturn, and assesses feasibility of various parametric and structural reforms. To do so, it develops a bespoke OLG model with heterogeneous agents, bequests, productivity shocks, market imperfections, and realistic representation of three distinct types of pension systems calibrated using real-world data. Numerical results are obtained through computer simulations. The estimates show that a well-designed multi-pillar pension scheme provides good results in a number of performance indicators without leading to excessive costs of transition, whereas maintaining the current PAY-GO scheme would lead to a gradual decrease in real pensions, lower pension-to-wage ratios, higher budget deficits, or any combination thereof, unless the statutory retirement age increases beyond 67 years by 2050.

2.1 Introduction

As the baby-boom generation slowly reaches retirement age, there has been a clear shift in demographic trends resulting in reduction of the working-age population share. In the Czech Republic, the old-age dependency ratio – the number of working-age to retired individuals – is expected to fall from 3.6:1 to 1.9:1 in just forty years if the minimum retirement age remains unchanged (United Nations, 2015) with other countries following a similar trend. In this situation, financial sustainability of pension systems has been a particularly discussed topic among both academics and policymakers, especially following the financial crisis of 2007–2008, which has put public finances under an unprecedented pressure. Indeed, many developed and developing countries are now in a dire need of pension system reforms in order to decrease their forecasted budget deficits in the years to come.

[1] This study was published as: Stepanek, M. (2019). Pension Reforms and Adverse Demographics: Options for the Czech Republic. *Czech Journal of Economics and Finance*, 69(2).

While there is a broad consensus that long-term financial sustainability of a pension systems in countries like Greece or Japan is impossible without substantial reforms (see e.g. Finke and Sabatini 2016 or OECD 2015), it is far from clear what the optimal solution for each country is. Several authors (e.g. Holzmann et al. 2005; Kaganovich and Zilcha 2012; Kotlikoff et al. 1999) argue that a structural change, substituting the existing state-run PAY-GO schemes with private funded systems – where people contribute towards their own retirement rather than finance pensions for others – could be more beneficial in the long-term than simple parametric changes aimed e.g. at increasing retirement age.

The argument follows from vulnerability of PAY-GO systems to adverse demographical changes and economic downturn due to reliance on intragenerational solidarity and social security tax revenues (Cipriani, 2018; Oksanen, 2009). At the same time, PAY-GO systems are generally immune to the direct effects of volatility of financial market returns. This is contrary to specifics of funded schemes, which are more resistant to demographic and potentially also political changes – as retirement benefits depend on individual's savings rather than government decisions – but may depend heavily on financial markets (Burtless, 2010; Casey, 2011; Miles and Černý, 2006). A structural change towards a funded pension system would also be extremely costly as either the current or future generations would need to essentially double their contributions to the pension system. Finally, there may be other potential long-term downsides of their financing structure (see e.g. Barr 2002 or Brooks, 2000).

This study focuses on the case of the Czech Republic, an exemplary country with ageing population and majority of pensioners wholly dependent on contributions from younger generations. It aims to complement results from the previous literature on performance and financial sustainability of pension systems (e.g. Aglietta et al., 2007; Alonso-García et al., 2018; Fehr, 2009; Makarski et al., 2017) and fill the gap in analytical evidence to determine whether there is a well-rounded optimal pension scheme that would provide future Czech pensioners with a decent income in retirement without putting an excessive burden on the younger generations through accumulation of external debt or raising social security tax rate. This is done through comparison of various scenarios with parametric and structural reforms using large-scale simulations of a bespoke overlapping generations (OLG) model with heterogeneous agents, bequests, productivity shocks and market imperfections. In order to provide real-world alternatives to the existing scheme, the structural pension reforms use detailed representations of the existing pension systems from Sweden (a multi-pillar scheme) and Chile (a fully funded scheme).

2.2 Existing research

This study is broadly in line with the recent literature on comparative assessments of pension systems in selected countries. For instance, Olivera (2016) evaluates the potential effects of a multi-pillar pension system on pension inequality in Peru; Laun and Wallenius (2015) develop a life cycle labour supply model to forecast labour supply implications of a Swedish pension reform; Blank et al. (2016) compare the Austrian and German pension systems; De La Fuente and Domenech (2013), Patxot et al. (2017) and Vidal-Melia (2014) analyse the financial impact, adequacy of pension benefits and actuarial fairness of the 2011 reform in Spain; and Fredriksen et al. (2019) analyse fiscal effects of the Norwegian pension reform.

Many studies aiming to estimate the future costs and benefits of pension system reforms are based on a series of explicit scenarios determining some of the main factors in the economy. Opposite to this approach, computable general equilibrium (CGE) models assume the economy to fit a predefined, appropriately calibrated theoretical framework and determine future outcomes through simulations of interactions within the economy. Some of the first studies using computer simulations in the area of pension systems were Arrau (1993), Cifuentes and Valdés-Prieto (1999), Cifuentes and Valdes-Prieto (1997) and Kotlikoff et al. (1999). More recent literature analysing pension systems using (stochastic) computer simulations focuses on broad spectrum of topics ranging from adequacy, efficiency, fairness and sustainability of pension systems to estimation of an optimal portfolio allocation in a mix between unfunded and funded schemes (see e.g. Auerbach and Lee, 2011; Bielecki et al., 2015; Devolder and Melis, 2015; Draper and Armstrong, 2007; Godínez-Olivares et al., 2016a; Makarski et al., 2017). For instance, Godínez-Olivares et al. (2016b) design an optimal automatic balancing mechanism to keep the required level of liquidity in pay-as-you-go pension systems by changing the contribution rate, retirement age and/or pension indexation, using population forecasts from Japan and Spain to validate their model. In another study, Alonso-García et al. (2018) construct a computable OLG model to show how a well-designed risk-sharing mechanism may help to restore sustainability of both defined benefit and defined contribution PAY-GO pension schemes using the Belgian population as an example.

The baseline OLG model used in this study was developed by Samuelson (1958) and Diamond (1965) and recently used in a similar context e.g. by Giammarioli and Annicchiarico (2004), Michel et al. (2010), Tyrowicz et al. (2018) and Verbič (2008) who use a simple two-period OLG model to investigate fiscal rules required to maintain sustainability of public finances in economies with a PAY-GO pension scheme. In another study, Nishiyama and Smetters (2007) analyse a partial privatisation of an unfunded scheme in a model with elastic labour supply facing idiosyncratic earnings shocks and longevity uncertainty. The problem of adverse population changes is then addressed using an OLG model e.g. in Miles and Černý (2006) and Oksanen (2009).

2.3 Characteristics of the selected pension systems

2.3.1 Pension system in the Czech Republic

The Czech pension system is a classic example of a PAY-GO scheme with no mandatory savings into pension funds. According to the current legislation, the statutory retirement age will increase by two months per additional year of birth from the current 63 years for men and 62 for women up to 65 years for both men and women by 2030 (MLSA, 2018). However, the model developed in this study also considers a scenario with further increase in retirement age up to 67 years by 2042 as per the previous legislation (MLSA, 2017). The existing social security taxes financing retirement benefits are set at 6.5% paid by employees and 21.5% paid by employers.

Pension transfers consist of a flat minimum benefit calculated as 9% of the average wage (CZK 2,440 and 27,006 in 2016, respectively) and a variable benefit determined as follows. The number of years that an individual contributed to the social security system is multiplied by 1.5% and determine the replacement rate factor δ_t. This is then multiplied by an income base, calculated using the average reported income while paying social security contributions, proportionally reduced for higher income (where income from previous years is multiplied by a predefined coefficient to reflect inflation). The income base cannot be lower than 25% of the average wage. Formally:

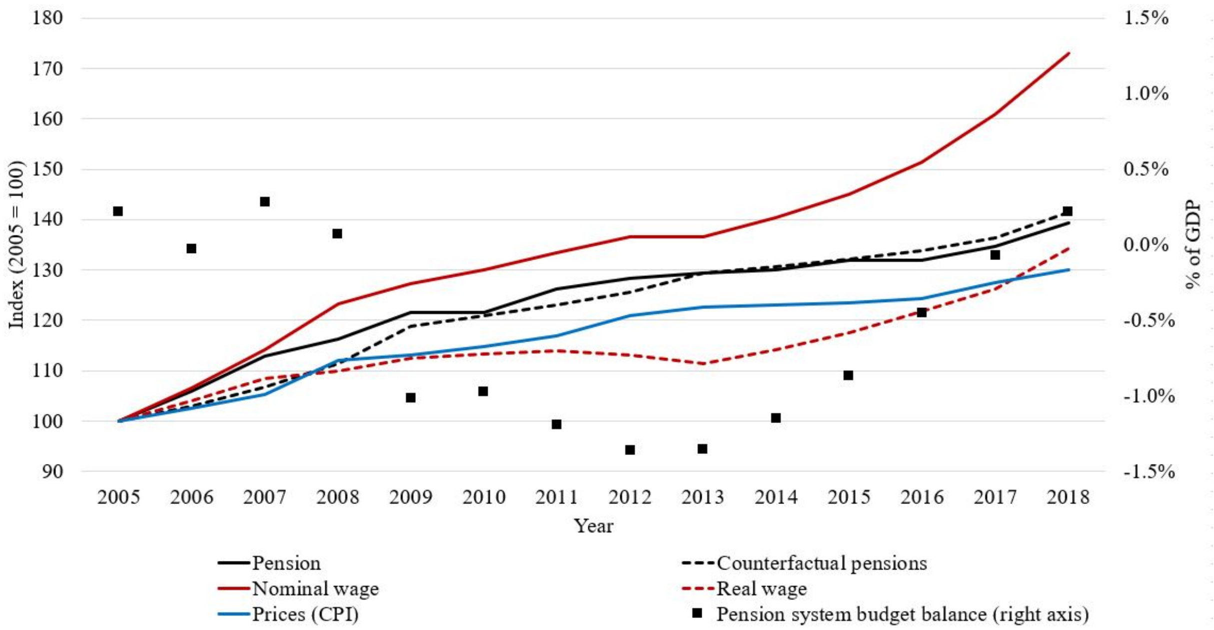
$$B_i = \frac{1}{T}\sum_{t=1}^{T} \delta_t \max(0.25 \times a_t, i_{i,t}) \tag{2.1}$$

$$i_{i,t} = \begin{cases} I_{i,t} & \text{if } I_{i,t} \le c^1 \\ I_{i,t} \times 0.26 & \text{if } (I_{i,t} > c^1 \wedge I_{i,t} \le c^2) \\ 0 & \text{if } I_{i,t} > c^2 \end{cases} \tag{2.2}$$

where B_i is the income base of individual i who contributed to the social security system for T years, a_t is the average monthly wage in year t, $I_{i,t}$ is the total reported monthly income, and c^1 and c^2 are regularly updated cut-offs set at CZK 12,423 and 112,928 in 2016, respectively.

According to the formula, there is an implicit upper bound on pension benefits at approximately 85.7% of the average wage for anyone who retired after forty years of contributing into the system. Hence, the pension system is highly redistributive by nature, with replacement rates (pensions to pre-retirement net wages) for the lowest income groups at nearly 100% and less than 25% for individuals with income at or above quadruple of the average income. The average reported replacement rates are at 54.3%.

Figure 2.1: Pensions and main macroeconomic indicators in the Czech Republic.



Source: The Czech Statistical Office, Ministry of Finance of the Czech Republic and the Czech Social Security Administration.

Following retirement, benefits may increase as a result of parliamentary action but otherwise remain unchanged in nominal terms. Historically, nominal pensions were supposed to increase at the level of inflation plus one third of increase in real wages. Figure 2.1 plots changes in nominal retirement benefits, real wages, consumer price index, nominal wages, and a counterfactual scenario in which nominal pensions increase by the minimum suggested amount. We can see that pension indexation surpassed the benchmark in the 2005-2007 period but otherwise indeed remained broadly at the level of inflation plus one third of changes in real wages. The level of indexation in 2019 (not shown) decreased slightly to 3.4% compared to 3.5% in 2018. Due to less than full nominal wage indexation, replacement rates have been decreasing down to approx. 50.6% for individuals with the average wage. The pension system budget was balanced until the economic downturn in 2008, followed by deficits in the 2009-2016 period and recovery into surplus in 2018.

A detailed description of the Czech Pension system, its estimated development in time, and effect of parametric and structural changes is presented in Bezděk (2000), Cipra (2012), Marek (2005), Schneider (2011) and Marek (2008), whose article builds on a very comprehensive assessment and sensitivity analysis for the Czech pension system in the light of various parametric changes to the existing scheme (Marek, 2007). An introduction of a balancing mechanism for the existing PAY-GO system is then briefly analysed by Hyzl et al. (2005).

2.3.2 Pension systems in Sweden and Chile

The following section briefly describes the two alternative pension schemes used in the analysis: the World Bank three-pillar system presented in Holzmann et al. (2005), with Swedish pension system being its real-world representative, and a fully funded system with Chilean scheme as its representative. The Swedish pension system is described and analysed in detail e.g. in Brown (2008), Könberg et al. (2006), Kruse (2010), Laun and Wallenius (2015), Palmer et al. (2000), Settergren (2003) and Settergren (2012). The pension system is primarily an unfunded scheme with workers contributing 7% of their earnings and employers contributing 10.21%; 86% of the total contributions finance a PAY-GO component (a defined-contribution plan – the income-based pension) and the remaining 14% finance a premium pension component (Swedish Pensions Agency, 2017).

The income-based pension (first pillar) is an unfunded scheme where all contributions are recorded in a personal account and the accumulated virtual funds are then divided by a predetermined annuity divisor upon retirement to determine the regular payments. The premium pension (second pillar) is calculated from accumulated savings using a similar formula (see next section for details). Finally, in addition to the income-based and premium pension, a guaranteed pension, a means-tested benefit, provides minimum pension for individuals older than 65 with low or no income and at least 40 years of residency in Sweden. It is financed from the government's budget.

An important component of the system is an automatic balancing mechanism, which affects indexing of income-based pension contributions. Under optimal circumstances, rate of indexing exactly reflects changes in nominal wages and a part of contributions is set aside, constituting a buffer fund used during economic downturn. If the pension system liabilities overweight assets, indexing is lowered proportionally so that the system returns to balance. The mechanism is formally defined in the next section.

In Chile, everyone working with a labour contract is obliged to contribute to the pension system since their very first job, creating a personal account at a privately owned and managed pension fund that invests the resources into financial assets of contributor's choice (SAFP, 2017).

The monthly contributions are set at 10% of pre-tax earnings up to a given upper bound on contributions. Besides the funded tier, there is also a form of a safety net (a zero-tier) financed from general taxes, aiming to alleviate poverty for the poorest and those that did not manage to put aside satisfactory amount of funds for retirement.

Pensioners in Chile can choose from four forms of account balance withdrawal: a lifetime annuity, programmed withdrawal, temporary income with deferred lifetime annuity, and immediate annuity plus programmed withdrawals. The principle – pre-calculated monthly income adjusted for inflation – is equal in all of them; the difference is in the amount, legal claim on remaining funds, and risk sharing. Only the standard annuity equivalent of the pension benefit calculation in the Swedish premium pension is modelled in this study.

2.4 The Model

The model developed for this study is a dynamic OLG model with exogenous labour supply and heterogeneous agents who leave bequests to their children. The model framework builds on the seminal work of Auerbach and Kotlikoff (1987) and is inspired by Börsch-Supan et al. (2006), Deger (2008), Heer and Maussner (2009), Ihori (1996), Marek (2008), Zodrow et al. (2013) and others. Additional model details and approach to its estimation are described in the Appendix. The terms economic agents (inhabitants) and households are used interchangeably throughout the model description. The computer script is broadly based on Heer and Maussner (2009) and further developed by the author. Note, that while the model uses the standard general equilibrium modelling framework, some of the scenarios (see Section 2.4.3) assume specific parameters, such as interest rate on retirement assets, to be exogenous rather than endogenous. This is in line with e.g. Annabi et al. (2011), Beetsma et al. (2003), Miles and Černý (2006) and Rausch et al. (2011), who use OLG models with explicit exogenous parametrisation in a variety of policy-oriented studies. The simulations were done in MATLAB R2016b.

The setup is as follows: at the beginning of each period (year), the remainder of the oldest cohort dies and a new generation is born. Size of the first newborn generation ($t = 1$) is normalised to one, while size of the subsequent generations ($t = 2, \ldots$) evolves according to the real-world demographic projections. Agents live for maximum of 60 periods and spend the first $T = 43$ years working and the last $T^R = 17$ years retired. The split was selected to broadly correspond to the current standard statutory minimum retirement age of 62-64 years and the average life expectancy of 79 years in the Czech Republic (World Bank, 2018). In line with the existing literature, the first 18 years of actual life are not modelled. Agents face positive probability of death each year, given by exogenous unconditional survival function calibrated using the real-world mortality rate projections. Upon death, all household's assets are immediately transferred to its immediate descendants, subject to an inheritance tax.

Agents are assumed to differ in their education, skills or health status – and therefore productivity and earnings – both within and across cohorts (Heijdra and Reijnders, 2018). To capture intragenerational wealth inequality, each generation is divided into $Z = \{1..12\}$ different income groups. Following Altig et al. (2001), $z = 1$ and $z = 12$ represent approx. the bottom and top 2% of the population cohort s in terms of income, respectively, $z = 2$ and $z = 11$ represent approx. the next bottom/top 8%, with the remaining 8 income classes representing approx. the other eight deciles. Following Heer and Maussner (2009) and Huggett (1996), agents may move between the income groups as a result of idiosyncratic productivity shocks following a Markov process given by

$$z_t = \zeta z_{t-1} + \epsilon_t, \tag{2.3}$$

where $\epsilon_t \sim N(0, \sigma_\epsilon)$; the next-period categorisation thus depends on its past realisations. Following Huggett (1996), distribution of agents' initial income follows a log-normal distribution calibrated so that, while the overall wealth distribution is simplified and does not correspond to reality, the resulting wealth Gini coefficient is close to that of the Czech Republic.

In addition, agent's income evolves over time, representing human capital accumulation, and has the characteristic hump-shaped profile with wages peaking at 31 years of agent's age (i.e. approx. 50 years of actual age). The overall labour-endowment process is given by $e(s, z) = e^{z_s + \overline{y}_s}$, where $\overline{y}_s$ is the mean log-normal income of agent of age s. The total annual income of household aged s in income class z in year t is therefore given by:

$$I_{s,z,t} = (1 - \tau_{z,t})\, e(s, z)\, l\, w_t, \tag{2.4}$$

where $\tau_{z,t}$ and w_t are the effective tax rate and equilibrium wage in the economy, respectively, and l denotes exogenous labour supply – the average share of time spent working per workday. The effective tax rate is calculated using marginal tax rates for different income levels $\tau^i_{z,t}$ and further contains social security contribution rate τ^r_t, assumed to be flat across all income groups as in the Czech Republic.

Agents have children at the age of $T^P = 30$ and bequests, given at the time of death, are assumed to be given out of 'joy of giving' (Kopczuk and Lupton, 2007), providing agents with utility directly from the making of bequests (see the Appendix for further details).

2.4.1 Household and firm optimisation

Agents are assumed to be rational and to optimise their utility over life cycle using a standard utility function common to all households:

$$U(s, z) = \mathbb{E}_s \left[\sum_{j=s}^{T+T^R} \pi_{j,t} \frac{c(j, z_j)^{1-1/\sigma_u}}{(1 - 1/\sigma_u)(1 + \rho)^{j-s}} + \frac{\alpha_z b(z)}{(1 + \rho)^{T+T^R-s}} \right], \tag{2.5}$$

where $b(z)$ denotes bequest planned to be made at the end of life by a representative household in income class z, α_z is the utility function weight placed on bequests as a result of the joy of giving motive, $c(j, z_j)$ is consumption at age j, conditional on being in income group z_j at that age, σ_u is the intertemporal elasticity of substitution, and $\pi_{j,t}$ represents probability of surviving additional year at age j, which effectively acts as additional discounting factor in addition to the pure time preference discounting ρ. The survival probability rate depends both on the probability of death at age s, $q_{s,t}$, and the probability of surviving up to that age:

$$\pi_{s,j,t} = \prod_{k=s}^{j+1} (1 - q_{k,t}) \tag{2.6}$$

Agents maximise lifetime utility subject to a dynamic lifetime budget constraint consisting of labour income $I_{s,z,t}$ (if working), pension transfers $p_{s,z,t}$ (if retired), interest payments from asset holdings, and bequests from their parents. Assets can be either standard taxable assets $A_{s,z}^{tax}$ with yield equivalent to the equilibrium interest rate r, or tax-preferred retirement savings assets $A_{s,z}^{ret}$ that accumulate at interest rate r_r (only available in the alternative pension schemes), which depends on the particular simulation scenario. In order to narrow down the impacts of a pension reform on retirement income, retirement savings $A_{s,z}^{ret}$ are not considered to raise domestic capital but rather to be invested abroad, i.e. the overall capital levels are always broadly consistent with the PAY-GO scenario. In reality, the additional accumulated capital would likely be partially invested domestically, further accelerating economic growth.

Voluntary savings for retirement – and therefore also their possible transfer to mandatory savings – are not modelled since they work the same way in all pension schemes and implementations and may therefore be disregarded without a change in the outcomes. $A_{s,z}^{ret}$ are assumed to be inaccessible throughout one's work life and thus enter the budget constraint as a liability while working and as pension benefit once retired. The budget constraints are therefore given by:

$$A_{s+1,z,t+1}^{tax} = A_{s,z,t}^{tax}\,(1 + r_{t+1}) + b_{s,z} + I_{s,z,t} - c(s,z) - A_{s,z,t}^{ret} \tag{2.7}$$

for workers and

$$A_{s+1,z,t+1}^{tax} = A_{s,z,t}^{tax}\,(1 + r_{t+1}) + p_{s,z,t} - c(s,z) \tag{2.8}$$

for pensioners. Additionally, $A_{s+1,z,t+1}^{tax} = b(z)$ for $s = T + T^R$, i.e. households do not plan any future savings other than bequests for their children in the last period of their lives. Note, that since labour income is inelastic, a shift in agent's consumption-saving pattern is the only way of responding to changes in the budget constraint.

The production sector consists of a representative firm producing output Y_t using capital K_t and effective labour N_t as inputs in a standard Cobb-Douglas production function given by:

$$Y_t = F(\Omega_t, K_t, N_t) = \Omega^{t-1} K_t^{\alpha} N_t^{1-\alpha}, \tag{2.9}$$

where Ω denotes a scaling constant representing technological advancement and $\alpha \in (0,1)$ is the output share of capital in the production.

We can derive the equilibrium wage w_t and interest rate r_t using the firm's maximisation problem. For simplicity, the model does not assume firms to pay any taxes on profit but, following discussion from the previous section, they are required to contribute to the social security system. Specifically, the cost of each unit of effective labour is $w \times (1 + \tau^N)$, where τ^N is the social security contribution paid by firm. That is, assuming a depreciation rate δ:

$$w_t = \frac{(1-\alpha)}{1+\tau^N}\,\Omega^{t-1} K_t^{\alpha}\, N_t^{-\alpha} \tag{2.10}$$

$$r_t = \alpha\,\Omega^{t-1} K_t^{\alpha-1}\, N_t^{1-\alpha} - \delta \tag{2.11}$$

2.4.2 Pension System

The initial pension system specification follows exactly the actual implementation in the Czech Republic, Sweden and Chile. Specifically, pension transfers are determined by income history of new pensioners and exogenously given replacement rates $rr_{z,t}$. As discussed in the previous section, the replacement rates are in form of marginal rates and decrease with income. An effective replacement rate, $rr^e_{z,t}$ can be calculated for each level of income using the income thresholds translated into the model as percentage of the average wage; PAY-GO pension transfers for a person from income group z retiring at age s in year t are then determined as:

$$p^{PG}_{s,z,t} = rr^e_t \sum_{j=1}^{T} \frac{I_{j,z,t-T+j}}{T} \tag{2.12}$$

Note, that z in $I_{j,z,t-T+j}$ represents income group at age $s = j$ and it may be that $z_j \neq z_T$, i.e. agent's previous income class differs from that at the retirement age. As in reality, pension calculation is based on agent's historical income record and the effective replacement rate rr^e_t is calculated using agent's overall pension base accumulated over time. All agents aged T are assumed to retire at the end of the period, with pension benefits determined at that time. Pensions may or may not be indexed afterwards, depending on the particular simulation scenario. Depending on the mechanism of pension budget balancing (if any), pensions may be proportionally lowered across all income classes, or the contribution rate τ^r_t may be increased if pension system liabilities exceed its assets. The pension system is modelled to be in deficit of 0.5% GDP, as in the Czech Republic in 2016, using the pension budget balance equation:

$$\sum_{s=1}^{T} \sum_{z\in Z} (\tau^r_t + \tau^e_t)\, I_{s,z,t}\, \mu_{s,z,t} \lesseqgtr \sum_{s=T}^{T+T^R} \sum_{z\in Z} \kappa\, p^{PG}_{s,z,t}\, \mu_{s,z,t}, \tag{2.13}$$

where $\mu_{s,z,t}$ is the measure of generation s in income class z and year t, τ^e_t is the social security contribution paid by employers, and κ is a scaling parameter reflecting the discrepancy between the old-age dependency ratio in the model and in reality, caused by difference in life expectancy vs retirement age and the implicit assumption that every household of working age is employed in the model, as opposed to positive unemployment rates in reality. The scaling parameter is calculated endogenously within the model. There is no inflation assumed in the model.

In most scenarios (see Section 2.4.4), pension budget is assumed to be unbalanced, resulting in budget deficits/surpluses P_t determined by Eq. 2.13. Since the government's role in the model reduces to collecting social security taxes and paying out pension benefits, pension deficit is equivalent to government budget deficit D_t. It is assumed to accumulate over time according to $D_{t+1} = D_t(1 + r_t) + P_t$ and, for simplicity, yield return of 1% p.a. Importantly, while the model assumes that all of firm's capital is covered by domestic savings (see Eq. 2.20 in the Appendix), government debt is assumed to be entirely covered by inflow of foreign capital. This could, in turn, lead to a crowding out effect on private investment and thus a negative impact on economic growth. The results may therefore overestimate economic growth in scenarios with cumulative government debt and vice versa for surpluses.

The premium pension in the multi-pillar scheme and pensions in the fully funded scheme are determined through contributions to designated pension funds. When agents retire, the funds are transformed into an annuity paid regularly for the rest of their lives. Formally, annuities are determined by dividing the funds accumulated by an appropriate annuity divisor D_x. For comparison purposes, calculation of annuity divisors in both the fully funded and the multi-pillar scheme follows the Swedish formula (Swedish Pensions Agency, 2017):

$$p^{FF}_{s,z,t} = \frac{1}{D_x} \left[\sum_{s=1}^{T} (1 + r_t)^{T-s} (1 - c^A) \, a_{s,z,t} \right] \times (1 - c^I) \tag{2.14}$$

$$D_x = \sum_{j=1}^{T} \frac{1}{(1 + r)^j} \frac{L_{j+1}}{L_j} \tag{2.15}$$

where the first expression in brackets represents the total accumulated wealth – c^A represents administrative fees on assets, c^I represents reduction in pension transfers due to imperfect annuity markets and $a_{s,z,t}$ are savings – and L_j is the number of survivors in age group j per 100,000 born.

Since the formula for calculation of the income-based pension in the Swedish pension scheme results in a substantially higher dispersion of pension benefits within a cohort than in the Czech pension system, it has been replaced by that used in the PAY-GO scheme. At the same time, this unfunded pillar in the multi-pillar scheme is indexed using an automatic balancing mechanism as in the Swedish pension system:

$$\frac{\xi^*_{s,z,t}}{\xi_{s,z,t}} = \psi_t \frac{I_t}{I_{t-1}} \tag{2.16}$$

where $\xi_{s,z,t} = \tau^r_t \, I_{s,z,t}$ is the original contribution made to the system and $\xi^*_{s,z,t}$ is the indexed contribution, with ψ_t being the balancing ratio defined as a ratio of pension system revenues to expenses.

The guarantee pension in the multi-pillar scheme decreases with income-based pension and is calculated as follows:

$$g_{s,z,t} = 2.13 \, \vartheta_t - p^{PG}_{s,z,t} - p^{IB}_{s,z,t} \qquad \text{if } p^{PG}_{s,z,t} + p^{IB}_{s,z,t} \leq 1.26 \, \vartheta_t \tag{2.17}$$

$$g_{s,z,t} = 0.87 \, \vartheta_t - 0.48 \left(p^{PG}_{s,z,t} + p^{IB}_{s,z,t} - 1.26 \, \vartheta_t \right) \qquad \text{if } p^{PG}_{s,z,t} + p^{IB}_{s,z,t} > 1.26 \, \vartheta_t \tag{2.18}$$

where $g_{s,z,t}$ is the calculated pension amount, ϑ_t is a price-related base amount set at 11.59% of average gross income following the Swedish example, and $p^{PG}_{s,z,t}$ and $p^{IB}_{s,z,t}$ represent the PAY-GO and income-based pension. In words, pensioners' benefits are topped up to at least $2.13 \times 11.59\% = 24.7\%$ of the average gross income. This is also shown in Figure 2.7. Note, that both the original PAY-GO pension and the new source of income (excluding premium pension) are considered in the calculation in case of a structural change to a multi-pillar scheme. The fully funded scheme also includes a safety net p^s_t that tops up pensions for low-income classes up to a certain amount, set to the minimum pension obtained in the baseline PAY-GO system. This is financed through the general taxation and thus appears only as increase in government indebtedness.

2.4.3 Calibration

The economy is characterised by labour supply calibrated using data on average annual hours worked from the OECD; intertemporal elasticity of substitution data obtained from Havranek et al. (2015); depreciation and productivity growth rate from the Penn World Tables (Feenstra et al., 2015); income and social security tax rates; and population predictions from the United Nations. The parameter values are presented in Table 2.1. For simplicity, the model assumes that the baseline productivity growth rate will remain at its historical 2005-2015 average.

Following Zodrow et al. (2013), rate of time preference ρ is set equal to 0.011; variance of earnings for a newborn generation is set as $\sigma_{y1} = 0.38$ and the path dependency parameter ζ from Equation 2.3 is set to 0.96 as in Huggett (1996); variance of idiosyncratic productivity shocks σ_e is set to 0.129 so that the overall wealth distribution in the economy can be characterised by Gini coefficient of 25.9 as in the Czech Republic (World Bank, 2018); and the utility function weight placed on bequests is set so that the bequest/income ratios resemble those identified by Fullerton and Rogers (1993). As in reality, the baseline tax rate is set at 15% of 1.34 times the gross personal income, and income above quadruple of the average wage is taxed by additional 7%. Each individual can deduct CZK 2,070 per month from their taxes (approx. 7.7% of the gross average wage). There is no inheritance tax in the Czech Republic and interest income is taxed as any other source of income at 15%.

Population predictions are based on the total population, mortality, and fertility indicators from United Nations (2015) for years 1996-2050. Following the model specification, I use fertility rates from year $t - 18$ to reflect that $s = 1$ corresponds to the real life age of 19. The initial mortality rates are set according to the UN data for 2016. From the second period onwards, size of the newborn generation evolves according to the ratio of fertility rates compared to the initial period, mortality rates evolve according to the UN data, and the population structure is defined endogenously within the model using a cohort-component model. The outcome of the model is a projection of the population by 1-year age and gender groups into the future. Formally, the population P of age s at time t is calculated as:

$$P_{s+1,t+1} = P_{s,t} + B_{s,t} - D_{s,t}, \tag{2.19}$$

where $B_{s,t}$ represents the total births in age group s at time t and D_s represents total deaths. There is no migration assumed in the model and the maximum age does not change throughout the simulated timeframe. The population predictions highlight three separate trends – decrease in fertility, increase in mortality, and shift in population structure with large cohorts reaching retirement age in the next decades.

The income and social contribution tax rates are assumed to remain constant regardless of the pension system implemented in order to maintain comparability of the results. In the multi-pillar scheme, 86.5% of all contributions are used to finance the unfunded scheme as per above. In the fully funded pension scheme, the whole amount of contributions from both the employer and the employee are put in the pension funds.

2.4.4 Scenarios

In what follows, performance of the baseline pension system is compared across multitude of variables. The counterfactuals are principally meant to show the extent of potential changes

Table 2.1: Calibration parameters

Symbol	Description	Source	Value
ρ	Rate of time preference	Zodrow et al. (2013)	0.0110
σ_e	Variance of idiosyncratic shocks	World Bank[a]	0.0129
σ_{y_1}	Variance of earnings for s = 1	Huggett (1996)	0.3800
σ_u	Intertemporal elasticity of substitution	Havranek et al. (2015)	0.5000
α_z	Utility function weight placed on bequests	Fullerton and Rogers (1993)[b]	Various
α	Output share of capital in production	Börsch-Supan et al. (2006)	0.35
δ	Depreciation rate	Feenstra et al. (2015)	0.0446
τ	Marginal taxation	OECD Tax Database	1.9%-35%
τ_I	Inheritance tax	EY Global Tax Guide	0%
τ_C	Tax on interest income	OECD Tax Database	17.1%
Ω	Baseline productivity growth rate[c]	OECD	1.0208
ϕ	Population scaling parameter	Czech Social security Administration	1.9051

[a] Calibrated so that the distribution of wealth, measured by the Gini coefficient, is corresponds to the World Bank data for each country.
[b] Calibrated for each income group so that the average bequest-annual income ratios correspond to Fullerton and Rogers (1993).
[c] Proxied by GDP per hour worked in constant prices.

rather than to pinpoint a particular most probable variant. To this end, each variable of interest is presented in several distinct scenarios that are then combined to create a set of snapshots of the overall system. A summary of the modelled scenarios is presented in Table 2.2, following the structure of Section 2.5. In all scenarios, the existing PAY-GO scheme in its current specification is in place at time $t = 1$ and any structural reforms will take place in $t = 2$. For simplicity, the model assumes that all reforms come as a surprise (an unanticipated shock) to the agents. This would not be true in reality, however, as agents would have to be aware of future developments for several years ahead and the pre-announced future policies would therefore have implications on households' behaviour even before they would actually take place.

In the first set of baseline scenarios, the two changing sensitivity parameters are productivity growth and rate of pension adjustment. The baseline productivity growth is assumed to remain constant over time at the 2005-2015 average level of growth of 2.08%. In two pessimistic scenarios ('Low' and 'Very low'), the growth rate is assumed to be at 50% and 75% of this, while in two optimistic scenarios ('High' and 'Very high'), it is set to 125% and 150% of the baseline rate. Rate of pension adjustment follows discussion in Section 2.3.1 and is modelled at the level of inflation plus one third of increase in real wages (baseline), at the rate of inflation ('None') and at the full rate of real wage increase ('Full').

In scenarios considering parametric changes to the pension system, the sensitivity parameters are pension adjustment (as above), statutory retirement age and pension budget balancing mechanism. Changes to statutory retirement age follow discussion in Section 2.3.1 and consider no changes to the existing situation, an increase to 65 years by 2030 (baseline), and an increase to 67 years by 2042. Pension budget is assumed to be unbalanced throughout the results at the baseline. In the alternative scenarios, budget may be forcedly balanced through changes to either the social security tax rate (so that pensions remain unchanged) or pension benefits (so that taxes remain unchanged).

Finally, in a range of scenarios considering structural changes to the pension system, the sensitivity parameters are retirement age (as above), pension scheme (baseline PAY-GO, multi-pillar and fully funded as per Section 2.4.2), rate of return on retirement assets and market imperfections. In case of a pension scheme change, the initial PAY-GO pensions are still paid during the transition period, yet their amount decreases proportionally to the number of years that the new pensioners contributed to the original social security system. The old pensions thus decrease to approx. 50% in $t = 24$ after correcting for changes in the real wage. Analogously, pensions from the new system are paid out immediately, but are low at first and increase over time with contributions made.

Rate of return on retirement assets is set to 3.5% at the baseline and at 1% and 6% in the pessimistic and optimistic scenarios, respectively, broadly in line with real world pension funds' performance (OECD, 2016). Finally, annuities are assumed to be actuarially fair (i.e. c^A and c^I in Equation (2.14) are both set to zero) and there are no further market imperfections assumed at the baseline. In the alternative scenarios, three distinct types of market imperfections are modelled: a financial market crash, administrative costs of running pension funds, and actuarially unfair annuity markets. The two latter parameters are set to 1.5% for annual fee on assets in pension funds and a 10% reduction in pension benefits due to imperfect annuity markets lower the eventual pension benefits. The parameters are taken from Murthi et al. (2001), OECD (2017) and Sluchynsky (2015) and correspond to the upper-bound estimates to reflect the full range of possible outcomes. In case of a financial market crash, the model assumes a drop in the market value of pension funds' assets by 40% as a result of a massive crash in $t = 10$, which broadly reflects the average drop in individual account balances across all pension funds in Chile in 2008.

Table 2.2: Sensitivity parameters and ranges for individual scenarios

Section	**Sensitivity parameter**	**Scenarios / parameter range**
Baseline simulation	Productivity growth rate	Very low; Low; Baseline; High; Very high
	Pension adjustment	None; 1/3; Full
Parametric changes	Retirement age	No change; Up to 65 years; Up to 67 years
	Pension adjustment	None; 1/3; Full
	Budget balancing mechanism	Taxes; Pensions
Structural changes	Pension scheme	No change; Multi-pillar; Fully funded
	Retirement age	No change; Up to 65 years; Up to 67 years
	Interest rate	1%; 3.5%; 6%
	Market imperfections	None; Administrative costs; Administrative costs + stock market crash

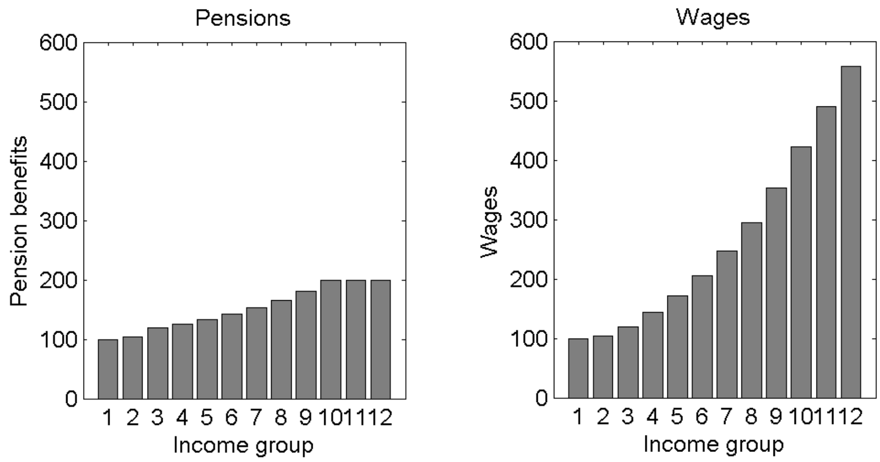
2.5 Simulation Results

This section first presents the estimated future development of the baseline Czech pension system in light of the assumed adverse population changes and potential parametric adjustments, followed by a comparison of all three pension schemes in a variety of scenarios. There are five main variables of interest, all of them expressed in real terms in absence of inflation in the model: pensions, degree of intra-generational wealth distribution among pensioners, social security tax rates, pension system indebtedness, and economic growth. The results are presented in several steps, each representing comparison along a different dimension. Throughout this section, $t = 0$ corresponds to year 2016.

2.5.1 Baseline comparison

Let us first inspect distribution of pensions and wages in the baseline model as depicted in Figure 2.2, in which each bar in the left and right exhibits correspond to data on the same income group. Clearly, the current scheme benefits lower income classes at the expense of individuals with higher income, as the wealthiest individuals have nearly six times higher gross wages than the bottom 10% of the population, but only two times higher pensions. As we will see later, this contribution to intra-generational income equality is one of the main factors distinguishing the Czech PAY-GO scheme from the funded schemes.

Figure 2.2: Pension and income distribution in the baseline pension system, 2016.

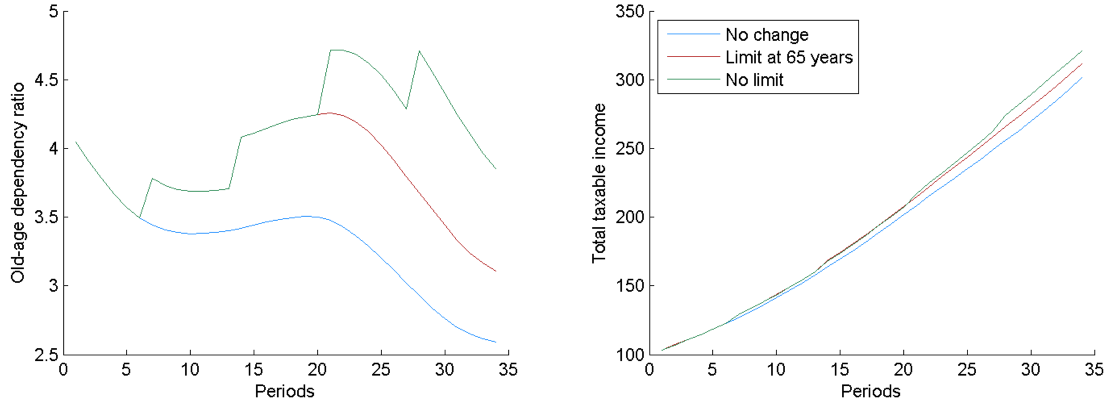


Notes: The values represent multiples of the lowest income class value, standardised to 100.

To fully appreciate the adverse population changes, consider the shifts in old-age dependency ratio and total taxable income over time as depicted in Figure 2.3. Without any adjustments in retirement age, the old-age dependency ratio decreases by nearly 40% over the span of 35 years. Increasing retirement age to 67 years by 2042 would keep share of pensioners in the population virtually unchanged, suggesting an appropriate rate of adjustment. In addition, while postponing retirement age affects principally the expenditure side of the pension budget by reducing the number of pensioners in the economy, we can see from the explicit (b) that the additional workers would help the revenue side as well.

As a first step in the comparative analysis, let us analyse the estimated changes in output, pensions, and pension budget balance (as percentage of GDP) in case of no parametric changes to the existing PAY-GO system, depicted in Table 2.3. The table presents fifteen distinct scenarios with the same starting point, differing in the rate of pension adjustment ('None' – indexation only at the level of inflation; '1/3' of changes in real wages; and 'Full' real wage indexation) and productivity growth rate as per Table 2.2, with each row representing a different scenario, i.e. a unique combination of the two sensitivity parameters. Note, that all scenarios are equivalent in 2016, representing the existing situation in the Czech Republic. Correspondingly, values of pensions, pension/wage ratios and output are standardised using the 2016 values to allow easier tracking of changes over time. All tables follow the same structure and since the 2016 values do not change across scenarios and there is no inflation in the model, results across all tables

Figure 2.3: Population changes. (a) Old-age dependency ratio, (b) Total taxable income as ratio compared to the $t = 1$ level.



Notes: Scenarios represent changes to retirement age. 'No limit' scenario represents the current legislation where retirement age increases regularly without an upper bound set to it.

are directly comparable. All scenarios in Table 2.3 assume that retirement age increases to 65 years for both genders by 2030. Changes in the equilibrium wage are not reported as it increases effectively at the same rate as output (see Equation 2.10).

Starting with output Y_t (column Y in Table 2.3), it is negatively correlated with pension indexation and there are substantial differences across the productivity growth scenarios. This is a result of the consumption smoothing; households respond to the prospect of a large drop in income when retired in scenarios with low or no indexation, choosing to save more during their working age in order to increase consumption in retirement, which, in turn, leads to a higher output.

Table 2.3: Baseline simulation results – unbalanced pension budgets, no structural changes. Assumptions: limited retirement age increase.

PGR	Pen. adj.	2016 P	2016 P/W	2016 Y	2016 B	2016 CB	2030 P	2030 P/W	2030 Y	2030 B	2030 CB	2050 P	2050 P/W	2050 Y	2050 B	2050 CB
Very low	Full	100%	100%	100%	-0.5%	-0.5%	127%	100%	127%	-0.4%	-26%	179%	100%	169%	-5.1%	-62%
Low		100%	100%	100%	-0.5%	-0.5%	142%	100%	142%	-0.4%	-26%	234%	100%	221%	-5.1%	-62%
Baseline		100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	306%	100%	288%	-5.1%	-62%
High		100%	100%	100%	-0.5%	-0.5%	177%	100%	177%	-0.4%	-26%	399%	100%	376%	-5.1%	-62%
Very high		100%	100%	100%	-0.5%	-0.5%	198%	100%	198%	-0.4%	-26%	519%	100%	490%	-5.1%	-62%
Very low	1/3	100%	100%	100%	-0.5%	-0.5%	109%	85%	128%	2.0%	-5%	122%	67%	173%	1.5%	54%
Low		100%	100%	100%	-0.5%	-0.5%	113%	79%	144%	2.9%	4%	134%	56%	228%	3.7%	98%
Baseline		100%	100%	100%	-0.5%	-0.5%	117%	73%	162%	3.8%	12%	147%	46%	300%	5.6%	137%
High		100%	100%	100%	-0.5%	-0.5%	122%	68%	181%	4.6%	20%	162%	39%	394%	7.1%	171%
Very high		100%	100%	100%	-0.5%	-0.5%	127%	63%	203%	5.4%	27%	177%	32%	515%	8.4%	201%
Very low	None	100%	100%	100%	-0.5%	-0.5%	100%	78%	129%	3.0%	5%	100%	54%	175%	4.0%	104%
Low		100%	100%	100%	-0.5%	-0.5%	100%	69%	145%	4.4%	18%	100%	41%	231%	6.7%	161%
Baseline		100%	100%	100%	-0.5%	-0.5%	100%	62%	163%	5.5%	29%	100%	31%	305%	8.6%	209%
High		100%	100%	100%	-0.5%	-0.5%	100%	55%	183%	6.6%	40%	100%	24%	399%	10.1%	248%
Very high		100%	100%	100%	-0.5%	-0.5%	100%	49%	205%	7.5%	49%	100%	18%	521%	11.2%	282%

Notes: PGR = Productivity Growth Rate, Adj. = Pension adjustment, Y = aggregate output, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 3% and 5%. In all tables, each row represents a separate scenario with a unique combination of the sensitivity parameters in the first 2-3 columns.

Pensions are reported twice: once in absolute terms and once relative to real wages in the economy (columns P and P/W in Table 2.3, respectively). By definition, the absolute value of pensions does not change in the scenario with no indexation and the pension-wage ratio remains constant in the full-indexation scenario. Similarly to other variables, the pension-wage ratio is set to 100% in 2016 and higher/lower values in the future correspond to higher/lower pension-wage ratio than in the initial period. Recall from Section 2.3.1, that replacement rates in the Czech Republic for individuals with an average wage were approx. 50.6% in 2018 (that is, their income decreased by nearly a half once retired); a decrease to 46% in 2050 as in the scenario with the baseline productivity growth and indexation at one third of growth in real wages (row 8, column 2050 P/W in Table 2.3), which broadly represents the average indexation in the last ten years, therefore corresponds to a real-world replacement rate of 23.3%, which is even lower than the existing social security tax rate of 28%.

Indeed, in scenarios with pensions indexed at one third of real wages (rows 6-10), pension budget ends in a substantial surplus (columns B and CB in Table 2.3, representing the annual and cumulative pension budget balance, respectively) at the cost of relatively poorer pensioners. This contrast is even starker in the scenarios with indexation only at the level of inflation (rows 11-15), where the pension-wage ratio decreases to just 31% in the scenario with baseline productivity growth, corresponding to real-world replacement rates of 15.7%. The replacement rates remain unchanged only in the scenarios with indexation at the level of growth in real wages, resulting in an accumulated debt of 62% GDP in 2050.

Finally, even though pensioners would maintain their existing relative income levels in the scenario with full pension indexation, this would be only at the cost of enormous indebtedness or cuts in other public policy areas, as all of the scenarios are estimated to lead to over 5% GDP deficit each year by 2050. Note that the projected indebtedness is equivalent in all scenarios as any changes in tax revenues due to economic growth are exactly matched by increase in pensions. To conclude, there will always be a trade-off between maintaining a balanced pension budget and disparity between income of workers and pensioners, regardless of the level of economic growth.

2.5.2 Parametric changes

If one cannot maintain sustainable long-term pension system financing and appropriate replacement rates at the same time regardless of economic growth, can other parametric changes to the current system help? According to Equation 2.13, in addition to adjusting the pension system's expenditure (pensions) as above, one may also adjust the revenue side (taxes) or their proportions (retirement age). Table 2.4 presents the projected performance indicators of the existing PAY-GO system in nine scenarios differing in indexation (as above) and retirement age (no change, up to 65 years, unlimited), all of which assume the baseline aggregate productivity growth. Note, that rows 2, 5 and 8 in Table 2.4 are equivalent to rows 3, 8 and 13 in Table 2.3 in their assumptions and results.

Recall, that the proposed linear increase of retirement age up to 67 years of age would keep the old-age dependency ratio virtually constant until 2050 (see Figure 2.3). As a result, the pension budget would be nearly in balance even in the full-indexation scenario – and in surplus should pensions be indexed at lower rates (see rows 3 and 6, columns B and CB in Table 2.4).[2] However, increasing retirement age to 65 years and maintaining it at that level thereafter would not be enough beyond 2035 (when the old-age dependency ratio starts to decrease), again

[2]The model slightly overstates the positive impact of a retirement age change due to the assumption of an arbitrary maximum age. In reality, average life expectancy is projected to increase more than in the model

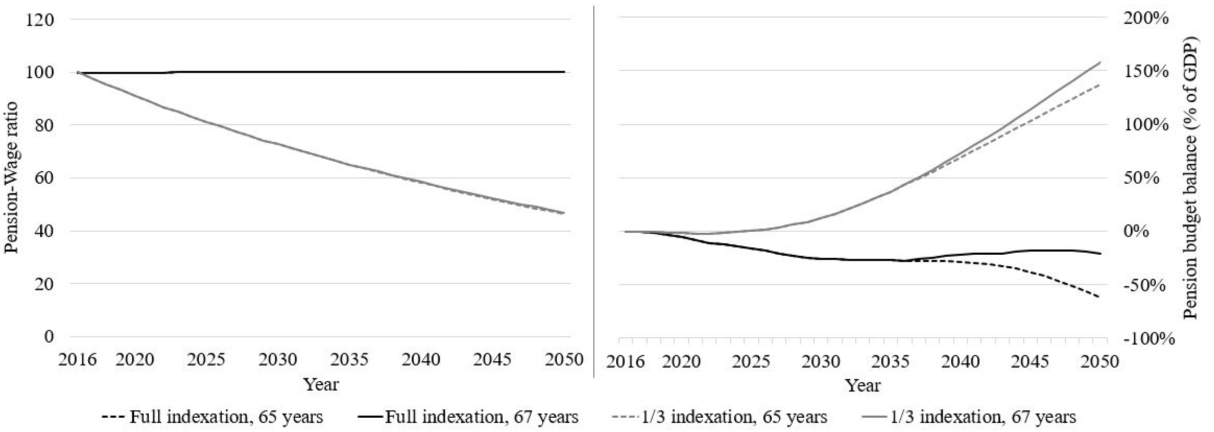
Table 2.4: Simulation results of a parametric change to the existing pension system, differing by assumed retirement age increase. Assumptions: baseline productivity growth.

Ret. Age	Adj.	2016 P	2016 P/W	2016 Y	2016 B	2016 CB	2030 P	2030 P/W	2030 Y	2030 B	2030 CB	2050 P	2050 P/W	2050 Y	2050 B	2050 CB
No change	Full	100%	100%	100%	-0.5%	-0.5%	160%	100%	154%	-3.4%	-40%	308%	100%	277%	-9.1%	-162%
Up to 65		100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	306%	100%	288%	-5.1%	-62%
Up to 67		100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	303%	100%	300%	-1.3%	-21%
No change	1/3	100%	100%	100%	-0.5%	-0.5%	118%	72%	157%	1.7%	1%	148%	46%	291%	3.9%	79%
Up to 65		100%	100%	100%	-0.5%	-0.5%	117%	73%	162%	3.8%	12%	147%	46%	300%	5.6%	137%
Up to 67		100%	100%	100%	-0.5%	-0.5%	117%	73%	162%	3.8%	12%	147%	47%	310%	7.3%	157%
No change	None	100%	100%	100%	-0.5%	-0.5%	100%	61%	159%	3.9%	20%	100%	30%	296%	7.5%	166%
Up to 65		100%	100%	100%	-0.5%	-0.5%	100%	62%	163%	5.5%	29%	100%	31%	305%	8.6%	209%
Up to 67		100%	100%	100%	-0.5%	-0.5%	100%	62%	163%	5.5%	29%	100%	32%	314%	9.7%	223%

Notes: R. age = Retirement age, Adj. = Pension adjustment, Y = aggregate output, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 4% and 5%.

resulting in high budget deficits and/or low replacement rates. Equally, old-age dependency ratio is projected to continue decreasing well beyond 2050 – retirement age would therefore need to increase beyond 67 years in the future. One must also consider practical applicability of such changes; increasing retirement age to 67 years may simply not be feasible in reality without appropriate changes to work arrangements for older people. The detailed changes in the pension-wage ratios and pension budget balance over time are depicted in Figure 2.4, showing the growing disparity in pension budget balance between the two alternative retirement age scenarios from 2035 onwards.

Figure 2.4: PAY-GO scheme: Explicit (a) - pension-wage ratios (left); Explicit (b) - pension budget deficit (right).



Assumptions: baseline productivity growth, varying retirement age and pension indexation.

The alternative ways of keeping finances under control are depicted in Table 2.5, which shows outcomes across three dimensions: retirement age, pension benefit adjustment (only partial and full) and balancing mechanism (taxes or pensions). Taxes are represented by the total social security taxation paid by employees and employers. By definition, pension adjustment is

due to survival probabilities at ages beyond the maximum age in the model increasing over time, resulting in comparatively greater decrease in the old-age dependency ratio than in the model.

available only in scenarios with taxes serving as a balancing mechanism. All scenarios assume baseline productivity growth rate.

Table 2.5: Simulation results of alternative pension budget balancing mechanisms. Assumptions: baseline productivity growth.

			2016					2030					2050				
R. Age	**Adj.**	**BM**	**P**	**P/W**	**Tax**	**B**	**CB**	**P**	**P/W**	**Tax**	**B**	**CB**	**P**	**P/W**	**Tax**	**B**	**CB**
No change	Full	TA	100%	100%	28%	-0.5%	-0.5%	156%	100%	34%	0.0%	-0.6%	289%	100%	45%	0.0%	-0.7%
Up to 65			100%	100%	28%	-0.5%	-0.5%	158%	100%	29%	0.0%	-0.6%	296%	100%	38%	0.0%	-0.7%
Up to 67			100%	100%	28%	-0.5%	-0.5%	158%	100%	29%	0.0%	-0.6%	301%	100%	30%	0.0%	-0.7%
No change	1/3	TA	100%	100%	28%	-0.5%	-0.5%	118%	72%	25%	0.0%	-0.6%	149%	45%	20%	0.0%	-0.7%
Up to 65			100%	100%	28%	-0.5%	-0.5%	118%	72%	21%	0.0%	-0.6%	149%	45%	17%	0.0%	-0.7%
Up to 67			100%	100%	28%	-0.5%	-0.5%	118%	72%	21%	0.0%	-0.6%	149%	45%	14%	0.0%	-0.7%
No change	-	PA	100%	100%	28%	-0.5%	-0.5%	132%	82%	28%	0.0%	-0.6%	197%	62%	28%	0.0%	-0.7%
Up to 65			100%	100%	28%	-0.5%	-0.5%	155%	98%	28%	0.0%	-0.6%	231%	74%	28%	0.0%	-0.7%
Up to 67			100%	100%	28%	-0.5%	-0.5%	155%	98%	28%	0.0%	-0.6%	280%	92%	28%	0.0%	-0.7%

Notes: R. age = Retirement age, Adj. = Pension adjustment, BM = Balancing mechanism, TA = taxes adjust, PA = pensions adjust, Tax = social security tax rate, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 4% and 5%.

We can see that the tax changes required to maintain a balanced budget vary substantially across the scenarios (see rows 1-6, column Tax in Table 2.5), in a similar way to changes in budget deficit in the previous analysis. In particular, the estimates suggest that taxes could be lowered by 50% by 2050 if pensions were indexed only at one third of growth in real wages and retirement age increased to 67 years (row 6). On the contrary, they would need to be increased by more than 17 pp in the scenario with full pension indexation and no changes in retirement age (row 1). Notice, that the output levels are slightly lower in the full indexation scenarios (rows 1-3) compared to results in Table 2.4. This is due to the assumption that increasing indebtedness has no immediate negative impact on the economy, whereas excessive taxation lowers consumption, savings and equilibrium wage. The difference may be further understated due to the assumption of full employment; in reality, higher taxes may also lead to higher unemployment rates and generally worse macroeconomic performance.

Finally, pensions would decrease by just 8% by 2050 if they served as balancing mechanism and retirement age increased without limits (row 9), and by 26% and 38% in scenarios with limited and no changes in retirement age (rows 7-8), respectively, keeping the current social security tax rates unchanged. Note, that this is a simplified scenario in which all pensions paid in a given period may be reduced proportionally in order to keep the pension budget balanced, as opposed to the automatic balancing mechanism (see Section 2.5.3), which would lower – or stop – pension indexation, but it would never lead to a decrease in real pensions.

2.5.3 Pension reform

The analysis up to this point shows that the only way of maintaining pension-wage replacement rates and pension budget deficits at their current levels in the the existing PAY-GO scheme is by increasing the retirement age without limits, keeping the old-age dependency ratio nearly constant over time. This section investigates whether a structural reform – a switch to an alternative pension scheme – would be more beneficial in the long term and what would be the implications in the short term.

In a first set of scenarios, consider a structural change taking place in period $t = 2$ with no market imperfections, baseline productivity growth, and 3.5% annual return on retirement assets. Table 2.6 compares the two alternative pension schemes to the baseline PAY-GO scheme (full indexation, unbalanced budget) as above (rows 1-3 in Table 2.6 are equivalent to rows 1-3 in Table 2.4).

Table 2.6: Simulation results of a structural change to the existing pension system, differing in assumed change in retirement age. Assumptions: baseline productivity growth and return on retirement savings.

PS	R. Age	2016 P	2016 P/W	2016 Y	2016 B	2016 CB	2030 P	2030 P/W	2030 Y	2030 B	2030 CB	2050 P	2050 P/W	2050 Y	2050 B	2050 CB
PG	No change	100%	100%	100%	-0.5%	-0.5%	160%	100%	154%	-3.4%	-40%	308%	100%	277%	-9.1%	-162%
	Up to 65	100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	306%	100%	288%	-5.1%	-62%
	Up to 67	100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	303%	100%	300%	-1.3%	-21%
M	No change	100%	100%	100%	-0.5%	-0.5%	129%	78%	158%	0.0%	-17%	258%	81%	285%	-2.3%	-37%
	Up to 65	100%	100%	100%	-0.5%	-0.5%	140%	86%	162%	1.3%	-11%	299%	96%	292%	-1.8%	-21%
	Up to 67	100%	100%	100%	-0.5%	-0.5%	140%	86%	162%	1.3%	-11%	355%	116%	301%	-1.3%	-15%
FF	No change	100%	100%	100%	-0.5%	-0.5%	153%	100%	146%	-7.2%	-163%	432%	147%	255%	-1.2%	-277%
	Up to 65	100%	100%	100%	-0.5%	-0.5%	178%	116%	149%	-5.8%	-154%	504%	174%	263%	-1.0%	-251%
	Up to 67	100%	100%	100%	-0.5%	-0.5%	178%	116%	149%	-5.8%	-154%	615%	216%	272%	-0.8%	-246%

Notes: PS = pension scheme (PG = PAY-GO, M = multi-pillar, FF = fully funded), R. age = Retirement age, Y = aggregate output, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 4% and 6%.

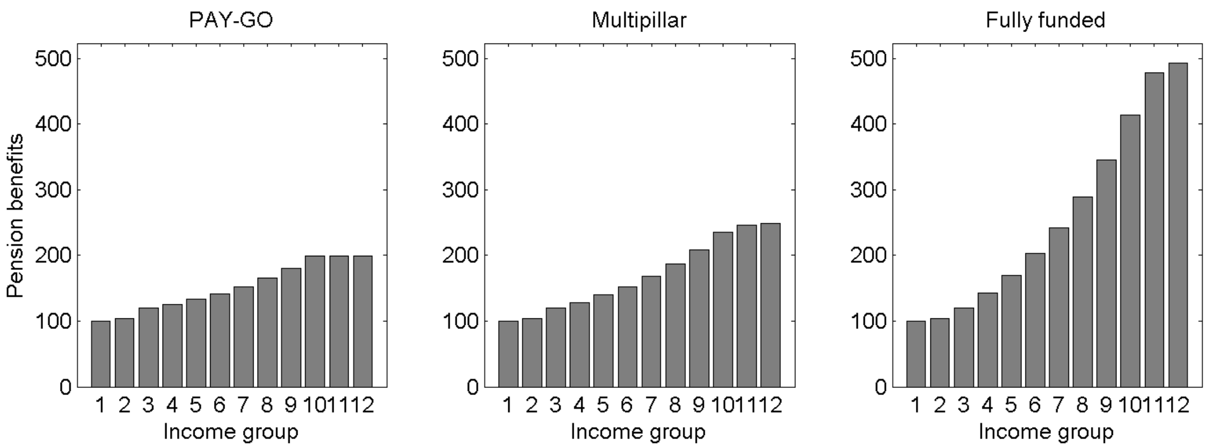
In the fully funded scheme, the model suggests substantially higher pensions without a significant effect on budget deficit in 2050 (rows 7-9). This is caused principally by high income classes, as replacement rates become essentially flat across income groups, unlike in the original pension scheme, where they exponentially decrease with income. This is also depicted in Figure 2.5.[3] Since public expenditure is reduced to payments to individuals caught by the pension safety net, budget deficits caused by adverse demographic changes are no longer a major issue in a fully funded scheme. At the same time, transition to a new pension scheme affects pension budget deficit twice – once due to necessity to finance PAY-GO pensions for all contributors to the old system and once due to inability to benefit from high intra-generational income redistribution as a consequence of low replacement rates of high-earning individuals, who would previously pay nearly the same proportion of their income in exchange for a very limited pension. As the cost of paying out the original PAY-GO pensions is highest in the early years after transition, pension budget deficit is in fact very high initially and decreases over time. Transition to a fully funded scheme thus leads to accumulated debt of more than 250% of GDP by 2050 (see Table 2.6, rows 7-9, column 2050 CB and also Figure 2.8).

The effects on economic growth may be understated since retirement savings $A_{s,z}^{ret}$ are assumed not to increase domestic capital, but, compared to the PAY-GO scheme, the results indicate that reduction in regular savings as a result of higher pensions would slightly decrease the aggregate economic output (rows 1-3 vs 7-9, column Y).

The gradual changes to structure of the average pensions and pensions received by the lowest income group during a transition to a fully funded scheme are depicted in Figure 2.6, in which pension transfers coming from different sources are differentiated by colour. On average, pension-

[3] Note, that since the safety net in the fully funded scheme is set so that the lowest income class cannot be worse off in terms of pensions as a result of the transition, virtually everyone in the economy is better off in the new system, although at the cost of increasing indebtedness.

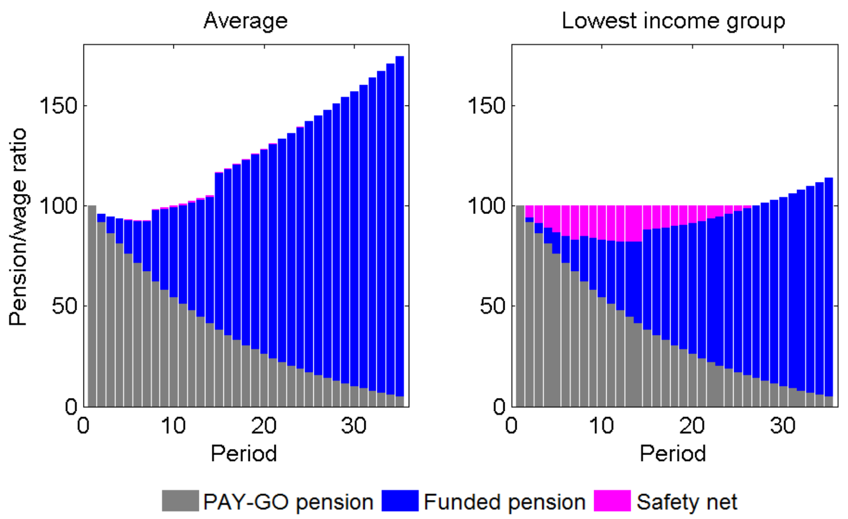
Figure 2.5: Intra-generational equality in pensions, 2050.



Notes: The values represent multiples of the lowest income class value, standardised to 100. Values are standardised within each pension scheme.

wage ratio is projected to decrease in the first years as a result of decreasing PAY-GO pensions and new savings not being able to accumulate sufficient accrued interest, but the funded pensions start to grow more rapidly than the PAY-GO pensions decrease in just about ten years after transition, leading to a net increase in pensions. Since replacement rates in a fully funded scheme are constant across generations, retirement age does not need to be adjusted constantly to reflect changes in the population structure as in the PAY-GO scheme. Unlike richer households, the lowest income groups would require additional support from the government through safety net payments as their savings would be too low at first. However, even they are projected to be eventually better off than in the existing scheme.

Figure 2.6: Composition of total pension benefits, transition towards a fully funded scheme.

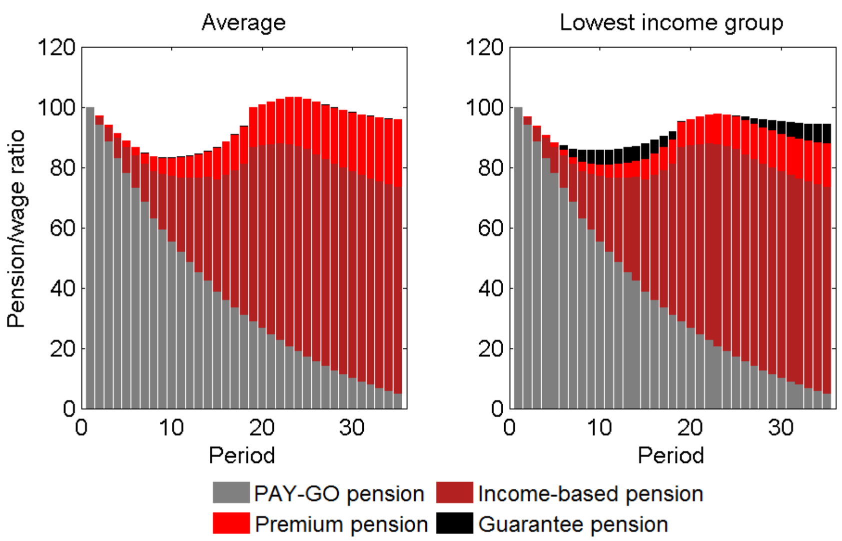


Notes: Pensions standardised within each figure. Assumptions: baseline productivity growth, limited retirement age increase, 3.5% return on savings.

Going back to Table 2.6, results of the multi-pillar scheme are essentially a convex combination of the other two schemes, proportional to the share of contributions going to the unfunded (86%) and funded (14%) pillars. In particular, the multi-pillar scheme is largely dependent on demographics, yet the automatic balancing mechanism prevents excessive budget deficits. As a result, the pension-wage ratios and budget deficits are generally lower than in the PAY-GO scheme (rows 4-6 vs 1-3, columns B and P/W). The lower pensions also lead to higher savings in standard taxable assets and therefore increased output. At the same time, contributions to the funded pillar accumulate gradually over time and lead to higher pensions than what would be achievable with the same pension budget balance in the PAY-GO scheme, while at a substantially lower cost of transition than the fully funded scheme. Indeed, the pension system accumulates virtually no debt despite the transition while providing higher pensions than the PAY-GO scheme by 2050.

The detailed dynamics of pension transfers are depicted in Figure 2.7. Similarly to a fully funded scheme, the average pension benefits are projected to drop at first – in fact more than in the fully funded scheme – due to the guarantee pension set lower than the safety net in the fully funded scheme, pensions of high income classes not able to outweigh the lack of accrued interest, and the balancing mechanism reducing indexation to reflect lower tax revenues and prevent budget deficits. Nevertheless, the pension-wage ratio stabilises within just 8 years, reaches its original level after 20 years and remains fairly constant thereafter using the automatic balancing mechanism. Notice, that since less than a fifth of all contributions goes towards the funded second pillar, the relative pension levels eventually decrease again, following changes in the old-age dependency ratio, yet the share of pensions being financed through the funded pillar increases over time, reducing the system's overall costs to the public.

Figure 2.7: Composition of total pension benefits, transition towards a multi-pillar scheme.



Notes: Pensions standardised within each figure. Assumptions: baseline productivity growth, limited retirement age increase, 3.5% return on savings.

Pensions of the lowest income group are again topped up; the amount received through the guarantee pension depends only on the income-based pension, as opposed to the safety net in the fully funded system, so the top-up will actually bring pensioners to nearly 100% of the original pension-wage ratio in later stages of the transition. The resulting average replacement rates

(Table 2.6, rows 4-6, column P/W) are thus not a product of high pensions of rich households like in the fully funded system – instead, they reflect a small decrease for the poor and a small increase for the rich. This may further be adjusted through ratio of contributions going towards the funded and unfunded pillars.

Finally, Table 2.7 shows results of structural changes with various rate of return on retirement assets (rows 1, 3 and 6 are equivalent to rows 2, 5 and 8 in Table 2.6). There are two facts to highlight. First, notice the high variation in the fully funded pensions (rows 5-7, column P/W) due to accrued interest, depicting strong reliance on performance of financial markets. Second, changes to rate of return on retirement assets have virtually no impact on the pension budget (rows 2-7, columns B and CB) because only a small share of the population is projected to receive additional payments from the government. Indeed, even a low rate of return on savings leads to higher resulting pensions than in the current system and the remaining budget deficit is a consequence of changes in the population structure (multi-pillar scheme) and remaining PAY-GO pensions to be paid (both schemes). On the other hand, the 6% return on savings, which may still be rather low considering the past performance of most state or private owned pension systems in the world (see OECD 2016), provides pensioners with income otherwise unachievable in the PAY-GO scheme.

Note, that the three scenarios reflect both the potential changes in the overall market returns but also differences in savings decisions. That is, while there may be some predefined investment guidelines set by the government as in Chile, where older workers are required to transfer their savings to funds investing principally in fixed-income assets, individuals may otherwise be able to choose from a wide variety of funds differing in their risk-return profiles and the resulting pensions are thus likely to vary to a far greater extent than in the existing PAY-GO scheme, highlighting the need of a proper regulation and education.

Table 2.7: Simulation results of a structural change to the existing pension system, differing in assumed return on retirement savings. Assumptions: baseline productivity growth, limited retirement age increase.

PS	IR	2016					2030					2050				
		P	P/W	Y	B	CB	P	P/W	Y	B	CB	P	P/W	Y	B	CB
PG	-	100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	306%	100%	288%	-5.1%	-62%
M	1.0%	100%	100%	100%	-0.5%	-0.5%	135%	83%	162%	1.3%	-11%	270%	86%	294%	-1.8%	-20%
	3.5%	100%	100%	100%	-0.5%	-0.5%	140%	86%	162%	1.3%	-11%	299%	96%	292%	-1.8%	-21%
	6.0%	100%	100%	100%	-0.5%	-0.5%	147%	90%	162%	1.3%	-11%	355%	114%	289%	-1.9%	-21%
FF	1.0%	100%	100%	100%	-0.5%	-0.5%	146%	95%	151%	-5.8%	-154%	307%	103%	273%	-1.0%	-248%
	3.5%	100%	100%	100%	-0.5%	-0.5%	178%	116%	149%	-5.8%	-154%	504%	174%	263%	-1.0%	-251%
	6.0%	100%	100%	100%	-0.5%	-0.5%	223%	147%	147%	-5.9%	-155%	886%	319%	252%	-1.0%	-253%

Notes: PS = pension scheme (PG = PAY-GO, M = multi-pillar, FF = fully funded), IR = Return on savings into pension funds, Y = aggregate output, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 4% and 6%.

2.5.4 Impact of market imperfections

The analysis thus far shows that while the existing Czech PAY-GO scheme leads to redistribution of wealth and therefore helps low income households to have decent pensions despite low contributions, it fares relatively poorly when faced with adverse demographic changes and requires constant increase in statutory retirement age as a result. The funded and multi-pillar schemes are more promising in this regard, offering higher pensions without extensive public indebtedness (disregarding the cost of transition). In reality, however, funded pension schemes also introduce new elements to the analysis – uncertainty and market imperfections (Krueger and Kubler, 2006; Merton, 1983; Sluchynsky, 2015) – that may greatly affect their resulting performance. Two scenarios depicting this are shown in Table 2.8 and Figure 2.8. In the first scenario, there is an annual fee on savings made into pension funds and pension annuities are not actuarially fair, giving, on average, pensioners back less than the optimal amount each year. In the second scenario, in addition to market imperfections, a stock market crash occurs at time $t = 10$, leading to a one-off reduction in value of retirement assets. The baseline results for comparison (rows 1, 2 and 5) are equivalent to rows 2, 5 and 8 in Table 2.6 and assume 3.5% interest rate on retirement assets, full pension indexation in the PAY-GO scheme and retirement age increasing to 65 years.

Table 2.8: Simulation results of a structural change to the existing pension system, differing in market imperfection scenarios. Assumptions: baseline productivity growth and return on retirement savings, limited retirement age increase.

PS	Scenario			2016					2030					2050		
		P	P/W	Y	B	CB	P	P/W	Y	B	CB	P	P/W	Y	B	CB
PG	-	100%	100%	100%	-0.5%	-0.5%	159%	100%	159%	-0.4%	-26%	306%	100%	288%	-5.1%	-62%
M	-	100%	100%	100%	-0.5%	-0.5%	140%	86%	162%	1.3%	-11%	299%	96%	292%	-1.8%	-21%
	AC	100%	100%	100%	-0.5%	-0.5%	137%	84%	162%	1.3%	-11%	278%	89%	294%	-1.8%	-21%
	AC+C	100%	100%	100%	-0.5%	-0.5%	130%	80%	163%	1.3%	-11%	269%	86%	295%	-1.8%	-21%
FF	-	100%	100%	100%	-0.5%	-0.5%	178%	116%	149%	-5.8%	-154%	504%	174%	263%	-1.0%	-251%
	AC	100%	100%	100%	-0.5%	-0.5%	155%	101%	150%	-5.8%	-154%	361%	122%	270%	-1.0%	-249%
	AC+C	100%	100%	100%	-0.5%	-0.5%	113%	74%	153%	-5.7%	-153%	301%	101%	273%	-1.0%	-247%

Notes: PS = pension scheme (PG = PAY-GO, M = multi-pillar, FF = fully funded), AC = Administrative costs, AC+C = Administrative costs and stock market crash, PY = aggregate output, P = average pension, P/W = ratio of average pensions to equilibrium wage, B and CB = pension (cumulative) budget balance. Pension and output values standardised using 2016 values and all results are directly comparable to other tables in this section. Refer to Section 2.4.4 for details on choice of sensitivity parameters. Equilibrium interest rate varies between 4% and 6%.

The alternative scenarios have no impact on the pension budget as pensions are generally high enough for most people to not require further support from the government. Pensions, on the other hand, differ substantially in the alternative scenarios. This is particularly true for the fully funded system, where pensions decrease by nearly 30% on average in 2050 compared to the optimal baseline scenario (rows 4-5, column P/W) just due to administrative costs and imperfect annuity markets. The effect of stock market crash is partially hidden in the table as it happens prior to 2030, yet we can clearly see the further difference in the resulting pensions (rows 4 and 7).[4]

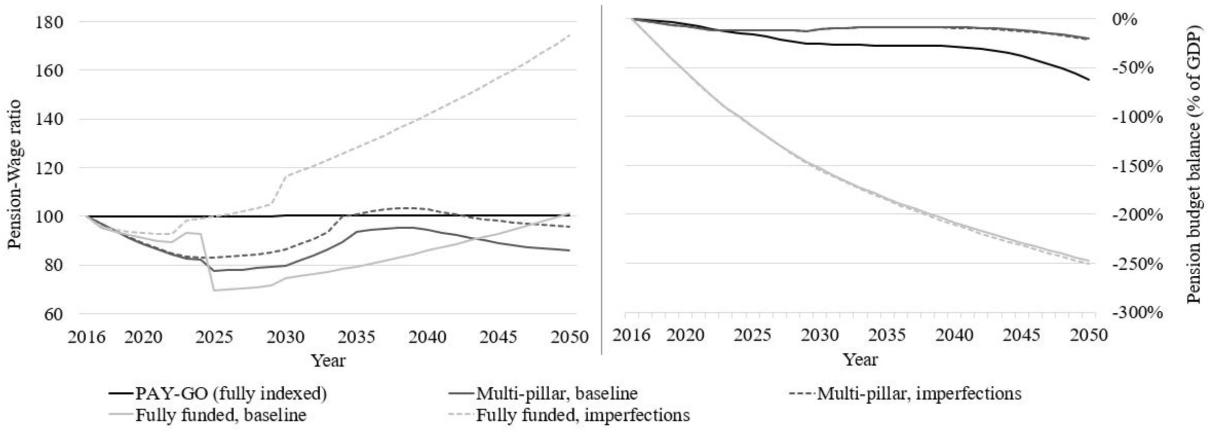
The projected long-term benefits of a transition to a fully funded scheme, offering higher pensions at lower cost to the public, are thus not guaranteed and come only at the cost of an enormous pressure on the public finances during the transition period. There are ways to reduce this cost or distribute it over time; for instance, Chile offered workers a choice between the old PAY-GO pension and the new pension scheme, in which previous contributions would be reflected in the future annuities, in effect maintaining at least some inflow of funds in the system.

[4]The actual effect of a stock market crash is underestimated in the model as the retirement savings $A^{ret}_{s,z}$ are considered effectively separated from the economy and there is no contagion effect spreading potential crisis across borders assumed in the model.

In the Czech Republic, the cost could also be partially offset by reduction in social security taxation to levels in other countries. Notwithstanding that, the costs would still be extremely high and the pension system challenges would all but shift from adverse demographics to poorly performing financial markets.

The multi-pillar scheme, if properly set up, diversifies the two risks at a considerably lower cost of transition. In particular, Figure 2.8 shows that the impact of a stock market crash is negligible even in the short-term and that the long-term financial sustainability is still improved compared to the PAY-GO scheme as a result of introduction of a funded pillar. In addition, the automatic balancing mechanism ensures that the budget would return to balance as soon as possible, as opposed to the existing scheme.

Figure 2.8: Structural changes: Explicit (a) - pension-wage ratios (left); Explicit (b) - pension budget deficit (right).



Assumptions: baseline productivity growth, retirement age increase up to 65 years, 3.5% return on savings.

2.6 Conclusions

Large post-war generations reaching retirement age and persistent trends of decreasing fertility and mortality are putting pension systems in many countries under an unprecedented pressure and are expected to do so in the next years and decades. The Czech Republic, with its ageing population and an unfunded pension system with vast majority of pensions financed from taxes collected within the same period – and thus heavily reliant on the old-age dependency ratio – is a prime example of the growing challenges. Indeed, it is clear that substantial changes to the existing scheme need to be made in order to avoid an excessive debt burden put on the next generations and that each year passed without a change will make such adjustments more difficult.

As noted by Alonso-García et al. (2018), the challenges to PAY-GO pension systems are threefold: they need to provide an adequate income for pensioners in retirement; pensions need to be in a reasonable proportion to contributions paid; and the pension system needs to be financially sustainable in the long run. While these are conflicting goals, it may be possible to improve in all directions at once by increasing efficiency or changing structure of the system, rather than just its parametrisation.

This study analyses both parametric and structural changes to the Czech pension system with the aim of estimating their long-term impact on pensioners and the system as a whole. The analysis is done through computer simulations of a bespoke OLG model of the Czech pension system, as well as two alternative schemes based on the real-world pension systems in Sweden and Chile. Using the latest projections of population ageing and various assumptions regarding economic growth, returns on retirement assets and pension system parametrisation – minimum retirement age, indexation of pensions, tax vs debt financing – the model indicates how each counterfactual scenario scores in the three conflicting measures above.

The results suggest that, conditional on a continuous economic growth, a decrease in the old-age dependency ratio due to population ageing may not necessarily lead to lower real pensions while keeping pension budget balanced in the existing PAY-GO scheme. At the same time, this is only at the cost of a growing disparity between pre-retirement earnings and pension benefits. Specifically, the real-world average replacement rates are estimated to decrease from 50.6% to just 23.3% in 2050 in a scenario with baseline productivity growth if pensions are indexed at the current level, i.e. inflation plus one third of changes in real wages. To avoid that, indexation must follow nominal wages completely; this would almost certainly lead to explosive pension budget deficits in absence of an increase in social security taxation or retirement age.

Importantly, the numerical simulations show that a gradual increase in the statutory retirement age up to 67 by 2042 may indeed almost entirely offset the adverse demographic changes until then, maintaining financially sustainable pension system and constant replacement rates. Nevertheless, retirement age would need to continue increasing even beyond that in the future, raising a question of practicality of such a scenario, especially for individuals employed in physically demanding professions. On the other hand, countries such as Finland, Cyprus, Denmark, Estonia, Greece, Italy, the Netherlands, Portugal and Slovakia have linked statutory retirement age to life expectancy and are going to increase it as a result (Finish Centre for Pensions, 2019). For the Czech Republic, life expectancy is assumed to increase from the current 79.2 years to 82.8 years by 2040 and keep increasing beyond that, to 85.8 years by 2070 and more (United Nations, 2019). Hence, the statutory retirement age could increase further than to 67 years by 2042 as assumed in the model, perhaps to 69 years by 2070 to broadly match the further changes in life expectancy, keeping the statutory retirement age at approx. 0.8 of population life expectancy.

Funded pension schemes may seem as an attractive alternative, offering greater protection against adverse demographic changes and providing a direct link between contributions paid and benefits received, providing improved results in all three dimensions cited by Alonso-García et al. (2018). However, the account balances transformed into lifetime annuities are inherently dependent on performance of financial markets and imperfections of annuity markets, potentially resulting in even lower pensions than in the existing PAY-GO scheme with no pension indexation. What is more, achieving desirable savings is possible only if interest rate on savings is at or above the growth rate of real wages. Transition towards a fully funded scheme would also be extremely costly, accumulating a debt of over 250% GDP by 2050, and lead to substantially different distribution of wealth in retirement compared to the highly redistributive existing PAY-GO scheme, which would likely face a fierce opposition in reality.

The multi-pillar scheme, modelled according to the existing Swedish pension system with indexing determined using an automatic balancing mechanism and a guarantee pension paid to the lowest income groups, emerges as perhaps an optimal compromise. It is vulnerable to both adverse demographic changes and financial market downturn, yet to a lesser extent than each of the individual schemes – plus this conflicting dependency may be adjusted by changing the PAY-GO and funded financing. In addition, a transition towards a multi-pillar scheme would be far less costly than to a fully funded one. In fact, the accumulated debt by 2050, including the cost of transition, is estimated to be lower in the multi-pillar scheme than in the existing PAY-GO scheme, although at the cost of lower pensions.

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Appendix

The following text expands on the model description from Section 2.4 and some of its limitations. Throughout the Appendix, $A_{s,z,t}$ represents taxable capital stock consisting of non-retirement assets of an agent of age s in income class z in period t, referred to as $A^{tax}_{s,z,t}$ in Section 2.4. In each period, new agents are born without wealth, $A_{1,z,t} = 0$, but may start accumulating capital through savings. Analogously, in the last period, agents sell all of their remaining capital stock for consumption and bequests left for their children.

Model equilibrium

The economy is assumed to be in an equilibrium in each period. The concept of equilibrium uses a recursive representation of the consumer's problem following Heer and Maussner (2009) and is characterised by the following properties:

1. Individual and aggregate behaviour are consistent:

$$K_t = \sum_{s=1}^{T+T^R} \sum_{z \in Z} A_{s,z,t} \tag{2.20}$$

$$N_t = \sum_{s=1}^{T} \sum_{z \in Z} e(s,z)\, l\, \mu_{s,z,t} \tag{2.21}$$

$$C_t = \sum_{s=1}^{T+T^R} \sum_{z \in Z} c(s,z,t) \tag{2.22}$$

2. Agents' dynamic programs and firms' optimisation problems are solved by satisfying Equations (2.5)–(2.11) using the relative prices w_t, r_t, pensions, and the individual policy rules $c_s(.)$ and $A_{s+1}(.)$.

3. The goods market clears:

$$\Omega^{t-1} K_t^{\alpha} N_t^{1-\alpha} = C_t + K_{t+1} - (1-\delta) K_t \tag{2.23}$$

The market equilibrium does not require pension budget to be balanced and therefore pensions to be set at an equilibrium level. On the contrary, various scenarios used in this study explicitly assume unbalanced government budget with exogenously given pension indexation. Equally, the interest rate on retirement assets is set exogenously in some scenarios, rather than equal to the equilibrium interest rate. This does not invalidate the market equilibrium as Equations 2.20-2.23 still hold and the exogenously given parameters are part of agents', firm's and government's decision-making processes, affecting consumption or social security tax rates. This is in line with previous studies (see e.g. Annabi et al. 2011; Beetsma et al. 2003; Miles and Černý 2006; Rausch et al. 2011).

Inheritance process

As described in Section 2.4, all agents are assumed to have children at age $T^P = 30$, leave bequests at the time of death, and face positive probability of death throughout their lives with a certain death at age $T + T^R$. The computer script does not simulate individual agents but rather the entire cohorts consisting proportionally of the $z = \{1..12\}$ income groups; each cohort aged $\{1..(T + T^R - T^P)\}$ thus receives some bequests each year. For simplicity, the model assumes that bequests received are proportional to own income, i.e. that poor/rich parents have poor/rich children. Assets of agents who die prior to age T^P are taken by the government. The average bequest per agent from income group z received when aged s in period t is thus equal to the total bequests left by agents from the same income group z who died aged $s + 30$ in the same period t, divided by the cohort size $\mu_{s,z,t}$:

$$b_{s,z,t} = (1 - \pi_{s+30,t}) A_{s+30,z,t} \frac{\mu_{s+30,z,t}}{\mu_{s,z,t}} \tag{2.24}$$

where $\pi_{T+T^R,t} = 0$.

Solution method

The simulation algorithm used in this study is based on Heer and Maussner (2009) and Nishiyama and Smetters (2007) and utilises value function iteration to compute agents' policy functions for respective periods and shocks. Specifically, the agent's decision functions are calculated using backward induction, i.e. by analysing the optimal behaviour in the last period of agent's live and, conditional on that, in all preceding periods.

Let $V_s(A_{s,z}, z_s)$ be the value of the objective function of an s-year old agent from income group z with wealth $A_{s,z}$ and idiosyncratic productivity level z_s. $V_s(A_{s,z}, z_s)$ is defined as the solution to the dynamic program:

$$V_s(A_{s,z}, z_s) = \max_{A_{s+1}, c_t} \{U(s,z) + \pi_s \, \mathbb{E}[V_{s+1}(A_{s+1}, z_{s+1})(1+\rho)^{-1} \mid A_{s,z}, z_s]\} \tag{2.25}$$

That is, subject to the budget constraints, optimal decision rules for consumption and next-period capital stock are functions of wealth and the idiosyncratic productivity shock, and associated with every optimal next period capital stock $A_{s+1}(A_{s,z}, z_s)$ is an optimal consumption policy $c(s,z)$. Note, that the agents implicitly take into consideration any potential inheritance received or given as per Equations 2.7-2.8.

Consequently, in each period, all agents can calculate the optimal consumption and saving behaviour in that period given their age, income group, probability of death and moving to another income group in the next period, and the existing market prices w_t and r_t, tax rates, pensions, and interest rate on retirement assets – all of which they are aware of. However, while agents can predict their own behaviour in the future (e.g. when they retire and how much they would consume given the projected income), the model assumes that they are unable to make proper predictions regarding the economy as a whole and assume, given the lack of a better estimate, that the market prices and other parameters would remain at their existing levels (note, that there is no inflation in the model). This includes inability to properly calculate impacts of long-term demographic changes assumed throughout this study or the resulting government's reaction. As a result, the number of possible scenarios to calculate decreases exponentially compared to a model with perfect foresight, making the computational time more manageable.

The main simulation process can thus be characterised as follows:

1. Parametrise the model and compute aggregate employment N_t.

2. Make an initial guess on the equilibrium values of K_t and compute values of w_t, r_t, pensions and other endogenously determined parameters.

3. Compute the household's decision functions by backward induction.

4. Compute the optimal consumption and saving behaviour for each cohort alive in period t.

5. Calculate the aggregate capital stock K_t.

6. Update K_t and repeat the process until convergence.

7. Once a market equilibrium is found, proceed to the next period and repeat the entire process, using K_{t-1} as a best guess for K_t.

Figure 2.9: Distribution of households by income group in the model, by age ($s = 1$ to $s = T$).

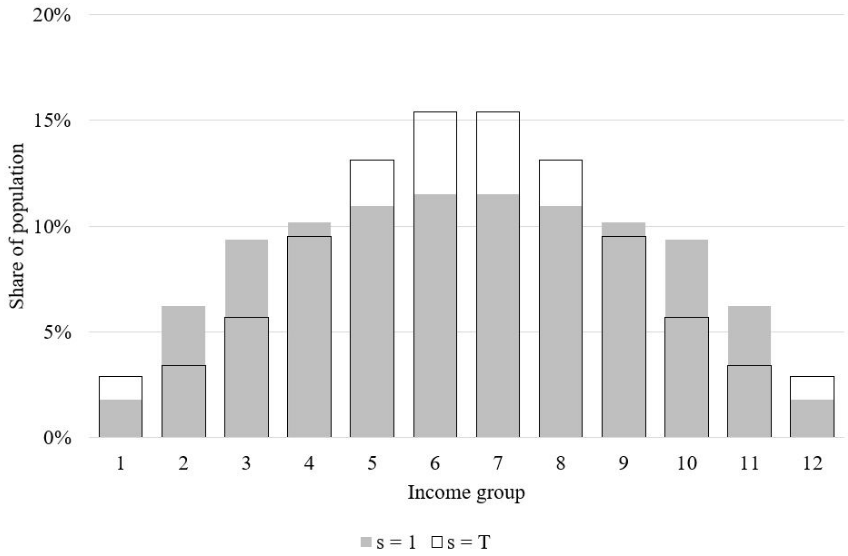


Table 2.9: Transition matrix for modelling idiosyncratic productivity shocks.

Income Group (t)	Income Group ($t+1$): 1	2	3	4	5	6	7	8	9	10	11	12
1	67%	18%	14%	1%	0%	0%	0%	0%	0%	0%	0%	0%
2	20%	59%	19%	2%	0%	0%	0%	0%	0%	0%	0%	0%
3	5%	14%	52%	27%	2%	0%	0%	0%	0%	0%	0%	0%
4	0%	1%	16%	57%	25%	1%	0%	0%	0%	0%	0%	0%
5	0%	0%	1%	18%	57%	23%	1%	0%	0%	0%	0%	0%
6	0%	0%	0%	1%	20%	57%	21%	1%	0%	0%	0%	0%
7	0%	0%	0%	0%	1%	21%	57%	20%	1%	0%	0%	0%
8	0%	0%	0%	0%	0%	1%	23%	57%	18%	1%	0%	0%
9	0%	0%	0%	0%	0%	0%	1%	25%	57%	16%	1%	0%
10	0%	0%	0%	0%	0%	0%	0%	2%	27%	52%	14%	5%
11	0%	0%	0%	0%	0%	0%	0%	0%	2%	19%	59%	20%
12	0%	0%	0%	0%	0%	0%	0%	0%	1%	14%	18%	67%

Transition matrix calculated as a result of the Markov process described in Equation 2.3.

Chapter 3

Sectoral impacts of international labour migration and population ageing in the Czech Republic

Abstract

This study assesses macroeconomic and sectoral impacts of demographic changes in the Czech Republic as a result of population ageing and international migration. To do so, it develops a unique dynamic Overlapping Generations Computable General Equilibrium (OLG-CGE) model with detailed representation of individuals of different ages, educational attainment and occupations, as well as interrelations among industrial sectors in producing intermediate and final outputs. The numerical simulations show that the Czech economy will face a substantial reduction in its effective labour supply and changes in aggregate as well as sectoral demand patterns, leading to lower economic growth (4.4% lower GDP by 2050 in absence of technological progress), increase in unit labour costs (5.2% higher wages in absence of inflation) and lower competitiveness of the economy as a whole. Replacement migration may alleviate the pressure, yet the current gross immigration would need to increase by at least 8-17 thousand individuals per year compared to the UN projections (a 15%-34% increase) without changing emigration patterns in order to offset the adverse long-term effects.

3.1 Introduction

The population in the Czech Republic, similarly to many other countries in Europe, has been going through unprecedented changes in the recent years, characterised principally by ageing, a result of long-term below-replacement fertility rates and decreasing mortality, and international migration, especially following the 2004 enlargement of the European Union. The median age in the Czech Republic increased from 35.3 in 1990 to 41.4 in 2015 (United Nations, 2017), while the average life expectancy increased from 71.4 in 1990 to 78.6 in 2015, resulting in a shift in the old-age dependency ratio — the number of retired to working-age individuals – from 19.3% to 26.9% in that time period (World Bank, 2018). In addition, the number of foreign nationals with various forms of residence statuses increased from just over 80,000 in 1993 to 425,000 in

2008 and 515,000 in 2018, while the number of Czech nationals living in another EU country reached approx. 125,000 in 2018 (European Commission, 2019; MICZ, 2019).

The exact effects of demographic changes and international migration on the economy and society in both the receiving country and the country of origin are difficult to estimate, not only because a large proportion of the relevant data, such as the share of spending in the receiving country, are often not collected, and may range from changes in wages (Nagarajan et al., 2016; Ratha et al., 2011) and tax revenues (Martinsen and Pons Rotger, 2017; Vargas-Silva, 2015) to human capital accumulation (Beine et al., 2008; Dinkelman and Mariotti, 2016) and innovation (Bosetti et al., 2015; Capello and Lenzi, 2019). In the context of the Czech Republic, population ageing has affected particularly the pension system, which will require a substantial reform in order to maintain a consistent pension-wage ratios in the future, and the labour force, which has been shrinking both in absolute and relative terms within the population as a whole. Net immigration, on the other hand, may help to counterbalance these effects by bringing additional working-age population in the economy.

Which effects will dominate and what will be the impact on the economy and the society as a whole? Saczuk (2013) argues that the need of replacement migration – use of international migration to offset population ageing (see e.g. Craveiro et al., 2019 and Gerber and Cheung, 2008) – is questionable at best and may be a purely academic exercise given the political situation in Europe. Still, understanding the potential implications of demographic changes conditional of various migration scenarios is essential for academics, businesses and policy-makers alike. Yet such an impact assessment is difficult due to data limitations and requires new methods of forward-looking analysis able to combine the various exogenous changes while enabling detailed insights into the potential outcomes.

This study develops a dynamic Overlapping Generations Computable General Equilibrium (OLG-CGE) model used to evaluate the micro- and macroeconomic impacts of population ageing and international migration in the context of the Czech Republic. This is done through computer simulations of scenarios assuming the baseline projected population ageing patterns as well as a return of a large number of Czechs working abroad and a sudden outflow of foreign workers. The model is calibrated in a high level of detail using the latest population and productivity estimates for 350 population groups differing in their education, occupation and sectoral affiliation, providing an accurate representation of the Czech economy and its internal economic mechanisms.

The analysis clearly outlines the extent of the underlying population changes, characterised by a projected 5.4% decrease in the overall population size and over 6% decrease in the effective labour supply in the next 30 years (keeping the default retirement age unchanged), and 4-year increase in the average age. This results in higher unit labour costs and a shift towards production relying more heavily on capital across all industries and industrial sectors being affected by various levels of initial increase and subsequent decrease in demand for their products and services. As a consequence, the Czech economy would see lower economic growth and competitiveness at the international markets.

The next section provides a brief overview of the relevant literature and sources for this study, followed by a description of the simulation model, its calibration, the three modelled scenarios with varying levels of migration, and an overview of the simulation results across a range of variables with a concluding summary.

3.2 Existing research

The impacts of population ageing have been thoroughly discussed in the academic literature from multiple angles, particularly regarding the negative supply side effects (e.g. Bloom et al., 2010; Culling and Skilling, 2018; Fougére and Mérette, 1999), pension system (e.g. Foster, 2018; Hess et al., 2017; Miles and Černý, 2006) and healthcare (e.g. Ashby and Beech, 2016; Geue et al., 2014; Lim et al., 2017), The general conclusion is that the projected demographic changes will result in higher costs to the public as higher proportion of the population will be in retirement and thus not contributing to the public finances. The literature also suggests that there is often an insufficient reaction from the policy makers in introducing reforms that may shift the burden more equally across the current and future generations.

Similarly, the effects of international migration on labour supply (e.g. Barrell et al., 2010; Czaika, 2018; Issac, 2013) or public finances (e.g. Aldén and Hammarstedt, 2016; Harper, 2016; Preston, 2014) have been studied in detail, indeed often in relation to population ageing (e.g. Hoff, 2016; Karl and Torres, 2015), noting that immigration may help to reduce the burden of population ageing, while emigration of young people may do the opposite. A specific strand of the literature then analyses the brain drain phenomena (e.g. Horvat, 2004; Veugelers, 2017; Zhang and Lucey, 2017), a human capital flight of skilled individuals providing significant economic benefits for both the migrants themselves and the receiving country - often at the expense of the country of origin. At the same time, emigration remittances and return migration can also have various positive effects on the country of origin (Barsbai et al., 2017 or Ratha et al., 2011).

The methodology used in this study combines the explicit modelling of age effects in OLG models with the simultaneous assessment of all economic activities - production, consumption, employment, taxes, savings and trade - in CGE models. The baseline OLG model used in this study was developed by Samuelson (1958) and Diamond (1965) and recently used to evaluate the effects of population ageing e.g. by Catalano and Pezzolla (2016) or Kim et al. (2016). The main sources of inspiration for the model were then the seminal work of Auerbach and Kotlikoff (1987), as well as newer publications of Heer and Maussner (2009), Ihori (1996), Lisenkova et al. (2013), Zodrow et al. (2013) and others. CGE models have an equally long history, originating in input-output and linear programming models, with Dervis et al. (1982), Lofgren et al. (2002) and Nordhaus and Yang (1996) representing some of the main pieces of literature. The the CGE model variation used in this study is broadly based on Burfisher (2017), Corong et al. (2017), Dixon and Jorgenson (2012), Garau et al. (2013), Fehr (2009) and Lecca et al. (2013). Both OLG and CGE models have been previously used in the context of the Czech Republic to address e.g. the issues of pension system, R&D investment or trade and environmental policies by Kiuila (2015), Křístková and Habrychova (2011), Křístková et al. (2012), Martin and Skinner (1998), Marek (2008) and Snudden and Klyuev (2011).

3.3 The model

This section describes the OLG-CGE model used in the simulation analysis. The computer script is based on Stepanek (2019); additional model details and approach to its estimation are described in the Appendix. The simulations were done in MATLAB R2019b.

The model is set up as follows. The Czech economy is assumed to be closed and represented by agents (households) of varying ages s, a representative firm in each of the $p = \{1..13\}$ industrial sectors, and the government. Each period (year), the remainder of the oldest cohort dies and a new generation is born. Agents live for maximum of 60 periods and spend the first $T = 43$ years working and the last $T^r = 17$ years retired, broadly corresponding to the default minimum retirement age of 62-64 years and the average life expectancy of 78 years in the Czech Republic (World Bank, 2018). In line with the existing literature, the first 18 years of actual life are not modelled. Agents face a positive probability of death each year, given by an exogenous unconditional survival function calibrated using the real-world mortality rate projections. Size of the first newborn generation ($t = 1$) is normalised to one, while size of the subsequent generations ($t = 2, ...$) evolves according to the real-world demographic projections.

Besides age, agents differ in their education, production sector and occupation, all of which define their productivity and income both within and across cohorts.[1] Specifically, the model assumes that workers' productivity can be roughly proxied by their wage as implied by the marginal revenue productivity theory of wages (Pullen, 2009). The size and average productivity of each population subgroup in the model, defined by age, education, sector and occupation, can therefore be directly calibrated on the real-world data from the Czech Republic in 2017 (CSO, 2018), and we can calculate the overall efficient labour as a combination of the average wage and the number of individuals. Hours worked are not considered in the equation as they are, on average, implicitly reflected in the wage differences. The full list of categories is presented in Table 3.4: given the 13 production sectors, 5 education groups and 5 occupation groups, each cohort is broken down into 325 separate units. In addition, agent's income evolves over time, representing human capital accumulation, and has the characteristic hump-shaped profile with average wages first increasing with age and subsequently decreasing again at higher ages. Unlike in Stepanek (2019), agents face no idiosyncratic productivity shocks and their assignment into one of the 325 subgroups, which effectively represent different income groups, does not change with age.

3.3.1 Household optimisation

New agents are born without wealth but may start accumulating capital through savings. Analogously, in the last period, agents sell all of their remaining capital stock for consumption. In absence of inflation in the model, the total annual income of an agent aged s, with education e, occupation o, in production sector p, in any given period t, is a combination of the baseline average income $e_{s,e,o,p}$ (a proxy for efficient labour as per above) and period-specific equilibrium wage $w_{e,o,p,t}$ (see Equation 3.11):

$$I_{s,z,t} = (1 - \tau)\, e_{s,z} w_{z,t}, \tag{3.1}$$

where τ is the effective tax rate for the given level of income, calculated using flat social security and progressive marginal tax rates (see Section 3.3.3 for details) and z is a composite subscript indicating one of the 325 income/productivity groups of agents determined by production sector, education and occupation. The baseline wage parameter $e_{s,z}$ is set equal to the

[1] The classification of educational attainment follows the International Standard Classification of Education (ISCE; UNESCO Institute for Statistics, 2012), industrial sectors are categorised following the Statistical Classification of Economic Activities in the European Community (NACE; European Commission, 2007), and occupations using the International Standard Classification of Occupations (ISCO; International Labour Organization, 2016).

real-world average wage in 2017 for each subgroup and the scaling equilibrium wage multiplier $w_{z,t}$ is set to one initially. That is, the total income is set to the real-world level for each subgroup in $t = 1$. From $t = 2$, income varies with $w_{z,t}$ (which fluctuates around one), which is determined by labour supply-demand interaction (Equation 3.11) and sectoral labour supply (Equation 3.13).

Agents are assumed to be rational and to optimise their utility over life cycle using a standard utility function common to all households:

$$U(s,z) = \mathbb{E}_s \left[\sum_{j=s}^{T+T^r} \pi_{j,t} \frac{C(j,z_j)^{1-1/\sigma_u}}{(1-1/\sigma_u)(1+\rho)^{j-s}} \right], \tag{3.2}$$

where $C(j,z_j)$ is the aggregate consumption across all production sectors at age j, conditional on being in income group z_j at that age, σ_u is the intertemporal elasticity of substitution, and $\pi_{j,t}$ represents probability of surviving additional year at age j, which effectively acts as an additional discounting factor in addition to the pure time preference discounting ρ. The survival probability rate depends both on the probability of death at age s, $q_{s,t}$, and the probability of surviving up to that age:

$$\pi_{s,j,t} = \prod_{k=s}^{j+1} (1 - q_{k,t}) \tag{3.3}$$

Agents maximise their lifetime utility subject to a dynamic lifetime budget constraint consisting of labour income $I_{s,z,t}$ (if working), pension transfers $p_{s,z,t}$ (if retired) and interest payments from asset holdings, determined by the next-period interest rate r_{t+1}:

$$A_{s+1,z,t+1} = A_{s,z,t}\,(1 + r_{t+1}) + I_{s,z,t} - P^c_t C(s,z) \tag{3.4}$$

for workers and

$$A_{s+1,z,t+1} = A_{s,z,t}\,(1 + r_{t+1}) + p_{s,z,t} - P^c_t C(s,z) \tag{3.5}$$

for pensioners. Additionally, $A_{1,z,t} = A_{T+T^R+1,z,t+1} = 0$, i.e. agents start with no wealth and consume all of their remaining wealth in the last period of their lives. In each period, the difference between the total income and consumption are savings in interest-bearing assets $A_{s+1,z,t+1}$ determined endogenously within the model. Since income is subgroup-specific, pensions, consumption and savings also vary by population subgroup. In the equations, P^c_t represents price of the aggregate consumption good C_t. The maximisation procedure yields the standard time path of consumption:

$$\frac{C_t}{C_{t+1}} = \left[\frac{1+\rho}{1+r_{t+1}} \frac{P^c_t}{P^c_{t+1}} \right]^{\frac{1}{\sigma_u}} \tag{3.6}$$

Each sector in the economy produces a representative good (or service) $Q_{p,t}$ with price $P^q_{p,t}$. Following the empirical findings from CSO (2018), agents' consumption behaviour is assumed to change with age – with younger individuals spending proportionally more on leisure, clothing or transport than older individuals, who spend more on housing or healthcare – but is otherwise constant across income groups z. This is defined formally using a consumption share parameter $\kappa_{s,p}$. Composition of overall consumption then depends both on agents' preferences $\kappa_{s,p}$ and the relative price of goods and services. Formally, following Fehr (2009), we define the aggregate private consumption good using a CES function as:

$$C_{s,z,t} = \left[\sum_{p=1}^{13} \kappa_{s,p} Q_{s,z,p,t}^{\omega}\right]^{\frac{1}{\omega}} \tag{3.7}$$

where $\omega = (\sigma_c - 1)/\sigma_c$, with σ_c being the elasticity of substitution between different consumption goods p. The corresponding demand for sectoral goods is then:

$$Q_{s,z,p,t} = \left(\frac{\kappa_{s,p}}{P_{p,t}^{q}}\right)^{\sigma_c} P_t^{c\,\sigma_c} C_{s,z,t} \tag{3.8}$$

That is, demand for individual goods and services is inversely related to their prices relative to price of the aggregate consumption and increases with overall consumption. As discussed in the Appendix, the solution algorithm proceeds accordingly, first determining the aggregate consumption profile given by Equation 3.2 and subsequently the demand for sectoral goods using Equation 3.8.

3.3.2 Firm optimisation

Each production sector p is represented by a firm producing goods or services $X_{p,t}$ using intermediate inputs $V_{i,p,t}$ in combination with its own value added $Y_{p,t}$. Value added is obtained through effective labour N_t and capital K_t, combined in a CES production function allowing their substitution as necessary:

$$Y_{p,t} = \left[\delta_p^k K_{p,t}^{\zeta} + \delta_p^l L_{p,t}^{\zeta}\right]^{1/\zeta} \tag{3.9}$$

where $\zeta = (\sigma_y - 1)/\sigma_y$, with σ_y being the value-added elasticity of substitution; and δ_p^k and δ_p^l are share parameters. Intermediate goods and value added are then combined using a Leontief production function:

$$X_{p,t} = \min\left(\frac{Y_{p,t}}{\alpha_p^y}; \frac{V_{i,p,t}}{\alpha_p^v}\right), \tag{3.10}$$

where $V_{i,p,t}$ is intermediate input produced in sector i and used in sector p, and α_p^y and α_p^v are scaling constants. That is, unlike value added, the final goods can be produced only using a constant ratio of intermediate inputs and value added.

Firms hire region-specific labour at the total cost of $(1+\tau^r)\, e_{s,z} w_{z,t}$, where τ^r is the social security contribution paid by firm and $w_{p,t}$ is the sector-specific equilibrium wage, and rent physical capital paying economy-wide rental rate r_t. The equilibrium prices can be derived using the firm's maximisation problem:

$$\frac{w_{p,t}}{P_{p,t}} = \frac{\delta_p^l}{1+\tau^r}\left(\frac{Y_{p,t}}{L_{p,t}}\right)^{1-\zeta} \tag{3.11}$$

$$\frac{r_t}{P_t} = \delta^k \left(\frac{Y_t}{K_t}\right)^{1-\zeta} - \delta, \tag{3.12}$$

where K and L are the aggregate capital and effective labour stock per production sector and δ is the depreciation rate of capital. As discussed above, the equilibrium wage is set to one in each sector initially, whereas $e_{s,e,o,p}$ is set to the average gross wage in the Czech Republic in 2017 for each group $\{s, e, o, p\}$. In the subsequent periods, $e_{s,e,o,p}$ remains constant to maintain the baseline differences among individuals with different characteristics, while the sectoral equilibrium wage, determined endogenously within the model, also starts to vary by age and productivity group based on relative changes in their representation in the overall sectoral labour force:

$$w_{s,z,t} = w_{t,p} \frac{L_{s,z,t}}{L_{s,z,1}} \frac{L_{p,1}}{L_{p,t}} \tag{3.13}$$

Prices of goods and services, $P^c_{p,t}$, evolve over time, balancing changes in demand and supply in each sector.

3.3.3 Government

Government's role in the model consists of collecting contributions to the social security system, paying out pensions and purchasing goods and services. For simplicity, the model assumes that the government's total consumption is always proportional to that of the households' in the same ratio as in $t = 1$. The initial pension system specification follows the actual implementation in the Czech Republic. Pension transfers are determined by income history of new pensioners and exogenously given replacement rates $h_{z,t}$, which are in form of marginal rates and decrease with income. An effective replacement rate, h^e_t can be calculated for each level of income using the income thresholds translated into the model as percentage of the average wage. Pension transfers in period t can be determined as:

$$p_{s,z,t} = h^e_t \sum_{j=1}^{T} \frac{I_{j,z,t-T+j}}{T} \tag{3.14}$$

The pension system budget is modelled to be in a balance initially. In the subsequent periods, pensions are indexed at the level of nominal wages, so that the pension replacement rates do not decrease, and the pension system budget may be in a deficit or surplus following the balance equation:

$$\sum_{s=1}^{T} \sum_{z \in Z} (\tau^r + \tau^e)\, I_{s,z,t}\, \mu_{s,z,t} \lesseqgtr \sum_{s=T}^{T+T^r} \sum_{z \in Z} \nu\, p_{s,z,t}\, \mu_{s,z,t}, \tag{3.15}$$

where $\mu_{s,z,t}$ is the measure of generation s in productivity class z and year t, τ^e_t is the social security contribution paid by employers, and ν is a scaling parameter reflecting the discrepancy between the old-age dependency ratio in the model and in reality, caused by difference in life expectancy vs retirement age and the implicit assumption that every household of working age is employed in the model, as opposed to positive unemployment rates in reality. The scaling parameter is calculated endogenously within the model.

3.3.4 Calibration

The model is calibrated to correspond, in its initial steady state, to the Social Accounting Matrix (SAM) for the Czech Republic and the rest of the World in 2011 as obtained from the Global Trade Analysis Project (GTAP, Aguiar et al., 2016). Specifically, the parameters obtained are primarily the total expenditure on domestic goods and services by private households and the government, as well as the amount of intermediate goods, capital and labour (differentiated by the five occupation groups) required for production. Data on average earnings and number of employees by age and productivity group z, as well as consumption patterns by age were obtained from the Czech Statistical Office for year 2017 (CSO, 2018). Other economic parameters, such as income and social security tax rates or pension replacement rates are set to their actual values in the Czech Republic as of March 2019. An overview of the calibration parameters is presented in Table 3.1.

The behavioural parameters were obtained from the relevant academic literature and databases. Following Zodrow et al. (2013), the rate of time preference ρ is set equal to 0.011; the intertemporal elasticity of substitution σ_u to 0.5 as estimated by Havranek et al. (2015); elasticity of substitution in demand for sectoral goods σ_c is set to 1.5 following Hobijn and Nechio (2018); depreciation rate δ to 4.46% following the Penn World Tables (Feenstra et al., 2015); marginal income tax rates vary across income classes between 1.9% and 35%, with social security taxes set to 6.5% paid by the employee and 25% paid by the employer as in reality; and the sector-specific value-added elasticity of substitution σ_y was obtained from Dimaranan et al. (2006) and is presented in Table 3.5. Changes in agents' consumption with age follow data on average annual expenses by expenditure group obtained by CSO (2018). A summary overview of the number of employees and median wage by sector are presented in Figure 3.5 in the Appendix.

Population predictions are based on the total population, mortality, and fertility indicators from United Nations (2017) for years 1996-2050. Following the model specification, fertility rates from year $t - 18$ are used to reflect that $s = 1$ corresponds to the real life age of 19. The initial mortality rates are set according to the UN data for 2019. From the second period onwards, size of the newborn generation evolves according to the ratio of fertility rates compared to the initial period, mortality rates evolve according to the UN data, and the population structure is defined endogenously within the model. The maximum age does not change. The population predictions highlight three separate trends: decrease in fertility, increase in mortality, and a shift in population structure with large cohorts reaching retirement age in the next decades. Data on migration patterns were obtained from the Eurostat database (European Commission, 2019) and are further described in the next section.

Table 3.1: Calibration parameters

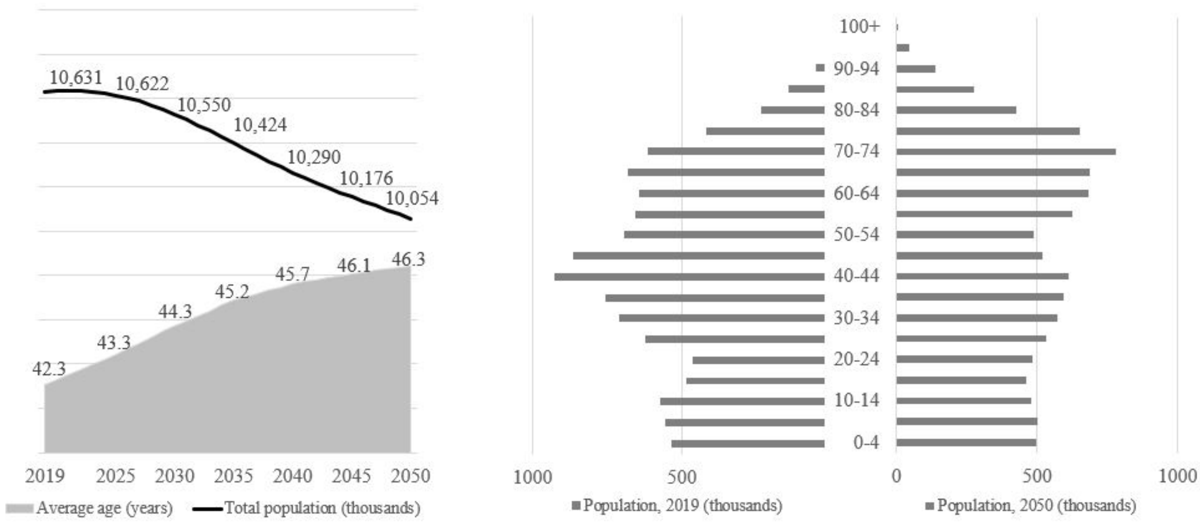
Symbol	Description	Source	Value
ρ	Rate of time preference	Zodrow et al. (2013)	0.0110
σ_u	Intertemporal elasticity of substitution	Havranek et al. (2015)	0.5000
σ_y	Value-added elasticity of substitution	Dimaranan et al. (2006)	See Table 3.5
σ_c	Elasticity of substitution between consumption goods	Hobijn and Nechio (2018)	1.5000
δ	Depreciation rate	Feenstra et al. (2015)	0.0446
τ	Marginal taxation	OECD Tax Database	1.9%-35%
-	Number of employees and wages	CSO (2018)	See Figure 3.5
-	CGE model parameters	Aguiar et al. (2016)	Various
κ	Consumption patterns by age	CSO (2018)	Various

3.3.5 Scenarios

In line with the study's objectives – assessment of the long-term impacts of demographic changes due to population ageing and international migration – three distinct scenarios are modelled. The two scenarios modelling higher- and lower-than-expected migration aim to outline the possibility to offset adverse effects of the inherent demographic changes in the Czech Republic. The scenarios were chosen to represent an unexpected yet realistic event or policy change with the aim to show that even such an unexpected migration shift would not overturn the effect of population ageing. They are then accompanied by calculation of net immigration shift necessary to fully offset such changes.

The first, *baseline scenario*, follows the projected medium variant of population development in the Czech Republic (a combination of natural population changes and international migration) reported in United Nations (2017). The projections assume effectively no net migration, the number of foreign nationals in the Czech Republic is thus assumed to remain at approx. 60 thousand and the overall population population changes reduce to the difference in birth and death rates as depicted in Figure 3.1. Czech population is expected to decrease by approx. 5.4% over the next 30 years, with the average age increasing by more than 4 years. Importantly, the large post-war cohorts currently aged 40-50 will substantially shift the old-age dependency ratio as they retire in the next decades.

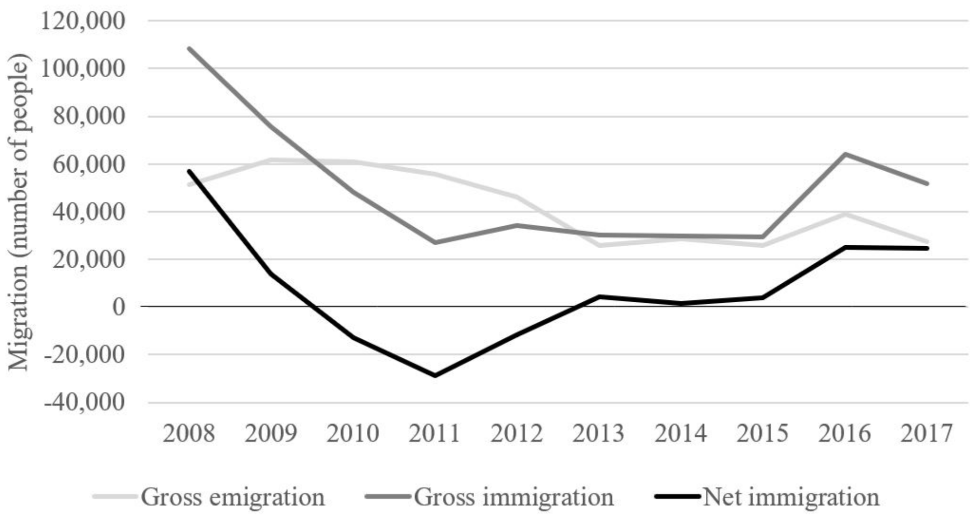
Figure 3.1: Total population size and average age (left graph) and population age distribution (right graph) in the Czech Republic in 2019-2050 as used in the baseline scenario.



Source: United Nations (2017)

The *immigration scenario* considers, in addition to the baseline demographic projections, a sudden inflow of migrants from abroad, specifically that 90% of the 45 thousand Czechs aged 19+ living in the UK (42% of all Czechs in the age group living in another EU/EFTA country) return due to Brexit. This represents approx. 1% of all employees in the Czech Republic. Return of Czech nationals is chosen over an inflow of foreign nationals because Czech Republic is relatively unattractive for foreigners outside of the Eastern Europe and former communist countries: more than 54% of the total 468 thousand foreign-born individuals in the Czech Republic in 2018 come from Slovakia, Ukraine and Vietnam (European Commission, 2019). The recent data suggest that this may be changing as the net migration to the Czech Republic was positive in 2016 and 2017 (see Figure 3.2), arguably as a result of the recent surge in immigration to Europe from the Greater Middle East and Africa, yet it remains to be seen whether it is a sustainable trend as the overall immigration to Europe has been on the decline since then (IOM, 2019).[2]

Figure 3.2: Gross and net migration flows to the Czech Republic.



Source: European Commission (2019)

The *emigration scenario* assumes an opposite trend, specifically that 40% of all foreign-born individuals aged 19+ living in the Czech Republic (approx. 177 thousand, or nearly 5% of all employees) suddenly leave. In both cases, the model assumes the same proportion of individuals to migrate across all age categories (e.g. 90% of individuals aged 21-30, 90% of those aged 31-40 and so on). For simplicity, it also assumes that the distribution across industries, occupations and education groups corresponds to that of the Czech Republic as a whole. The migration is assumed to happen at the beginning of the second period, i.e. $t = 2$. For comparison purposes, none of the scenarios considers a shift in the default retirement age.

3.4 Simulation results

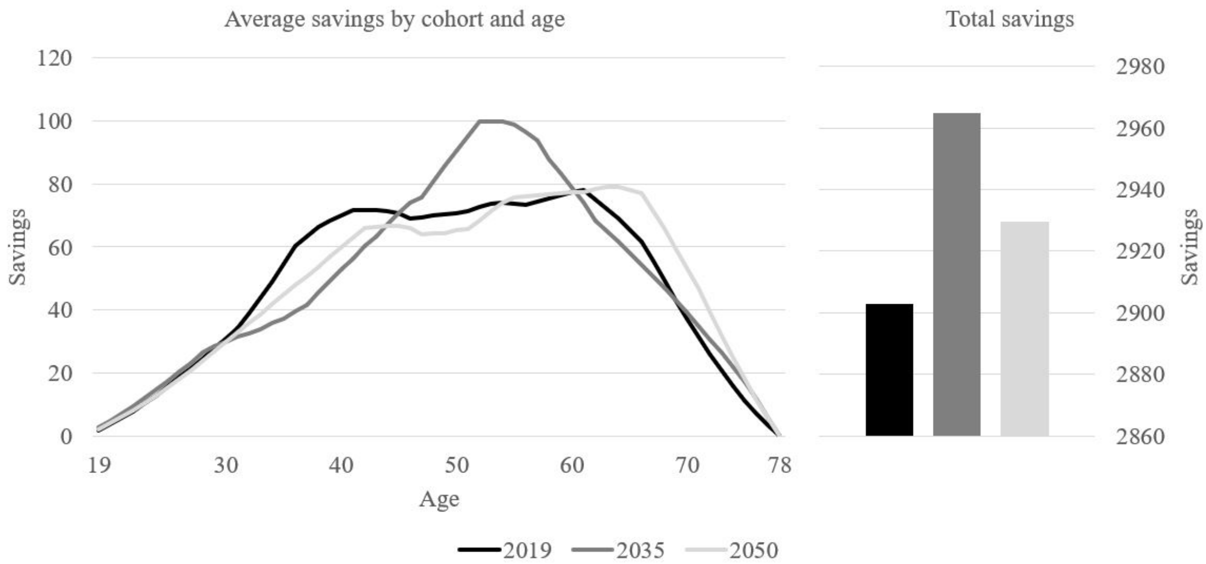
This section reports on the economic impacts of the assumed demographic and migration changes on individuals in the Czech society, industrial sectors, and the economy as a whole. First, we analyse results of a baseline scenario following the UN population projections, followed by two alternative scenarios characterised by higher-than-expected immigration and emigration. Note that since there is no inflation or long-term macroeconomic productivity improvement (as a result of technological advancement) assumed in the model, all of the changes are a result of the inherent changes in the population structure.

[2]The migration patterns depicted in Figure 3.2 vary over time, with the initial high migration being caused primarily by the Czech Republic joining the Schengen Area of free movement within Europe. The UN estimate that there should be approx. zero net migration to the Czech Republic in the next decades (United Nations, 2017).

3.4.1 Baseline scenario

The baseline scenario represents the expected population and migration development projected by United Nations (2017), characterised by a continuous population decrease (5.4% by 2050) and ageing (4 years increase in average age, see Figure 3.1).

Figure 3.3: Savings, baseline scenario.

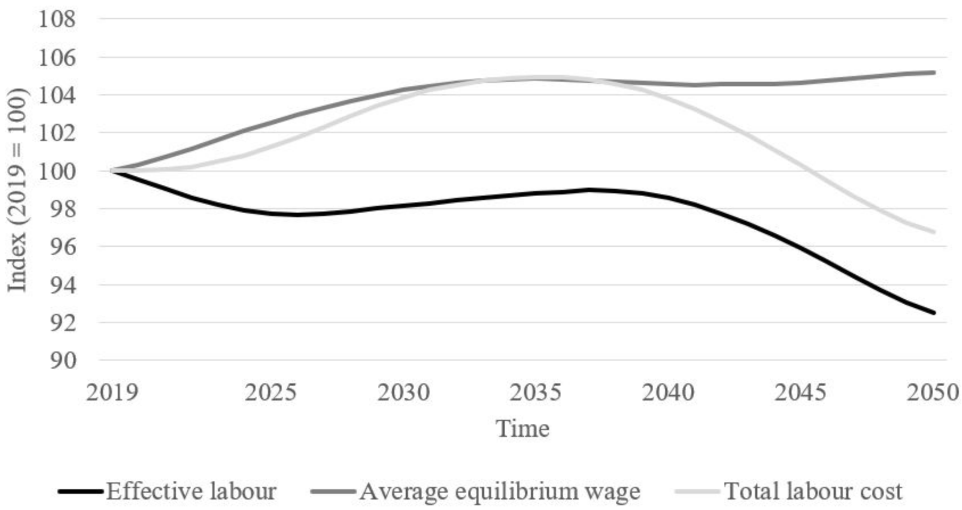


Values standardised using agents' maximum achieved average savings (maximum = 100).

In the model, population ageing results in comparatively higher costs of labour due to the shape of agents' income curves (see Figure 3.6 in the Appendix), which, on the agents' side, results in increasing income per capita and, on the firms' side, increases costs of production and prompts substitution effects in the production technology. In addition, agents' savings increase with age (up to retirement) as they put a share of their income aside for later use each month, resulting in higher average savings per capita as well in the slowly ageing society. Both factors contribute to higher overall accumulation of capital in the economy, albeit the changes are relatively smaller than changes in the amount of efficient labour available. We can see this in Figure 3.3; the total savings increase by 2.1% between 2019 and 2035 and then decreases again, principally as a result of increasing number of individuals being in retirement and slowly consuming their savings. Indeed, we can see that the overall distribution of savings by age cohort shifts to the right, with the total amount of capital held by retirees increasing from 22% in 2019 to 28% in 2050. As a consequence, the equilibrium interest rate decreases from 3.5% to 3.34% over the assumed time period.

At the same time, the economy faces a gradual decrease in labour force and the amount of effective labour available to firms, only partially offset by higher proportion of older, more productive workers. This is shown in Figure 3.4. The average equilibrium wage (across all sectors in the economy) increases by 5.2% by 2050 as a result, shifting the cost of production factors from capital towards labour and decreasing competitiveness of the Czech economy as a whole due higher cost of production. Analysing the results in detail, there are subtle differences in the elements affecting the average equilibrium wage and total labour cost; the initial dip in effective labour supply is immediately reflected in rising wages (years 2020-2025), yet the subsequent increase is not (years 2030-2035), due to a higher proportion of individuals reaching a peak in their consumption profile (around retirement age), resulting in higher demand for goods and services (see also Table 3.2). Finally, the further decrease in labour supply leads to even higher equilibrium wage while the overall labour costs decrease due to the lower number of agents paid and, to a lesser extent, sector differentiation (see below).

Figure 3.4: Effective labour supply, average equilibrium wage and total labour costs, baseline scenario.



The underlying changes in population size and age structure with the associated shifts in income and consumption preferences (see Section 3.3.1) have a profound effect on the aggregate demand and, in turn, on performance of the 13 production sectors, as outlined in Table 3.2, and the economy as a whole. Indeed, since demand and supply are equal each period, the aggregate output of the economy decreases correspondingly as shown in Table 3.3, resulting in a 4.4% reduction in GDP-equivalent by 2050.[3] The matrix of sector-wide effects is more complex as sectoral demand figures cover both final and intermediate goods, i.e. the indirect effects of higher demand (and therefore production) in one sector on the other associated sectors. Here, the model results show an overall decrease of demand in agriculture, mining and construction sectors, as well as and higher-than-average demand for utilities and financial and insurance activities initially, followed by an economy-wide decrease in demand below the 2019 values by 2045.

For completeness, changes in the equilibrium wage by sector are depicted in Table 3.6 in the Appendix, resembling the overall pattern from Figure 3.4 as well as the demand changes by sector from Table 3.2. In particular, wages are projected to gradually increase over time across all sectors as a result of changes in demand and decline in labour force.

To sum up, the Czech economy is projected to be substantially affected by changes in the demographic structure – population shrinking and ageing – in the next decades, resulting in higher capital accumulation, lower labour supply associated with higher costs of each unit of labour and decrease in demand for products and services. As a consequence, the Czech economy will see lower economic growth, increase in unit labour costs and lower competitiveness of the

[3]Since the model does not assume any technological progress over time, the GDP impact shows as an absolute decrease. In reality, this would rather be manifested as a decrease in economic growth rate.

Table 3.2: Sectoral demand changes (% change compared to 2019), baseline scenario.

	Final household demand in 2019 (% of total)	% change in demand					
		2025	2030	2035	2040	2045	2050
Agriculture, forestry and fishing	1.0	-1.74	-0.71	0.08	-1.81	-3.25	-7.11
Mining and quarrying	0.1	-0.54	0.21	0.65	-0.51	-1.28	-4.89
Manufacturing	37.6	0.17	0.70	1.10	0.61	-2.08	-5.71
Electricity, gas, air	6.6	0.28	0.75	1.19	0.75	-1.71	-5.33
Water supply, sewerage	0.9	0.13	0.68	1.06	0.58	-2.12	-5.73
Construction and real estate	15.3	-1.98	-1.35	-0.76	-1.12	-1.79	-6.11
Wholesale and retail trade	11.2	0.59	1.07	1.41	1.15	-0.48	-3.75
Transportation and storage	6.7	0.35	0.88	1.23	0.85	-1.37	-4.79
Recreation	3.1	0.25	0.80	1.20	0.70	-1.78	-5.33
Information and communication	6.0	0.24	0.68	1.16	0.70	-1.85	-5.54
Financial and insurance activities	1.6	0.17	0.64	1.11	0.62	-2.15	-5.87
Professional activities	5.5	0.19	0.70	1.14	0.67	-1.97	-5.59
Public	4.5	0.01	0.60	0.98	0.42	-2.64	-5.71

economy as a whole. The agriculture and construction sectors are projected to be affected the most, with the total demand for their products and services dropping by more than 6% by 2050. Other industries will see a modest increase and subsequent decrease in demand and increase in unit cost of labour, pushing their production more towards utilising capital instead. The next section analyses the extent to which further changes in immigration/emigration patterns contribute to the overall picture.

3.4.2 Scenarios with migration changes

This section considers two alternative scenarios with higher-than-expected inflow/outflow of workers to/from the Czech Republic in period $t = 2$, as described in Section 3.3.5 and depicted in Figure 3.7 in the Appendix using the amount of effective labour available in the economy. As we can see, the differences, amounting to approx. 0.5% higher and 2.5% lower labour supply in the immigration and emigration scenarios at first, respectively, gradually diminish over time as the older generations retire. The higher labour supply in the immigration scenario is insufficient to fully offset the natural decrease due to demographic changes, whereas the assumed emigration scenario leads to labour supply levels at the 2040 level in the baseline scenario.

The simulation results for the main variables of interest across the three scenarios are presented in Table 3.3. As in the baseline scenario results, all of the variables closely follow changes in the population size and structure, although the extent of changes varies by variable. Importantly, for none of the variables the higher immigration offsets the natural demographic changes. On the contrary, we can use the projected loss in effective labour force to calculate an increase in net inflow of migrants in productive age that would maintain the current level of effective labour supply and thus help to prevent increasing unit labour costs and prices of goods and services. Such an increase in the number of workers would also lead to aggregate demand above the 2019 levels and improve the old-age dependency ratio, lowering the pressure on the public

Table 3.3: Main simulation results, comparison of the three scenarios.

Scenario	Variable	Year						
		2019	2025	2030	2035	2040	2045	2050
Baseline	Capital accumulation	100.0	102.2	102.7	103.0	103.2	103.1	102.2
	Effective labour	100.0	97.8	98.2	98.8	98.6	96.0	92.5
	Equilibrium wage	100.0	102.5	104.3	104.9	104.6	104.6	105.2
	Economic output	100.0	99.7	99.4	98.8	98.2	99.3	95.6
Immigration	Capital accumulation	100.0	102.6	103.1	103.5	103.7	103.6	102.5
	Effective labour	100.0	98.2	98.6	99.2	98.9	96.2	92.7
	Equilibrium wage	100.0	102.5	104.2	104.9	104.6	104.7	105.2
	Economic output	100.0	99.7	98.6	98.5	96.4	99.8	96.1
Emigration	Capital accumulation	100.0	100.3	100.6	101.0	101.3	101.4	100.8
	Effective labour	100.0	95.8	96.4	97.3	97.4	95.0	91.9
	Equilibrium wage	100.0	102.7	104.3	104.7	104.3	104.3	104.8
	Economic output	100.0	96.7	97.5	98.7	99.0	97.1	93.9

All results shown as index of the 2019 baseline scenario value for the given variable.

pension system. Given the average of 1.3% decrease in the effective labour in the 2020-2035 period and 2.8% in the 2036-2050 period, net immigration would need to increase by at least 8 thousand individuals per year on average compared to the UN projections (15.4% of the current gross immigration, assuming the same distribution of skills as in the overall Czech population; European Commission, 2019) in the 2020-2035 period and by 17 thousand (33.5%) in the 2036-2050 period in order to offset the negative effects of population ageing and shrinking in the long term.

3.5 Conclusions

This study analyses consequences of the expected demographic changes – population ageing and shrinking – as well as international migration on the example of the Czech Republic, with the aim to highlight the impacts on the consumers, production sectors and the economy as a whole and thus contribute to the debate on the need for a long-term solution regarding demographic changes. The Czech population is projected to see approx. a 5.4% decrease in its overall population size over the next 30 years, with nearly null net immigration and the average age increasing by more than 4 years over the same period (United Nations, 2017). In the assumed absence of changes in the statutory retirement age and with a large Generation X cohort slowly approaching retirement age, the demographic changes will result in disproportionately higher impact on the labour force, with the effective labour supply projected to decrease by more than 7% in the model.

The study utilises numeric simulations of a bespoke OLG-CGE model explicitly taking into account both the changes in the population size and age structure and the various interlinked activities in the economy: production, consumption, employment, taxes and savings. This allows assessment of counterfactual scenarios in a perfectly controlled environment with only one changing exogenous variable: the Czech population. Three distinct scenarios are analysed: a baseline scenario corresponding to the medium variant projected by the United Nations; a scenario with higher-than-expected immigration, assuming arrival of 90% of the 45 thousand

Czechs aged 19+ living in the UK; and a scenario with an unexpected outflow of 40% of the approx. 443 thousand foreign-born individuals aged 19+ living in the Czech Republic.

The model results show that, on the positive side, the ageing population will hold comparatively higher savings, promoting capital accumulation in the economy, and demand more goods and services, leading to higher output of the economy as a whole. This effect will, however, be eventually outweighed by the decreasing population size, leading to an ultimate drop in the aggregate demand of more than 2% by 2050. At the same time, the decreasing labour supply will lead to higher equilibrium wages and cost of production, which will force firms to substitute some of the labour input in their production for capital, increasing the average capital/labour ratio by 10% by 2050. The impacts are estimated to differ by sector as a result of shifting consumer preferences with age and complex interrelations between production sectors, where production in one sector often requires substantial intermediate inputs from another. The agriculture and construction sectors are projected to be the worst affected, with demand for their products decreasing by more than 6% by 2050. On the whole, the demographic changes would lower economic growth (4.4% lower GDP by 2050 in absence of technological progress), increase unit labour costs (5.2% higher wages in absence of inflation) and lower competitiveness of the economy at the international markets.

The effects are then amplified in the scenario with unexpected emigration, while the assumed higher immigration in the other alternative scenario is insufficient to outweigh the long-term negative effects. In this regard, replacement migration could be considered as a remedy to the adverse effects of demographic changes, yet net immigration would need to increase by at least 8 thousand individuals per year on average in the 2020-2035 period and by 17 thousand in the 2036-2050 period compared to the UN projections in order to negate the long-term demographic changes, representing approx. 15.4%-33.5% of the current gross immigration. On one hand, this may be realistic given the recent surge in immigration (see Figure 3.2), yet it remains to be seen whether such a trend is sustainable. In addition, as discussed e.g. by Saczuk (2013), replacement migration efforts may be difficult due to skills mismatch or increasing social tensions.

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Appendix

The following text expands on the model description from Section 3.3 and provides additional details on the computation methodology.

Model equilibrium

The economy is assumed to be in an equilibrium in each period. The concept of equilibrium uses a recursive representation of the consumer's problem following Heer and Maussner (2009) and is characterised by the following properties:

1. Individual and aggregate behaviour are consistent:

$$N_t = \sum_{s=1}^{T} \sum_{z \in Z} e_{s,z} w_{z,t} \tag{3.16}$$

$$K_t = \sum_{s=1}^{T+T^R} \sum_{z \in Z} A_{s,z,t} \tag{3.17}$$

$$C_t = \sum_{s=1}^{T+T^R} \sum_{z \in Z} C_{s,z,t} \tag{3.18}$$

2. Agents' dynamic programs and firms' optimisation problems are solved by satisfying Equations (3.2)–(3.13) using the relative prices w_t, r_t, pensions, and the individual policy rules $C_s(.)$ and $A_{s+1}(.)$.

3. The goods market clears:

$$X_t = C_t + K_{t+1} - (1 - \delta) K_t, \tag{3.19}$$

4. Intermediate goods $V_{i,p,t}$ and value added $Y_{p,t}$ are sufficient to generate production in each sector:

$$X_t \leq \alpha_p^y \cdot Y_{p,t} \tag{3.20}$$

$$X_t \leq \alpha_p^v \cdot V_{i,p,t} \tag{3.21}$$

5. Prices of goods and services $P^c_{p,t}$ are set so that the sectoral goods market clears given Equations 3.7-3.8:

$$X_{p,t} = Q^d_{p,t} \tag{3.22}$$

Solution method

The simulation algorithm used in this study is based on Stepanek (2019), which follows earlier works of Heer and Maussner (2009) and Nishiyama and Smetters (2007), and further developed to work in a multi-sectoral environment following principally the works of Garau et al. (2013) and Fehr (2009). It utilises value function iteration to compute agents' policy functions governing their optimal consumption and savings patterns conditional on the economic situation in each period. With a set of police functions for each group of agents z, firms set prices $P^c_{p,t}$ to put the sectoral demand and supply in equilibrium.

Specifically, the agent's decision functions are calculated using backward induction, i.e. by analysing the optimal behaviour in the last period of agent's live and, conditional on that, in all preceding periods. Let $V_s(A_{s,z}, z_s)$ be the value of the objective function of an s-year old agent from group z with wealth $A_{s,z}$. $V_s(A_{s,z}, z)$ is defined as the solution to the dynamic program:

$$V_s(A_{s,z}, z) = \max_{A_{s+1}, c_t} \{ U(s,z) + \pi_s \, \mathbb{E}[V_{s+1}(A_{s+1}, z)(1+\rho)^{-1} \mid A_{s,z}, z] \} \tag{3.23}$$

That is, subject to the budget constraints, optimal decision rules for consumption and next-period capital stock are functions of wealth and the idiosyncratic productivity shock, and associated with every optimal next period capital stock $A_{s+1}(A_{s,z}, z)$ is an optimal consumption policy $C(s,z)$. Consequently, in each period, all agents can calculate the optimal aggregate consumption and saving behaviour in that period given their age, income group, probability of death, and other variables in the model.

Given the total consumption policy $C(s,z)$, agents then determine their sectoral consumption given the set of prices $P^q_{p,t}$ according to Equation 3.8. At the same time, firms use the available capital and effective labour to produce goods and services for consumption. If there is a mismatch between demand and supply at the sectoral and/or aggregate level, prices $P^q_{p,t}$, w_t and r_t adjust accordingly.

The main simulation process can thus be characterised as follows:

1. Parametrise the model using behavioural parameters, calculate the optimal consumption and savings profile and set the scaling constants so that the outputs correspond to the empirical data in period $t = 1$.

2. In each subsequent period, use the outputs from the previous period $t-1$ as a starting

point and demographic changes as a source of variation to compute changes in w_t and r_t and, consequently, the set of endogenous parameters, such as pensions.

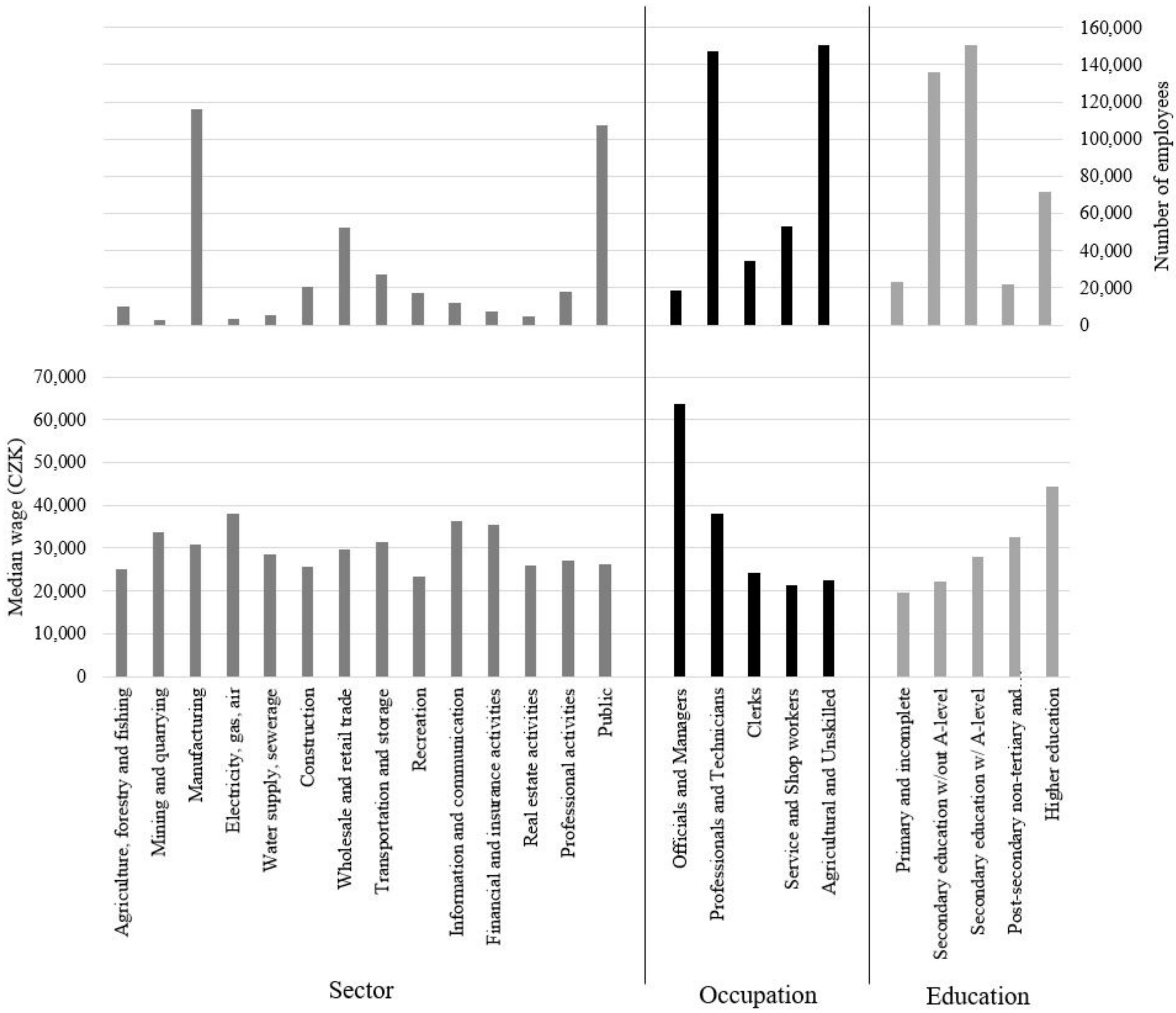
3. Compute the household's decision functions by backward induction as for $t = 1$, resulting in the optimal aggregate consumption and saving behaviour for each cohort alive in period t.

4. Calculate the optimal sectoral demand and supply of goods and services.

5. Update prices $P^q_{p,t}$, w_t and r_t to increase/decrease the amount of consumption, savings and production to minimise the demand/supply differences.

6. Repeat steps 2-5 until the sectoral and aggregate demand and supply are in balance and proceed to the next period.

Figure 3.5: Total number of employees and median wage by sector, occupation group and educational attainment.



Source: CSO (2018)

Table 3.4: Industry, education and occupation classifications

	Original classification		**Adjusted classification**	
	Category name	**ID**	**Category name**	**ID**
Production sectors	Agriculture, forestry and fishing	1	Agriculture, forestry and fishing	1
	Mining and quarrying	2	Mining and quarrying	2
	Manufacturing	3	Manufacturing	3
	Electricity, gas, air	4	Electricity, gas, air	4
	Water supply, sewerage	5	Water supply, sewerage	5
	Construction	6	Construction and real e. (groups 6, 12)	6
	Wholesale and retail trade	7	Wholesale and retail trade	7
	Transportation and storage	8	Transportation and storage	8
	Accommodation and food services	9	Recreation (groups 9, 18)	9
	Information and communication	10	Information and communication	10
	Financial and insurance activities	11	Financial and insurance activities	11
	Real estate activities	12	Professional activities	12
	Professional activities	13	Public (groups 14, 15, 16, 17, 19)	13
	Administrative and support services	14		
	Public administration and defence	15		
	Education	16		
	Human health and social work	17		
	Arts, entertainment and recreation	18		
	Other service activities	19		
Educational attainment levels	Primary and incomplete education	1	Primary and incomplete education	1
	Secondary education without A-levels	2	Secondary education without A-levels	2
	Secondary education with A-levels	3	Secondary education with A-levels	3
	Post-secondary and bachelor's education	4	Post-secondary and bachelor's education	4
	Higher education	5	Higher education	5
Occupation groups	Armed forces occupations	1	Officials and Managers	1
	Managers	2	Professional, Technicians (groups 3, 4)	2
	Professionals	3	Clerks	3
	Technicians and associate professionals	4	Service and Shop workers	4
	Clerical support workers	5	Agricultural and Unskilled (7, 8, 9, 10)	5
	Service and sales workers	6		
	Skilled agricultural workers	7		
	Craft and related trades workers	8		
	Plant and machine operators	9		
	Elementary occupations	10		

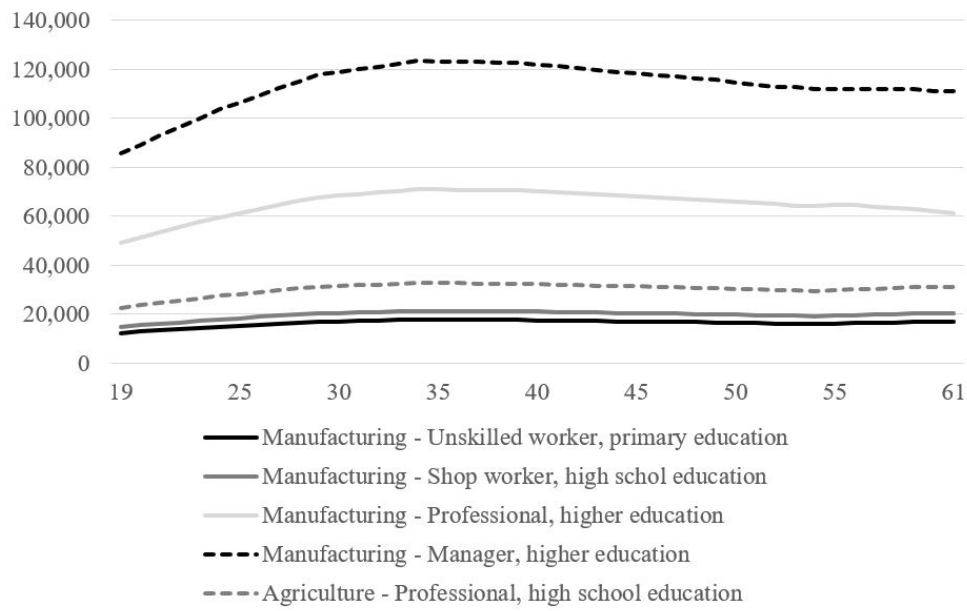
Note: The sectoral names were shortened for presentation purposes. The full classifications are available in UNESCO Institute for Statistics (2012), European Commission (2007) and International Labour Organization (2016).

Table 3.5: Value-added elasticity of substitution parameters used in the model.

Sector	σ_y
Agriculture, forestry and fishing	0.22
Mining and quarrying	1.26
Manufacturing	1.26
Electricity, gas, air	1.26
Water supply, sewerage	1.26
Construction	1.40
Wholesale and retail trade	1.68
Transportation and storage	1.68
Recreation	1.26
Information and communication	1.26
Financial and insurance activities	1.26
Professional activities	1.26
Public	1.26

Source: Dimaranan et al. (2006)

Figure 3.6: Selected income profiles used in the model.

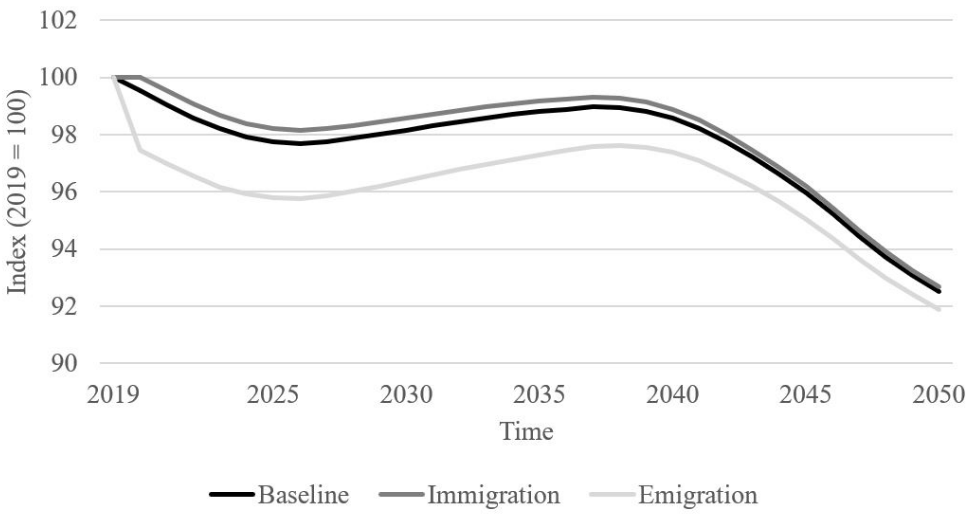


Source: CSO (2018)

Table 3.6: Changes in the equilibrium wage by sector (% change compared to 2019), baseline scenario.

	Share of effective labour in 2019 (% of total)	% change in equilibrium wage					
		2025	2030	2035	2040	2045	2050
Agriculture, forestry and fishing	2.0	0.00	2.11	3.49	3.62	3.16	2.90
Mining and quarrying	0.7	0.00	2.65	3.95	4.06	3.88	4.30
Manufacturing	28.4	0.00	2.60	3.90	4.02	3.82	4.17
Electricity, gas, air	1.2	0.00	2.69	3.95	4.10	3.94	4.37
Water supply, sewerage	1.2	0.00	2.60	3.89	4.00	3.79	4.16
Construction and real estate	5.6	0.00	2.50	3.83	3.93	3.68	3.93
Wholesale and retail trade	12.6	0.00	2.56	3.86	3.97	3.75	4.06
Transportation and storage	6.2	0.00	2.41	3.75	3.87	3.57	3.72
Recreation	3.0	0.00	2.68	3.99	4.05	3.90	4.34
Information and communication	4.9	0.00	2.67	3.90	4.08	3.90	4.30
Financial and insurance activities	3.3	0.00	2.60	3.85	4.03	3.82	4.14
Professional activities	5.3	0.00	2.62	3.91	4.06	3.87	4.24
Public	25.5	0.00	2.47	3.80	3.91	3.65	3.88

Figure 3.7: Effective labour supply as a result of migration.



Chapter 4

The economic implications of later school start times in the United States

Abstract[1]

Numerous studies have shown that later school start times (SST) are associated with positive student outcomes, including improvements in academic performance, mental and physical health, and public safety. While the benefits of later SST are well documented in the literature, in practice there is opposition against delaying SST. A major argument against later SST is the claim that delaying SST will result in significant additional costs for schools due to changes in bussing strategies. However, to date, there has only been one published study that has quantified the potential economic benefits of later SST in relation to potential costs. The current study investigates the economic implications of a state-wide universal shift in school start times to 8.30 a.m., including the benefits of higher academic performance of students and reduced car crash rates. The benefit–cost projections suggest that delaying school start times is a cost-effective population-level strategy, which could have a significant impact on public health and the US economy.

4.1 Introduction

Inadequate sleep among adolescents has emerged as a public health epidemic (Basch et al., 2014). Even though teens need an average of 8 to 10 hours of sleep each night, about 60% of middle school students report weeknight sleep duration of less than nine hours and only about 7% of high school students report 9 hours or more of sleep per night (Basch et al., 2014). The existing literature has shown that a lack of sleep among adolescents is associated with numerous adverse outcomes, including poor physical and mental health, behavioural problems, suicidal ideation and attempts, attention and concentration problems, and suboptimal academic performance (Hart et al., 2013; Lowry et al., 2012; Lytle et al., 2011; Miller et al., 2008; Pasch et al., 2010; Pallesen et al., 2011; Sabia et al., 2017; Short et al., 2013). In addition, insufficient sleep is

[1] This study was published as: Hafner, M., Stepanek, M., and Troxel, W. M. (2017). The economic implications of later school start times in the United States. *Sleep health*, 3(6), 451-457. The presented version contains additional details from the original report preceding the journal publication, published as: Hafner, M., Stepanek, M., and Troxel, W. (2017). Later school start times in the U.S.: An economic analysis. Report, RAND Corporation, Santa Monica, CA.

associated with motor vehicle crashes, the leading cause of death of teenagers (Fischer and Retting, 2016).

Many factors have been found to be associated with adolescent sleep loss, including busy social lives, school work, participation in afterschool activities, and use of technology in the bedroom (Carskadon, 2002). Furthermore, known biological changes in adolescent sleep–wake cycles contribute to delayed sleep–wake cycle (Crowley et al., 2007). Rise times are primarily determined by a factor of public policy, and that factor is school start times (SST) (Knutson and Lauderdale, 2009). In order to accommodate the known biological shift in adolescent sleep–wake cycles leading to later bedtimes and later wake-times, major medical organisations recommend that middle and high schools start no earlier than 8:30 a.m. (Adolescent Sleep Working Group, 2014; Owens et al., 2010). Despite these recommendations, Wheaton et al. (2015) estimate that 82% of middle and high schools start before 8:30 a.m., with an average start time at 8:03 a.m., showing significant variance of SST across different states. While the benefits of later SST are well-documented in the literature, in practice there is often opposition against delaying SST. A major argument against later SST is the claim that delaying SST will result in significant additional costs for schools due to changes in bussing strategies.

To our knowledge, however, there has only one been one published study to date that has aimed to quantify the potential benefits of later SST in relation to potential costs. Specifically, Jacob and Rockoff (2011) examined the cost-benefits of delaying school start times and found a benefit–cost ratio of 9:1 for a 1-hour later start time among middle and upper grades. Costs were estimated to be $150 per year per student, based on Edwards (2012), and were determined by a change in the school bus system, from a three-tiered bus system to a single-tier system. Cumulatively, the study estimated an average $17,500 gain per student in terms of lifetime earnings compared to $1,950 in costs per student over his/her school career. While the analysis shows a high benefit-to-cost ratio, it is important to highlight that the time horizon for the potential benefits is protracted over the average working life of an individual (i.e., about 45 years).

Against this background, the current study examines the potential economic impact from delaying SST for middle and high schools to 8:30 a.m. as opposed to the current start times in each of the selected US states. The analysis departs from the approach taken by Jacob and Rockoff (2011) in several ways. First, instead of assuming a one hour later school start time, the current distribution of school start times across different states is taken into account and the impact of an 8:30 a.m. SST is modelled. Second, when calculating the benefits of SST, this study takes into account the effects on student lifetime earnings as well as the potential impact of reduced car crashes among adolescents, which can have a negative impact on future labour supply of an economy if young adults die prematurely. Third, the previous analysis focused only on a general potential gain per student, whereas this study looks at potential economic effects for different regions, taking into account the variation of school start times and economic factors across different US states. Finally, this study also takes into account potential multiplier effects of increased lifetime earnings of individuals.

4.2 Methods

The analysis is done in two steps: first, we estimate the amount of extra sleep per night that students may get as a result of shift in SST and how that may affect their mortality rates and educational attainment. Second, we apply the estimated parameters in an economic simulation model to assess the aggregate impacts on the economy. The model builds on the long tradition of computable general equilibrium models, which have been extensively applied for economic policy analysis (see e.g. Allan et al., 2014; Lofgren et al., 2013; Zodrow et al., 2013). Such models are based on a detailed theoretical framework simulating the behaviour of various agents and depicting relationships between subjects in an economy described by a set of parameters, equations and conditions that are to be satisfied simultaneously. The equations are then evaluated using mathematical software (in this case MATLAB, 2016b), giving a set of numerical results. The model explicitly allows for the analysis of multiple comparable scenarios which differ only in the selected set of parameters, for example by creating both a baseline (or status quo) and a 'what if' situation showing how the economy would evolve under different policy scenarios. The specific model applied in this study is an overlapping generations (OLG) model; it allows simulation of behaviour of different cohorts of individuals over their life cycle, which is particularly applicable to the selected topic.

4.2.1 Insufficient sleep, academic performance and mortality

As a first step, we analyse how a US-wide policy change shifting SST to 8:30 a.m. would affect students in the 47 US states for which the data on middle and high school starting times are available from Wheaton et al. (2015) and which, on average, show SST earlier than 8:30 am.[2] The assumed population affected by the policy change are students from grade 6 to grade 12. Specifically, following Adolescent Sleep Working Group (2014), we assume that delaying SST would lead to extended sleep duration for adolescents, which would subsequently impact the economy in a given state through various channels for which there were sufficient and robust parameters from the existing literature.[3] In particular, this study focuses on two specific beneficial channels that could be derived from later SST.

The first channel is mortality from motor vehicle crashes. For various reasons, particularly the ability to drive from the age of 16 (with Learners Permit available from the age of 14 in some states), popularity of car transport in the US, good healthcare and generally low mortality rates associated with natural causes of death in the 10-19 age group, car crashes are a major cause of death among teenagers. Specifically, for the US population aged 15-19, transport injuries constitute 28.8% of all deaths, with car accidents being the most prevalent, covering 79.4% of all such deaths (Roth et al., 2018). The data for car crash mortality include the underlying cause

[2] The average school start time data are not available for the District of Columbia and Maryland, and the average start times in Alaska and North Dakota are later than 8:30 a.m.

[3] For instance, while it has been documented that longer sleep duration can be associated with improvements in mental and physical health outcomes for students, including lower levels of depression, suicide ideation or calorie intake, it has been proven difficult to translate the existing empirical estimates on these effects into suitable model parameters. Similar applies to the potential morbidity and disability implications of car crashes involving adolescents, which could lead to large medical expenses, disability payments and a potential loss of future earnings. As this study does not take these effects into account, the predicted economic effects serve as a lower bound estimate. Note that the empirical literature suggests that delaying SST is not associated with later bed time, but is associated with later rise times, which results in a net increase in sleep duration among students (see for example a systematic review by Minges and Redeker, 2016).

of death data provided by CDC (2017b) on weekday motor vehicle fatalities among teenagers age 16 to 18, combined with parameters from Tefft (2014), which show that about one fifth of fatal motor vehicle crashes involved a driver impaired by sleepiness, drowsiness or fatigue. Together with the estimate from Danner and Phillips (2008), which suggests that the car crash rate decreases by 16.5% due to an hour delay in SST, we provide a broad assessment of the potential reduction of car crash mortality rates.[4] Note that in the simulation model the reduced mortality levels affect the economy twice: once through the direct impact of the individual (not) being alive and productive, and potentially having children to contribute in the future.

We estimate the effect on mortality rates and size of future population using a cohort-component model calibrated on data from CDC (2017a) on the existing baseline population projections, mortality and fertility rates. Specifically, the cohort-component model starts with the base population in each state and is categorised by age and gender. The base population subsequently evolves by applying assumptions on mortality and fertility so that the population changes according to natural population changes (births minus deaths), which depends on the particular modelled scenario. The outcome of the model is a projection of the population by 1-year age and gender groups into the future, applied to each of the states. Formally, the population P in state s of age a, gender g at time t is calculated as:

$$P_{s,a+1,g,t+1} = P_{s,a,g,t} + B_{s,a,g} - D_{s,a,g} + I_{s,a,g} - E_{s,a,g}, \tag{4.1}$$

where $B_{s,a,g}$ represents the total births, $D_{s,a,g}$ total deaths, and $E_{s,a,g}$ and $I_{s,a,g}$ represent emigration and immigration, respectively. Note that as a consequence of the cohort-component model, the effects of longer sleep will propagate through the economic model with a one year lag. This is mainly a notation issue; in reality, some of the effects would likely be visible in the immediately.

The second channel is the impact on academic performance – increased high-school and college graduation rates. We assume, in line with the human capital theory widely used in the economic literature for decades, that higher education contributes to the economy by increasing the potential productivity of graduates, i.e. that individuals with higher educational attainment would generally be more productive. However, the theory is not without disputes. In particular, the signalling theory suggests, in contrary to the human capital theory, that higher education contributes to economic performance by enabling employers to differentiate potential employees who will, on average, be more productive from those who will be less productive. The theories are sometimes considered mutually exclusive to a large extent; for instance, Gerber and Cheung (2008) consider the following reasons for the observable income disparity: universities increase human capital, graduates signal their status to employers, university students garner more valuable social capital, and university graduates have enjoyed advantages such as family affluence or ability that generate more favourable outcomes. However, as argued e.g. by Marginson (2019) and Pericles Rospigliosi et al. (2014), the links between education and work are complex, context-bound, varying by country, field of study, occupation or industry, and the individual avenues of effect may be supporting, rather than contradicting each other. What is more, the benefits of longer sleep for teenagers may go beyond educational attainment as the

[4] Some studies found up to 70% decreases in car crashes in some districts following a delay in SST by one hour (Wahlstrom et al., 2014).

brain functionality is develops at that stage of life and longer sleep may increase one's long-term productivity and performance regardless of change in educational attainment.

Sabia et al. (2017) estimate that one additional hour of sleep increases the probability of high school graduation by 8.6% and the college attendance rate by 13.4% on average, both with decreasing marginal returns for each hour of additional sleep.[5] The positive effect on adolescents' academic performance and likelihood of high school graduation are, in turn, assumed to impact their productivity (through human capital accumulation) as well the jobs they are able to obtain in the future.

This is modelled in two steps. First, we derive the current educational attainment distribution using the proportion of high school dropouts n, high school graduates h and college graduates u in each state by gender g, age a and ethnicity r, with data from the United States Census Bureau US Census Bureau (2016).[6] The educational attainment data are not directly available for all gender–ethnicity–state combinations, unlike the overall population data, but for gender–ethnicity pairs and states separately. The two datasets are combined assuming that the differences across gender and ethnicity groups are independent by state but are jointly determined by the overall educational attainment in the given state. Formally, the multivariate joint probability distribution of any individual belonging to a given population group $\{s, g, r\}$ is given by:

$$e_{s,g,r} = e_{g,r} \times e_s, \tag{4.2}$$

where e is the share of individuals with the given educational attainment. We can then calculate the overall educational attainment in a state by combining the number of individuals that attend a given institution and their dropout and graduation rates for all three considered tiers of education as:

$$e^n_{s,g,r} = 1 - e^h_{s,g,r} - e^u_{s,g,r} \tag{4.3}$$
$$e^h_{s,g,r} = s^h_{s,g,r} \times g^h_{s,g,r} - e^u_{s,g,r} \tag{4.4}$$
$$e^u_{s,g,r} = s^u_{s,g,r} \times g^u_{s,g,r} \tag{4.5}$$

where $s^h_{s,g,r}$ and $s^u_{s,g,r}$ represent the number of individuals that attend high school and university, respectively, whereas $g^h_{s,g,r}$ and $g^u_{s,g,r}$ represent their graduation rates.

In a second step, we estimate the level of productivity after the policy change, denoted by θ^*, through the distribution of educational attainment as per above, information on the distribution of average school start times, assumed effect of longer sleep, and information on the average income per age–state–gender–ethnicity combination. To determine the average change in sleep duration due to changes in SST, Δ, we use data on the distribution of SST for different U.S. states from Wheaton et al. (2015) provided in 30-minute intervals: before 7:30 a.m., 7:30–8:00 a.m., and 8:00–8:30 a.m. For simplicity, it is assumed that those intervals correspond to a

[5] Keyes et al. (2015) suggest that less than 60% of students aged 12 to 19 get 7 or more hours of sleep per night. Hence, in order to be conservative in the predictions of economic benefits of delayed SST, we assume that only students who sleep on average less than 7 hours will profit from the policy shift of later SST to 8:30 a.m. or later.

[6] Hispanic refers to individual of any race of Hispanic origin. The "Other" category includes Asians, Native Americans and all other ethnicities.

starting time of 7:30 a.m., 7:45 a.m., and 8:15 a.m. and therefore a net average increase in sleep duration of 60, 45, and 15 minutes, respectively.

In line with Sabia et al. (2017), we assume that only students who get on average less than 7 hours of sleep per night, as compared to the recommended 8–10 hours, would benefit from the delay in SST. In order to derive the exposure–response relationship of the delay in the SST for students sleeping less than 7 hours, we need to determine the size of their population and their average amount of sleep at baseline. The proportions of students aged 12 to 19 sleeping less than 7 hours a night are taken from Eaton et al. (2010) and Keyes et al. (2015). In order to determine the average sleep duration at baseline for students sleeping less than 7 hours a night, we draw on further granular information from McKnight-Eily et al. (2011), who report that about 6%, 10%, 23%, and 30% of students get on average ≤4, 5, 6, and 7 hours of sleep per night, respectively. To remain conservative, we assume that in each of these groups, students sleep exactly 4, 5, 6, and 7 hours, resulting in a weighted average of 6.12 hours of sleep per night for students who receive less than 7 hours of sleep per night on average. We then apply the parameter estimates from Sabia et al. (2017) to derive changes θ^* using:

$$e^{*n}_{s,g,r} = e^{n}_{s,g,r} - (e^{*h}_{s,g,r} - e^{h}_{s,g,r}) - (e^{*u}_{s,g,r} - e^{u}_{s,g,r}) \tag{4.6}$$

$$e^{*h}_{s,g,r} = (0.086\Delta - 0.005 \times (2l\Delta + \Delta^2) + s^{h}_{s,g,r}) \times g^{h}_{s,g,r} - (e^{*u}_{s,g,r} - e^{u}_{s,g,r}) \tag{4.7}$$

$$e^{*u}_{s,g,r} = (0.134\Delta - 0.009 \times (2l\Delta + \Delta^2) + s^{u}_{s,g,r}) \times g^{u}_{s,g,r} \tag{4.8}$$

where Δ represents the average inrease in sleep duration per night as a result of later SST.

Finally, we use information on the average earnings per highest educational attainment level collected by US Bureau of Labor Statistics (2017) to approximate the difference in productivity. However, we also need to reflect that the shift in SST would take several years to have a full impact as some students may only be exposed for a short period of time, and also due to a delay between when potential college attendees graduate and when they enter the labour market. To do this, we assume in the model -– and consistent with the other data presented above — that the high school and college education takes four years to complete and that the estimated effects decrease linearly for students exposed less than the full four years of the delay in SST. For instance, assuming that the policy would be implemented at the beginning of the first year (0), students graduating at the end of the first year (1) would only see 25% of the estimated effects of higher academic performance. In addition, only students that do not pursue tertiary education would have an immediate impact on the labour market, whereas students who go to college would only enter the labour market with a four years delay, albeit more likely with a higher entry salary. Hence, in the predictions of this model, the full effect of higher educational attainment associated with the delay in SST on a treated cohort would emerge 8 years after the policy shift.

Putting all the pieces together, the total predicted relative change in productivity level θ for individuals of age a in state s is as follows:

$$\frac{\theta^*_{a,s}}{\theta_{a,s}} = \sum_{i\in\{n,h,u\}} \sum_{r\in R} \sum_{g\in G} \frac{e^{*i}_{s,g,r,a}}{e^{i}_{s,g,r,a}} \mu^{i}_{s,g,r,a} \frac{m^{i}_{g,r,a}}{m^{i}_{a}} \tag{4.9}$$

That is, the average aggregate increase in productivity at any given point in time due to a delay in SST is a weighted sum of the relative changes in educational attainment of all individuals of the specific age, gender, ethnicity, living in the given state, weighted by the share of such individuals within the total population of the given age and education in that state, $\mu^i_{s,g,r,a}$, multiplied by the relative average earnings of each group, $m^i_{g,r,a}$, compared to the average earnings of all individuals with the same level of education of that age m^i_a. This aims to replicate heterogeneity of effects of educational attainment across different socio-economic population subgroups.

4.2.2 Simulation model

The simulation model used in our study is an overlapping generations (OLG) model first introduced by Samuelson (1958) and Diamond (1965), and later developed by Auerbach and Kotlikoff (1987) who used simulated a pioneering large-scale numerical OLG model to evaluate fiscal policies. Unlike other models assuming all workers to be essentially equal, OLG model by definition assumes that the modelled economy is represented by people of different ages, which is necessary to capture effects of sleep deficiency through various means. Moreover, to allow for effects to differ across income groups, we further differentiate among workers in terms of their skill in a similar fashion to Heer and Maussner (2009) and Krueger and Ludwig (2007).

The economy has three sectors — households, firms, and government — which continuously interact on the markets just as in reality. Specifically, firms, representing the production sector, hire labour supplied by households to create output, paying wages in exchange for labour and interest rate as a cost of capital. In absence of international trade and public enterprises, all assets within the economy are ultimately in possession of people and they also constitute the final consumer of all production. The government collects income taxes from individuals and subsequently provides them with retirement benefits. We assume that the foreign trade effect is negligible as sleep deficiency has no direct influence on it and do not explicitly model foreign economies.

Households

Each period (year), the oldest cohort dies and a new generation is born, following the population projections as per above. All individuals are assumed to live 60 years at maximum from the inception of their professional careers, of which they spend 44 years working and 16 in retirement, reflecting that the retirement age is set at 66 years in the U.S. and the average life expectancy is slightly over 80 years. In line with the existing literature, the first 18 years of actual life are not modelled. Agents face positive probability of death each year, given again by the demographic model.

All individuals that end their education with at most a high school diploma are assumed to start working at the age of 18 in the model, while those with a bachelor's degree are assumed to start working at the age of 22. The labour supply is exogenously set to 8 hours per workday for everyone. Besides the explicit modelling of differences in educational attainment, we model the differences in people's skillsets and other personal characteristics through determination of a labour-endowment distribution and its changes over time so that the ultimate distribution of labour output resembles what we can observe in reality. This can be understood also as a tool to model intra-generation wage distribution, including probability of being unemployed, ill, unable to work or, on the other hand, promoted or finding a better job. Specifically, we assume that each individual is subject to idiosyncratic productivity shocks log-normally distributed with mean y_1 and variance σ_{y_1}. Following Heer and Maussner (2009) and Huggett (1996), agents may move between the income groups as a result of idiosyncratic productivity shocks following a Markov process given by

$$z_t = \zeta z_{t-1} + \epsilon_t, \tag{4.10}$$

where $\epsilon_t \sim N(0, \sigma_\epsilon)$; the next-period categorisation thus depends on its past realisations. In order to approximate the autoregressive process, the continuum of all possible shocks must be limited; to do so, we follow Huggett (1996) and discretize the state space Z containing all shocks into nine realisations ranging from $-2\sigma_{y_1}$ to $2\sigma_{y_1}$, effectively representing various income groups in the population. The probability of having a given productivity shock can then be computed using integration over corresponding area under the normal distribution, and the efficiency index $e(z, s) = e^{z_a + \overline{y}_a}$, where s represents an agent's age and $\overline{y}_a$ is the mean log-normal income of s-aged workers. Given equilibrium wage w_t defined below, effective tax rate τ and exogenous labour supply n, the total annual salary I can then be calculated as:

$$I_{s,z,t} = (1 - \tau)\, e(z, s)\, w_t\, n. \tag{4.11}$$

Following Huggett (1996), distribution of agents' initial income follows a log-normal distribution calibrated so that, while the overall wealth distribution is simplified and does not correspond to reality, the resulting wealth Gini coefficient is close to that of the US. We assume that the individual's productivity and earnings change over time, following the age–productivity profile reported by Hanse (1993). We assume that individuals may belong to any income class despite their education and that the change in school starting time -– and the number of graduates — increases the aggregate productivity and wage levels rather than alters the wage distribution profile, adding more individuals in the higher income classes. This is principally due to the lack of detailed data on wage distribution of individuals per educational attainment level. Note that the shift in productivity differs by gender, ethnicity, state, and age, shifting the entire age–productivity profile.

Agents are assumed to be rational and to optimise their utility over life cycle using a standard utility function common to all households:

$$U(s, z) = \mathbb{E}_s \left[\sum_{j=s}^{T+T^R} \pi_{j,t} \frac{c(j, z_j)^{1-1/\sigma_u}}{(1 - 1/\sigma_u)(1 + \rho)^{j-s}} \right], \tag{4.12}$$

where $c(j, z_j)$ is consumption at age j, conditional on being in income group z_j at that age, σ_u is the intertemporal elasticity of substitution, $\pi_{j,t}$ represents probability of surviving additional year at age j, and ρ is the discount factor.

Agents maximise lifetime utility subject to a dynamic lifetime budget constraint consisting of labour income $I_{a,z,t}$ (if working), pension transfers $p_{s,z,t}$ (if retired), and interest payments from one-year bond holdings earning risk-free equilibrium interest rate r_t. The budget constraints are therefore given by:

$$A_{s+1,z,t+1} = A_{s,z,t}\,(1 + r_{t+1}) + I_{s,z,t} - c(s, z) - A_{s,z,t} \tag{4.13}$$

for workers and

$$A_{s+1,z,t+1} = A_{s,z,t}\,(1 + r_{t+1}) + p_{s,z,t} - c(s, z) \tag{4.14}$$

for pensioners. Additionally, $A_{s+1,z,t+1} = 0$ for $s = T + T^R$, i.e. households consume all their remaining wealth in the last period of their lives.

Firms and government

Firms produce output using effective labour N_t and capital K_t, which are hired at wage w_t and interest rate r_t, equal to the marginal product of labour and capital, respectively, as determined within the competitive equilibrium framework. Capital also depreciates at rate δ. Production is characterised by constant returns to scale and we assume the standard neoclassical Cobb–Douglas production function in form of:

$$Y_t = F(\Omega_t, K_t, N_t) = \Omega^{t-1} K_t^{\alpha} N_t^{1-\alpha} \tag{4.15}$$

$$w_t = \frac{(1-\alpha)}{1+\tau}\,\Omega^{t-1} K_t^{\alpha}\, N_t^{-\alpha} \tag{4.16}$$

$$r_t = \alpha\, \Omega^{t-1} K_t^{\alpha-1}\, N_t^{1-\alpha} - \delta \tag{4.17}$$

where Ω denotes a scaling constant representing technological advancement (multifactor productivity growth) and $\alpha \in (0, 1)$ is the output share of capital in the production. Given the lack of multifactor productivity level data at the state level, we use the real GDP growth per state, multiplied by the ratio of multifactor productivity growth and real GDP growth at the aggregate US level, as a proxy. The model assumes no inflation and all predicted changes to GDP are therefore in real terms.

The total factor productivity growth is assumed to be constant in all years; while not particularly realistic due to existence of business cycles and other external and internal disturbances, the constant value fits purposes of this study as we are mainly interested in output differences between the status quo and an optimal scenario. Arguably, lower labour productivity and output would also slightly diminish the total factor productivity growth in the long term; hence, our estimates are conservative as the potential difference would have been bigger in case of lower productivity growth in the status quo scenario.

The government has no active role in the economy and only collects taxes from individuals in exchange for future unilateral pension transfers set at the current average retirement income reported by US Census Bureau (2015). For simplicity, we assume that the taxes and pension system repayment rates (i.e. the ratio of retirement benefit to the average wage) remain constant over time as these have effectively no effect on our analysis. The set of equations governing the model equilibrium and the simulation technique follows Stepanek (2019).

4.2.3 Calibration

The model is calibrated as follows. The exogenous labour supply calibrated using data on average annual hours worked, capital-labour ratio α, and capital stock depreciation rate δ come from the Penn World Tables (Feenstra et al., 2015); intertemporal elasticity of substitution data is obtained from Havranek et al. (2015); and historical performance of the US economy is based on data from US Bureau of Economic Analysis (2016). Following Zodrow et al. (2013), rate of time preference ρ is set equal to 0.011; variance of earnings for a newborn generation is set as $\sigma_{y1} = 0.38$ and the path dependency parameter ζ is set to 0.96 as in Huggett (1996). The state-specific income tax rates are set to their real-world levels. The population projections and probability of death follows the demographic modelling presented above. The parameter values are presented in Table 4.3. The graduation rates are then reported in Table 4.4.

Since a shift in SST to 8:30 a.m. would likely come at a cost, e.g. due to a change in the bus system from a three-tier to a one- or two-tier system, we present the model findings also in form of a benefit-cost analysis. We follow the prior estimates of Jacob and Rockoff (2011) and consider a cost estimate of \$150 per student per year ('Normal' scenario), as well as three arbitrary higher estimates of \$350 ('High' scenario), \$500 ('Very high' scenario) and \$700 (not reported in the figures and tables) to document a full range of possible outcomes, which would in reality depend on the local circumstances of each state or school district.[7] We assume that the cost per student will occur in perpetuity after the policy shift to 8:30 a.m. SST; this is likely overestimating the actual costs as the majority of the costs would likely accrue at the beginning of the policy shift in the form of upfront investments for new bus routes. Finally, following Jacob and Rockoff (2011), we also assume one alternative scenario for each cost scenario above in which each school needs to make an upfront investment of \$110,000 ('Normal' scenario), \$220,000 ('High' scenario) and \$330,000 ('Very high' scenario) to infrastructure (e.g. additional lighting equipment) in the \$150, \$350 and \$500 recurring cost scenario, respectively.

4.3 Results

In what follows, we present the projected cumulative gains of postponing school starting times for middle and high school students in present-day values (2016 \$ figures) aggregated across all 47 states, followed by a breakdown of the benefits by student, comparison against the potential costs per student, and the overall benefit–cost ratios by state.

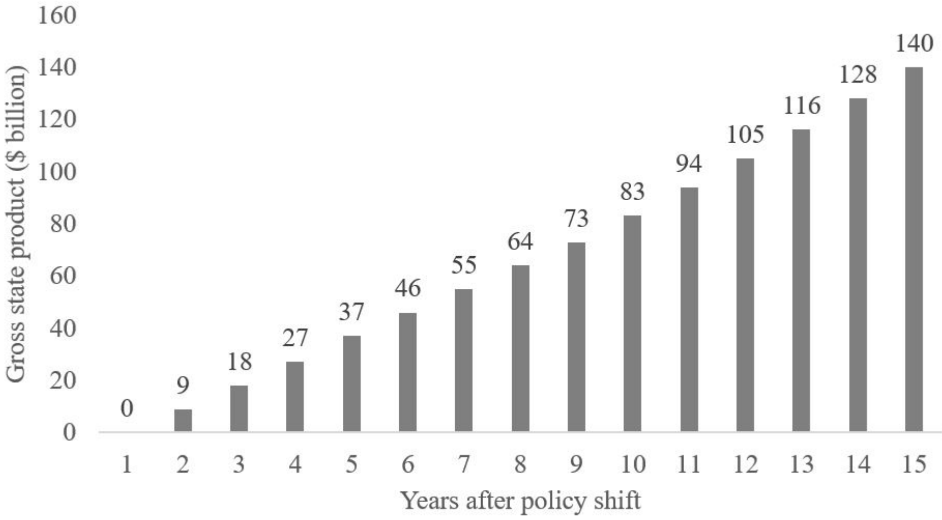
4.3.1 Predicted cumulative gains and benefit–cost ratios across the US

Figure 4.1 depicts the cumulative economic gains from delayed SST in present-day value across the 47 US states included in the analysis. The economic gains are displayed as higher levels of economic output that would occur if SST would be delayed compared to the status quo. Economic output is measured as gross state product (GSP). The state-level results are then presented in 4.1 and discussed further in the next subsection.

In the first year of the shift to 8:30 a.m. SST, the model projects no immediate economic gain, given that the first cohort of students graduating from high school is only experiencing one-year of change in the SST policy before graduation. However, as more students will benefit over time from the delayed SST as they enter the labour market, the gains are increasing over time. For instance, after year two of the policy shift, the model projects an economic gain of

[7] While it is difficult to precisely model the cost implications of other factors such as increased stress on family and home life, we assume that the additional higher cost estimates applied in the model would cover some of these potential costs. In addition, it is assumed in the model that a delay in SST would not affect parent's labour supply as that there is no strong evidence in the literature suggesting that a delay of roughly 30 minutes to 60 minutes would induce parents of 6 to 12 grades to alter their hours of work or stop working altogether.

Figure 4.1: Projected cumulative economic gains.



Note: The projected discounted cumulative gains of delayed SST to 8:30 a.m. aggregated across 47 US states since the change of policy (from one to fifteen years).

about $8.6 billion which represents about 0.04% of total US Gross Domestic Product (GDP). After five years, the economic gain increases to about $37 billion, and to $83 billion and about $140 billion after 10 and 15 years, respectively.

Furthermore, Figure 4.2 reports the average benefit–cost ratio per student across the 47 US states using the four different cost estimates. Under the assumption that the costs per student are $150, the benefits are predicted to outweigh the costs per student after about 2 years of delaying SST to 8:30 a.m. After 13 years, the benefit–cost ratio would reach 3:1 and continue to increase annually, reaching 4:1 after 20 years. Assuming a higher cost of $350 per student per year, a universal state-wide delay in SST is projected to outweigh the cost after 7 years. Remarkably, assuming a high cost of $500, the break-even point would be 16 years. Even when assuming a high cost of $700 per student per year, the economic benefits of delaying SST would outweigh the cost per student after 25 years.

4.3.2 Variation across states: Gains per student and benefit–cost ratios

The findings presented thus far represent average figures across the 47 US states, but a state-by-state analysis reveals significant regional variation in the effects, as presented in Table 4.1, which shows the total projected gains by state.

For instance, in Alabama, the economic gain per student (reported as a benefit-cost ratio in Table 4.2) after 2 years is estimated to be about $31 per student. This is significantly lower than the average of $346 per student across the 47 states. Other states with relatively low gains per student are Arkansas, Idaho and Mississippi (between $177 and $190). On the other hand, states such as Delaware and Massachusetts would proportionally gain more than $700 per student after 2 years. Other states with relatively large gains per student are Connecticut, New Jersey, Ohio, Rode Island and Virginia. Note that the difference is mainly driven by variation in

Table 4.1: Projected cumulative economic gain by state ($ million)

	Years after policy change									
	2 years		5 years		10 years		15 years		20 years	
State	**$**	**%**	**$**	**%**	**$**	**%**	**$**	**%**	**$**	**%**
Alabama	11	0.0%	85	0.0%	328	0.2%	764	0.4%	1,277	0.6%
Arizona	189	0.1%	758	0.3%	1,683	0.6%	2,753	1.0%	3,855	1.3%
Arkansas	55	0.1%	264	0.2%	557	0.5%	978	0.8%	1,421	1.2%
California	1,106	0.0%	4,482	0.2%	10,229	0.4%	17,229	0.7%	24,849	1.0%
Colorado	155	0.1%	632	0.2%	1,516	0.5%	2,718	0.9%	3,960	1.3%
Connecticut	135	0.1%	574	0.2%	1,350	0.5%	2,304	0.9%	3,286	1.3%
Delaware	46	0.1%	193	0.3%	456	0.7%	773	1.1%	1,088	1.6%
Florida	641	0.1%	2,507	0.3%	5,544	0.6%	9,174	1.0%	12,858	1.5%
Georgia	257	0.1%	1,049	0.2%	2,373	0.5%	3,924	0.8%	5,572	1.1%
Hawaii	39	0.1%	186	0.2%	380	0.5%	613	0.8%	865	1.1%
Idaho	28	0.0%	115	0.2%	263	0.4%	440	0.7%	635	1.0%
Illinois	261	0.0%	1,091	0.1%	2,559	0.3%	4,535	0.6%	6,753	0.9%
Indiana	153	0.1%	712	0.2%	1,579	0.5%	2,849	0.9%	4,170	1.2%
Iowa	98	0.1%	405	0.2%	917	0.5%	1,433	0.8%	1,988	1.1%
Kansas	59	0.0%	302	0.2%	636	0.4%	1,064	0.7%	1,530	1.0%
Kentucky	94	0.1%	516	0.3%	1,089	0.6%	1,760	0.9%	2,452	1.3%
Louisiana	120	0.1%	501	0.2%	1,176	0.5%	2,029	0.9%	2,917	1.2%
Maine	29	0.1%	121	0.2%	288	0.5%	494	0.9%	708	1.2%
Massachusetts	371	0.1%	1,419	0.3%	2,990	0.6%	4,769	1.0%	6,606	1.4%
Michigan	295	0.1%	1,218	0.3%	2,894	0.6%	4,794	1.0%	6,728	1.4%
Minnesota	188	0.1%	753	0.2%	1,772	0.5%	2,960	0.9%	4,200	1.3%
Mississippi	48	0.1%	233	0.2%	502	0.5%	846	0.8%	1,211	1.1%
Missouri	181	0.1%	740	0.3%	1,750	0.6%	3,115	1.1%	4,488	1.5%
Montana	26	0.1%	107	0.2%	229	0.5%	363	0.8%	505	1.1%
Nebraska	39	0.0%	164	0.2%	379	0.3%	654	0.6%	965	0.9%
Nevada	53	0.0%	219	0.2%	524	0.4%	919	0.7%	1,351	1.0%
New Hampshire	33	0.0%	156	0.2%	362	0.5%	628	0.9%	905	1.2%
New Jersey	385	0.1%	1,541	0.3%	3,568	0.6%	5,920	1.0%	8,297	1.5%
New Mexico	56	0.1%	222	0.2%	493	0.5%	786	0.8%	1,091	1.2%
New York	493	0.0%	2,077	0.2%	4,960	0.4%	8,847	0.6%	13,130	0.9%
North Carolina	263	0.1%	1,084	0.2%	2,469	0.5%	4,157	0.8%	5,926	1.2%
Ohio	435	0.1%	1,746	0.3%	3,724	0.6%	6,010	1.0%	8,360	1.4%
Oklahoma	104	0.1%	410	0.2%	914	0.5%	1,504	0.8%	2,132	1.2%
Oregon	83	0.0%	338	0.2%	778	0.4%	1,356	0.6%	1,999	0.9%
Pennsylvania	276	0.0%	1,213	0.2%	2,990	0.4%	5,387	0.8%	7,908	1.1%
Rhode Island	36	0.1%	164	0.3%	364	0.7%	592	1.1%	821	1.5%
South Carolina	130	0.1%	567	0.3%	1,254	0.6%	1,951	1.0%	2,677	1.3%
South Dakota	23	0.1%	101	0.2%	214	0.5%	346	0.7%	490	1.0%
Tennessee	120	0.0%	515	0.2%	1,219	0.4%	2,131	0.7%	3,122	1.0%
Texas	851	0.1%	3,412	0.2%	7,686	0.5%	12,835	0.8%	18,307	1.1%
Utah	68	0.1%	277	0.2%	691	0.5%	1,175	0.8%	1,679	1.1%
Vermont	17	0.1%	70	0.2%	159	0.5%	270	0.9%	385	1.3%
Virginia	330	0.1%	1,182	0.3%	2,650	0.6%	4,277	0.9%	5,975	1.2%
Washington	264	0.1%	1,214	0.3%	2,518	0.6%	4,031	0.9%	5,608	1.3%
West Virginia	38	0.1%	155	0.2%	362	0.5%	610	0.8%	871	1.2%
Wisconsin	152	0.1%	634	0.2%	1,511	0.5%	2,552	0.8%	3,642	1.2%
Wyoming	23	0.1%	99	0.3%	225	0.6%	378	1.0%	535	1.3%

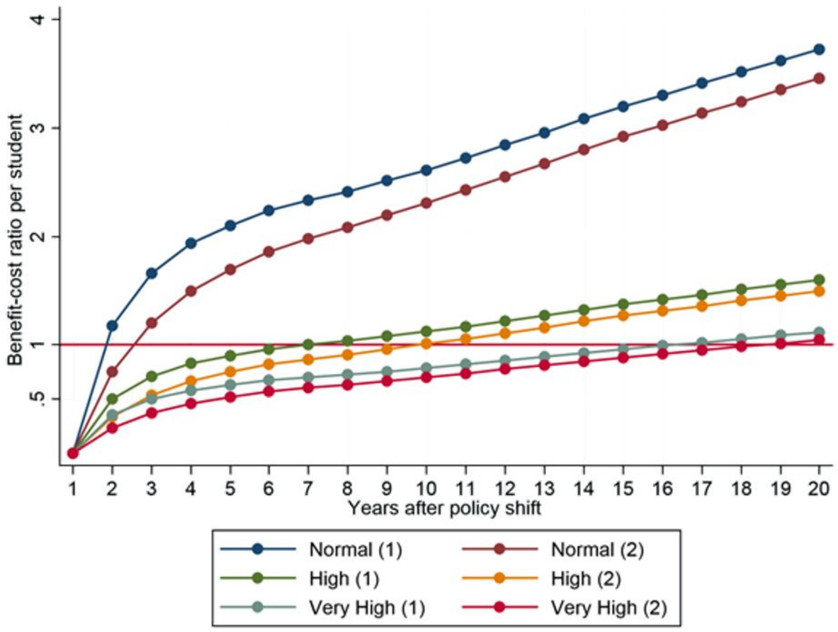
Notes: The table reports the predicted discounted cumulative economic gains ($ million GSP) of of delayed SST to 8:30 a.m. across all 47 U.S. states that would occur in years after the policy change, compared to status quo.

Table 4.2: Projected benefit–cost ratios by state ('Normal' cost scenario)

	Years after policy change									
	2 years		5 years		10 years		15 years		20 years	
State	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**
Alabama	0.1	0.1	0.4	0.3	0.8	0.7	1.3	1.2	1.8	1.6
Arizona	1.3	0.8	2.2	1.7	2.6	2.3	3.1	2.9	3.6	3.3
Arkansas	0.7	0.4	1.3	1.1	1.5	1.3	1.9	1.8	2.3	2.1
California	1.1	0.7	2.0	1.6	2.5	2.2	3.0	2.7	3.6	3.3
Colorado	1.0	0.6	1.7	1.4	2.3	2.0	3.0	2.7	3.5	3.3
Connecticut	1.8	1.1	3.2	2.6	4.1	3.6	5.1	4.7	6.0	5.5
Delaware	2.5	1.6	4.4	3.6	5.7	5.1	7.1	6.5	8.2	7.6
Florida	1.6	1.0	2.6	2.1	3.1	2.8	3.8	3.4	4.3	4.0
Georgia	0.9	0.6	1.6	1.3	2.0	1.7	2.4	2.2	2.8	2.6
Hawaii	1.6	1.0	3.3	2.7	3.7	3.3	4.4	4.0	5.0	4.7
Idaho	0.6	0.4	1.1	0.9	1.3	1.2	1.6	1.5	1.9	1.8
Illinois	0.9	0.6	1.6	1.3	2.0	1.8	2.6	2.4	3.2	2.9
Indiana	0.9	0.6	1.8	1.5	2.2	2.0	2.9	2.7	3.5	3.3
Iowa	1.3	0.9	2.3	1.9	2.9	2.6	3.3	3.0	3.8	3.5
Kansas	1.0	0.6	2.1	1.7	2.5	2.2	3.0	2.7	3.5	3.3
Kentucky	0.9	0.6	2.1	1.7	2.4	2.1	2.8	2.6	3.2	3.0
Louisiana	1.3	0.8	2.3	1.8	2.9	2.6	3.7	3.4	4.4	4.0
Maine	0.9	0.6	1.7	1.3	2.2	1.9	2.7	2.5	3.2	3.0
Massachusetts	2.4	1.5	3.9	3.1	4.5	4.0	5.2	4.8	5.9	5.5
Michigan	1.1	0.7	2.0	1.6	2.6	2.3	3.1	2.8	3.6	3.3
Minnesota	1.2	0.8	2.1	1.7	2.7	2.4	3.3	3.0	3.8	3.5
Mississippi	0.6	0.4	1.2	1.0	1.5	1.3	1.8	1.6	2.1	2.0
Missouri	1.2	0.7	2.0	1.6	2.6	2.3	3.4	3.1	4.0	3.7
Montana	1.2	0.7	2.0	1.6	2.3	2.1	2.7	2.5	3.1	2.8
Nebraska	0.9	0.6	1.6	1.3	2.0	1.8	2.5	2.3	3.0	2.8
Nevada	0.7	0.4	1.1	0.9	1.5	1.3	1.9	1.8	2.3	2.1
New Hampshire	1.0	0.6	1.9	1.6	2.5	2.2	3.1	2.9	3.7	3.4
New Jersey	1.9	1.2	3.2	2.6	4.0	3.6	4.9	4.5	5.6	5.2
New Mexico	1.3	0.8	2.1	1.7	2.6	2.3	3.0	2.7	3.4	3.2
New York	1.0	0.6	1.8	1.5	2.4	2.1	3.1	2.8	3.7	3.4
North Carolina	1.2	0.7	2.0	1.6	2.5	2.3	3.1	2.9	3.6	3.4
Ohio	1.4	0.9	2.4	1.9	2.8	2.5	3.3	3.0	3.7	3.5
Oklahoma	1.0	0.6	1.7	1.3	2.0	1.8	2.4	2.2	2.8	2.6
Oregon	1.0	0.6	1.7	1.4	2.2	1.9	2.8	2.5	3.3	3.1
Pennsylvania	0.9	0.6	1.8	1.4	2.4	2.1	3.1	2.8	3.7	3.5
Rhode Island	1.8	1.2	3.5	2.8	4.2	3.7	5.0	4.6	5.7	5.3
South Carolina	1.1	0.7	2.0	1.6	2.4	2.1	2.7	2.5	3.1	2.9
South Dakota	1.0	0.6	1.9	1.5	2.2	1.9	2.6	2.3	3.0	2.8
Tennessee	0.8	0.5	1.4	1.1	1.8	1.6	2.3	2.1	2.8	2.6
Texas	1.1	0.7	1.9	1.6	2.4	2.1	2.9	2.6	3.4	3.1
Utah	0.8	0.5	1.3	1.1	1.8	1.6	2.3	2.1	2.7	2.5
Vermont	1.2	0.8	2.2	1.8	2.7	2.4	3.4	3.1	4.0	3.7
Virginia	2.0	1.3	3.1	2.5	3.8	3.3	4.4	4.1	5.1	4.7
Washington	1.7	1.1	3.3	2.7	3.8	3.3	4.4	4.0	5.0	4.7
West Virginia	0.8	0.5	1.4	1.1	1.8	1.6	2.2	2.0	2.6	2.4
Wisconsin	1.2	0.8	2.2	1.7	2.8	2.5	3.5	3.2	4.1	3.8
Wyoming	1.6	1.0	2.9	2.3	3.6	3.1	4.4	4.0	5.1	4.7
Average	**1.2**	**0.8**	**2.1**	**1.7**	**2.6**	**2.3**	**3.2**	**2.9**	**3.7**	**3.5**

Notes: Column (1) assumes cost of $150 per student per year and column (2) assumes that in addition to the $150 per student per year, each school has to invest $110,000 upfront for updates in school infrastructure related to after-school activities (e.g. update of lighting equipment).

Figure 4.2: Projected average benefit–cost ratios.



Note: The figure plots the projected benefit–cost ratios of delayed SST to 8:30 a.m. across 47 U.S states after the change of policy. The 'Normal', 'High' and 'Very high' scenarios represent \$150, \$350 and \$500 annual cost per student, either alone (1) or in combination with an upfront investment cost of \$110,000, \$220,000 and \$330,000, respectively (2).

the state-wide initial average SST and underlying economic factors which also vary significantly by state (e.g. the industrial composition or average productivity levels).

Table 4.2 reports the detailed benefit–cost ratios by state assuming the cost per student to implement the delayed SST to 8:30 a.m. would be \$150 per student per year. The findings suggest that with the exception of Alabama, in every other state, the economic benefits for delaying SST would outweigh the costs within 5 years after the change. The predicted benefit–cost ratio after five years varies from 0.4 (Alabama) to 4.4 (Delaware). Even after two years, a majority of states are predicted to reach a benefit–cost ratio of at least 1:1, meaning that for every \$1 spent, there is a \$1 return on investment. The ratios are lower in the alternative scenario with an upfront infrastructure investment of \$110,000, but progressively converge to the baseline scenario results over time. The analogous tables for the 'High' (\$350 recurring and \$220,000 one-off cost; Table 4.6) and 'Very high' (\$500 recurring and \$330,000 one-off cost; Table 4.7) scenarios are reported in the Appendix.

4.4 Discussion

This study aims to measure the economic gains associated with delaying school start times in states across the US to 8:30 a.m. and thus contribute to the debate around the costs and potential benefits of tackling the issue of insufficient sleep worldwide. The channels of effect in this study are twofold: car crashes mortality and impaired academic performance. That is, the analysis assumes that later SST would result in few car accidents and hence lower mortality rates (and consequently higher labour supply) and better academic performance leading to higher human capital accumulation in the economy. Overall, the analysis considers only parameters with a robust empirical evidence from the prior literature concerning the impact of sleep loss on affects adolescents' health and academic performance; the resulting estimates should therefore be considered lower-bound estimates, as there are likely other, yet not fully observed negative impacts of insufficient sleep on the economy, such as the effects on mental health, including depression and suicide attempts, or higher probability of being obese.

On the cost side, this study uses a previous estimate of $150 per student per year but also uses higher cost estimates to assess the effectiveness of the policy change at a broader range of costs. Furthermore, beyond the assumed increased transportation costs, it is possible that there could be other costs which are not included in our model calculations, such as the costs of having to reschedule afterschool activities. Nevertheless, even if higher cost estimates (e.g. $500 per student per year) are applied, which likely would cover some of these additional costs to parents and the wider society, the benefits from delaying SST are still projected to outweigh the costs after just fifteen years. Indeed, in conjunction with the previous studies showing the widespread consequences of adolescent sleep loss on health, safety, and academic performance (Mitchell et al., 2013; Magee and Hale, 2012; Owens et al., 2014; Troxel et al., 2015; Umlauf et al., 2011; Vorona et al., 2014; Wheaton et al., 2016) these benefit–cost projections suggest that delaying school start times is a cost-effective population-level strategy which could have a significant impact on public health and the US economy.

These findings must be interpreted within the constraints of the study and the specific modelling approach. First, our model is a hypothetical experiment that presupposes a state-wide universal shift in school start times to 8:30 a.m. or later. This presupposition may seem unjustified given that start times are generally determined at the local district level. However, there are several examples of proposed policy initiatives in states across the country, including a bill in California that mandates that California middle and high school start no earlier than 8:30 a.m. (Myers, John, 2017). Thus, the hypothetical policy shift modelled in the current analysis is potentially a conceivable strategy. Second, we focused on the cost-benefits of later SST for the 47 states for which there was available data from the CDC on SST and the average start time was before 8:30 am, and therefore do not have estimates for Maryland, District of Columbia, North Dakota, and Alaska. Third, the specific modelling approach taken in this study is in part based on the assumptions that may influence the modelling outcome. It is important to emphasise that whenever an assumption had to be made, we aimed to make sure that the specific assumption would be conservative, hence leading to a potential underestimation of the potential true effect.

Finally, as mentioned, our model focuses on two specific factors that drive costs: the impact of sleep insufficiency on motor vehicle crashes/mortality and academic achievement/high school graduation rates. These factors were chosen because we were able to collect and derive robust estimates from the literature. However, as mentioned, there are numerous other costs associated with mental and physical morbidity that were not included in our model. For instance, the combined public health costs of the obesity epidemic in children and adolescents and its associated cardiovascular morbidities are estimated at $45 billion a year, and sleep loss is longitudinally associated with increased risk of obesity in children and adolescents (Magee and Hale, 2012). Further, insufficient sleep among teens is associated with an increased risk of engaging in property and violent crime (Umlauf et al., 2011). The direct and indirect costs of crime, including direct economic losses, increased insurance rates, loss of productivity, and various aspects of the criminal justice system, from police, to courts, to juvenile facilities and prisons are estimated in the billions of dollars (US Department of Justice, 2000). In addition, the association between insufficient sleep and adolescent risk for mental health problems and other risk-taking behaviours, including substance use, could also contribute to substantial societal costs. The findings thus provide a strong case to counter the argument that changing school start times is too costly to endeavour a change. Policymakers, educators, and community members should shift from the narrow and often short-sighted focus on the costs of shifting to healthy start times to a focus on the significant benefits associated with later SST, including demonstrable long-term public health and economic benefits.

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Appendix

Table 4.3: Model calibration parameters

Parameter	**Symbol**	**Value**	**Source**
Share of students sleeping <7 hours/night	-	0.6000	Keyes et al. (2015)
Average baseline amount of sleep	-	6.1200	McKnight-Eily et al. (2011)
Average annual hours worked	-	1,765.0	Feenstra et al. (2015)
Capital–labour ratio	α	0.6036	Feenstra et al. (2015)
Capital stock depreciation rate	δ	0.0471	Feenstra et al. (2015)
Rate of time preference	ρ	0.0110	Zodrow et al. (2013)
Variance of earnings for $a = 1$	σ_{y_1}	0.3800	Huggett (1996)
Elasticity of intertemporal substitution	σ_u	0.5940	Havranek et al. (2015)
GDP; Gross State Product (GSP)	-	Various	US Bureau of Economic Analysis (2016)
Average real GDP growth rate (1997–2015)	-	Various	US Bureau of Economic Analysis (2016)
Productivity-real GDP ratio (1995–2014)	-	0.4361	OECD (2016)

Table 4.4: Graduation rates used in the model

Variable	**Granularity**	**Description**	**Source**
High school graduation rate (2014– 2015)	State, ethnicity	The share of students who graduate in 4 years with a regular high school diploma (as a percentage of all students in the class)	(1)
High school graduates (2015)	State/gender and ethnicity	Share of persons 25 to 29 years old with a regular high school diploma (as a percentage of the total population of that age)	(2)
University graduation rate (2013)	State, gender and ethnicity	Percentage of students who graduated within 150% of normal/expected time (as a share of all students in the program).	(3)
University graduates (2015)	State, gender and ethnicity	Share of persons with a bachelor's degree (as a percentage of the total population)	(2)

(1) National Center for Education Statistics (2016a)
(2) US Bureau of Economic Analysis (2016) and National Center for Education Statistics (2016b)
(3) The Chronicles of Higher Education (2016)

Table 4.5: School information and increase in sleep length by state

State	# schools	# students	Net increase in sleep length (mins)
Alabama	680	344,000	36
Arizona	860	506,000	24
Arkansas	450	292,000	23
California	3,880	3,303,000	22
Colorado	730	527,000	33
Connecticut	380	260,000	40
Delaware	90	63,000	44
Florida	1,570	1,406,000	26
Georgia	1,030	955,000	22
Hawaii	280	81,154	28
Idaho	370	157,000	18
Illinois	1,590	1,008,000	19
Indiana	740	559,000	28
Iowa	550	249,000	13
Kansas	540	204,000	24
Kentucky	710	358,000	25
Louisiana	630	316,000	48
Maine	240	105,000	34
Massachusetts	700	527,000	34
Michigan	1,540	891,000	33
Minnesota	1,100	522,000	16
Mississippi	570	272,000	40
Missouri	900	530,000	30
Montana	220	78,000	15
Nebraska	370	150,000	17
Nevada	260	276,000	33
New Hampshire	180	116,000	41
New Jersey	870	698,000	28
New Mexico	310	151,000	20
New York	2,070	1,670,000	27
North Carolina	1,120	768,000	25
Ohio	1,640	1,061,000	35
Oklahoma	700	356,000	17
Oregon	480	282,000	19
Pennsylvania	1,280	1,001,000	38
Rhode Island	100	68,000	37
South Carolina	500	411,000	25
South Dakota	230	78,000	15
Tennessee	760	533,000	29
Texas	3,940	2,556,000	22
Utah	410	297,000	22
Vermont	100	46,000	25
Virginia	850	555,000	26
Washington	930	526,000	23
West Virginia	300	160,000	31
Wisconsin	860	423,000	29
Wyoming	130	50,000	27

Source: Wheaton et al. (2015) and authors' calculations.
Note: Net increase in average sleep time calculated using proportions schools in 3 start time intervals (before 7:30 a.m.; 7:30-8:00 a.m. and 8:00-8:30 a.m. Information on for Hawaii obtained directly from Hawaii State Department of Education.

Table 4.6: Projected benefit–cost ratios by state ('High' cost scenario)

	Years after policy change									
	2 years		5 years		10 years		15 years		20 years	
State	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**
Alabama	0.1	0.0	0.2	0.1	0.3	0.3	0.6	0.5	0.8	0.7
Arizona	0.5	0.4	0.9	0.8	1.1	1.0	1.3	1.2	1.5	1.4
Arkansas	0.3	0.2	0.6	0.5	0.7	0.6	0.8	0.8	1.0	0.9
California	0.5	0.3	0.8	0.7	1.1	0.9	1.3	1.2	1.5	1.4
Colorado	0.4	0.3	0.7	0.6	1.0	0.9	1.3	1.2	1.5	1.4
Connecticut	0.8	0.5	1.4	1.1	1.8	1.6	2.2	2.0	2.6	2.4
Delaware	1.1	0.7	1.9	1.6	2.5	2.2	3.0	2.8	3.5	3.3
Florida	0.7	0.5	1.1	0.9	1.3	1.2	1.6	1.5	1.9	1.7
Georgia	0.4	0.3	0.7	0.6	0.8	0.8	1.0	0.9	1.2	1.1
Hawaii	0.7	0.5	1.4	1.2	1.6	1.4	1.9	1.7	2.2	2.0
Idaho	0.3	0.2	0.5	0.4	0.6	0.5	0.7	0.6	0.8	0.8
Illinois	0.4	0.3	0.7	0.6	0.9	0.8	1.1	1.0	1.4	1.3
Indiana	0.4	0.3	0.8	0.7	1.0	0.9	1.3	1.2	1.5	1.4
Iowa	0.6	0.4	1.0	0.8	1.3	1.1	1.4	1.3	1.6	1.5
Kansas	0.4	0.3	0.9	0.8	1.1	1.0	1.3	1.2	1.5	1.4
Kentucky	0.4	0.3	0.9	0.7	1.0	0.9	1.2	1.1	1.4	1.3
Louisiana	0.6	0.4	1.0	0.8	1.3	1.1	1.6	1.5	1.9	1.8
Maine	0.4	0.3	0.7	0.6	0.9	0.8	1.2	1.1	1.4	1.3
Massachusetts	1.0	0.7	1.7	1.4	1.9	1.7	2.2	2.1	2.5	2.4
Michigan	0.5	0.3	0.8	0.7	1.1	1.0	1.3	1.2	1.5	1.4
Minnesota	0.5	0.4	0.9	0.7	1.2	1.0	1.4	1.3	1.6	1.5
Mississippi	0.3	0.2	0.5	0.4	0.6	0.6	0.8	0.7	0.9	0.8
Missouri	0.5	0.3	0.9	0.7	1.1	1.0	1.5	1.3	1.7	1.6
Montana	0.5	0.3	0.8	0.7	1.0	0.9	1.2	1.1	1.3	1.2
Nebraska	0.4	0.3	0.7	0.6	0.9	0.8	1.1	1.0	1.3	1.2
Nevada	0.3	0.2	0.5	0.4	0.6	0.6	0.8	0.8	1.0	1.0
New Hampshire	0.4	0.3	0.8	0.7	1.1	1.0	1.3	1.2	1.6	1.5
New Jersey	0.8	0.5	1.4	1.1	1.7	1.6	2.1	1.9	2.4	2.3
New Mexico	0.5	0.4	0.9	0.8	1.1	1.0	1.3	1.2	1.5	1.4
New York	0.4	0.3	0.8	0.6	1.0	0.9	1.3	1.2	1.6	1.5
North Carolina	0.5	0.3	0.9	0.7	1.1	1.0	1.3	1.2	1.6	1.5
Ohio	0.6	0.4	1.0	0.8	1.2	1.1	1.4	1.3	1.6	1.5
Oklahoma	0.4	0.3	0.7	0.6	0.9	0.8	1.0	1.0	1.2	1.1
Oregon	0.4	0.3	0.7	0.6	0.9	0.8	1.2	1.1	1.4	1.3
Pennsylvania	0.4	0.3	0.8	0.6	1.0	0.9	1.3	1.2	1.6	1.5
Rhode Island	0.8	0.5	1.5	1.2	1.8	1.6	2.2	2.0	2.4	2.3
South Carolina	0.5	0.3	0.9	0.7	1.0	0.9	1.2	1.1	1.3	1.2
South Dakota	0.4	0.3	0.8	0.7	0.9	0.8	1.1	1.0	1.3	1.2
Tennessee	0.3	0.2	0.6	0.5	0.8	0.7	1.0	0.9	1.2	1.1
Texas	0.5	0.3	0.8	0.7	1.0	0.9	1.2	1.2	1.5	1.4
Utah	0.3	0.2	0.6	0.5	0.8	0.7	1.0	0.9	1.1	1.1
Vermont	0.5	0.4	0.9	0.8	1.2	1.1	1.5	1.3	1.7	1.6
Virginia	0.9	0.6	1.3	1.1	1.6	1.5	1.9	1.8	2.2	2.0
Washington	0.7	0.5	1.4	1.2	1.6	1.5	1.9	1.8	2.2	2.0
West Virginia	0.3	0.2	0.6	0.5	0.8	0.7	0.9	0.9	1.1	1.0
Wisconsin	0.5	0.4	0.9	0.8	1.2	1.1	1.5	1.4	1.7	1.6
Wyoming	0.7	0.5	1.2	1.0	1.5	1.4	1.9	1.7	2.2	2.0
Average	**0.50**	**0.34**	**0.9**	**0.75**	**1.12**	**1.01**	**1.37**	**1.27**	**1.60**	**1.50**

Notes: Column (1) assumes cost of $350 per student per year and column (2) assumes in addition to the $350 per student per year, each school has to invest $220,000 upfront for updates in school infrastructure related to after-school activities (e.g. update of lighting equipment).

Table 4.7: Projected benefit–cost ratios by state ('Very high' cost scenario)

	Years after policy change									
	2 years		5 years		10 years		15 years		20 years	
State	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**	**(1)**	**(2)**
Alabama	0.0	0.0	0.1	0.1	0.2	0.2	0.4	0.4	0.5	0.5
Arizona	0.4	0.3	0.7	0.5	0.8	0.7	0.9	0.9	1.1	1.0
Arkansas	0.2	0.1	0.4	0.3	0.5	0.4	0.6	0.5	0.7	0.6
California	0.3	0.2	0.6	0.5	0.7	0.7	0.9	0.8	1.1	1.0
Colorado	0.3	0.2	0.5	0.4	0.7	0.6	0.9	0.8	1.1	1.0
Connecticut	0.5	0.4	1.0	0.8	1.2	1.1	1.5	1.4	1.8	1.7
Delaware	0.8	0.5	1.3	1.1	1.7	1.5	2.1	2.0	2.4	2.3
Florida	0.5	0.3	0.8	0.6	0.9	0.8	1.1	1.0	1.3	1.2
Georgia	0.3	0.2	0.5	0.4	0.6	0.5	0.7	0.7	0.8	0.8
Hawaii	0.5	0.3	1.0	0.8	1.1	1.0	1.3	1.2	1.5	1.4
Idaho	0.2	0.1	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.5
Illinois	0.3	0.2	0.5	0.4	0.6	0.5	0.8	0.7	1.0	0.9
Indiana	0.3	0.2	0.6	0.5	0.7	0.6	0.9	0.8	1.1	1.0
Iowa	0.4	0.3	0.7	0.6	0.9	0.8	1.0	0.9	1.1	1.1
Kansas	0.3	0.2	0.6	0.5	0.7	0.7	0.9	0.8	1.1	1.0
Kentucky	0.3	0.2	0.6	0.5	0.7	0.7	0.9	0.8	1.0	0.9
Louisiana	0.4	0.3	0.7	0.6	0.9	0.8	1.1	1.0	1.3	1.2
Maine	0.3	0.2	0.5	0.4	0.7	0.6	0.8	0.8	1.0	0.9
Massachusetts	0.7	0.5	1.2	1.0	1.4	1.2	1.6	1.4	1.8	1.7
Michigan	0.3	0.2	0.6	0.5	0.8	0.7	0.9	0.9	1.1	1.0
Minnesota	0.4	0.2	0.6	0.5	0.8	0.7	1.0	0.9	1.1	1.1
Mississippi	0.2	0.1	0.4	0.3	0.4	0.4	0.5	0.5	0.6	0.6
Missouri	0.4	0.2	0.6	0.5	0.8	0.7	1.0	0.9	1.2	1.1
Montana	0.3	0.2	0.6	0.5	0.7	0.6	0.8	0.7	0.9	0.9
Nebraska	0.3	0.2	0.5	0.4	0.6	0.5	0.8	0.7	0.9	0.9
Nevada	0.2	0.1	0.3	0.3	0.5	0.4	0.6	0.5	0.7	0.7
New Hampshire	0.3	0.2	0.6	0.5	0.7	0.7	0.9	0.9	1.1	1.0
New Jersey	0.6	0.4	1.0	0.8	1.2	1.1	1.5	1.4	1.7	1.6
New Mexico	0.4	0.3	0.6	0.5	0.8	0.7	0.9	0.8	1.0	1.0
New York	0.3	0.2	0.5	0.4	0.7	0.6	0.9	0.8	1.1	1.0
North Carolina	0.4	0.2	0.6	0.5	0.8	0.7	0.9	0.9	1.1	1.0
Ohio	0.4	0.3	0.7	0.6	0.8	0.7	1.0	0.9	1.1	1.0
Oklahoma	0.3	0.2	0.5	0.4	0.6	0.5	0.7	0.7	0.9	0.8
Oregon	0.3	0.2	0.5	0.4	0.7	0.6	0.8	0.8	1.0	0.9
Pennsylvania	0.3	0.2	0.5	0.4	0.7	0.6	0.9	0.9	1.1	1.0
Rhode Island	0.6	0.4	1.0	0.9	1.3	1.1	1.5	1.4	1.7	1.6
South Carolina	0.3	0.2	0.6	0.5	0.7	0.7	0.8	0.8	0.9	0.9
South Dakota	0.3	0.2	0.6	0.5	0.7	0.6	0.8	0.7	0.9	0.8
Tennessee	0.2	0.2	0.4	0.3	0.5	0.5	0.7	0.6	0.8	0.8
Texas	0.3	0.2	0.6	0.5	0.7	0.6	0.9	0.8	1.0	1.0
Utah	0.2	0.2	0.4	0.3	0.6	0.5	0.7	0.6	0.8	0.8
Vermont	0.4	0.3	0.7	0.5	0.8	0.7	1.0	0.9	1.2	1.1
Virginia	0.6	0.4	0.9	0.8	1.1	1.0	1.3	1.2	1.5	1.4
Washington	0.5	0.3	1.0	0.8	1.1	1.0	1.3	1.2	1.5	1.4
West Virginia	0.2	0.2	0.4	0.4	0.5	0.5	0.7	0.6	0.8	0.7
Wisconsin	0.4	0.2	0.7	0.5	0.9	0.8	1.0	1.0	1.2	1.1
Wyoming	0.5	0.3	0.9	0.7	1.1	1.0	1.3	1.2	1.5	1.4
Average	**0.35**	**0.23**	**0.63**	**0.52**	**0.78**	**0.70**	**0.96**	**0.88**	**1.12**	**1.05**

Notes: Column (1) assumes cost of $500 per student per year and column (2) assumes in addition to the $500 per student per year, each school has to invest $330,000 upfront for updates in school infrastructure related to after-school activities (e.g. update of lighting equipment).

Chapter 5

Individual, workplace, and combined effects modelling of employee productivity loss

Abstract[1]

This study investigates a wide range of influences on workplace productivity loss using data collected from 31,950 employees in the UK. Influences of employees' socioeconomic characteristics, lifestyle, commuting, physical and mental health, well-being, and job and workplace environment were assessed using structural equation models, allowing systematic decomposition of the complex network of influences and creating new, deeper insights. The results show that mental health, physical health, job characteristics and support from organisation are the most important (direct or indirect) determinants of employees' productivity and that 93% of the indirect influences are mediated through mental and/or physical health. Some influences that appear as strong predictors in simple models lose most of their explanatory power in more complex models with additional explanatory variables. The results suggest that there is a need for a more tailored strategy to improve employees' wellbeing as well as the overall organisational, work and management culture.

5.1 Introduction

Comprehension of employees' productivity and performance has been a goal of academics and organisations alike for decades. Initially, the major research focus was on *absenteeism*, generally defined as not showing up for work, due to its evident implications for performance of organisations and relative ease of measurement (Johns, 2010). However, more recently *presenteeism* has been gaining attention as it is suggested to cause higher aggregate productivity loss than absenteeism (see e.g. Collins et al., 2005, or Parsonage, 2007). Presenteeism is defined in different ways in the literature, most often as being at work with decreased performance, productivity and work quality due to a health problem or injury (Braakman-Jansen et al., 2011; Hutting et al., 2014).

[1]This study was published as: Stepanek, M., Jahanshahi, K., and Millard, F. (2019). Individual, Workplace, and Combined Effects Modeling of Employee Productivity Loss. *Journal of Occupational and Environmental Health Medicine*, 64(6).

A multitude of absenteeism- and presenteeism-related factors has been suggested and empirically tested as determinants of productivity loss, including physical and mental health (Alonso et al., 2011; Zelenski et al., 2008), lifestyle (Wolf et al., 2009), personal and family factors (Johns, 2011), relationships (Hansen and Andersen, 2008), work strain (Darr and Johns, 2008) or job and workplace characteristics (Kuoppala et al., 2008). However, the studies so far have considered a narrow pathway of effects and have largely overlooked interrelations between influences. Moreover, limiting analysis to a small set of variables may conflate various separate, though often correlated, effects and hence fail to capture the main underlying explanations.

The present study aims to shed a light on this research gap through simultaneous analysis of an extensive set of workplace productivity factors. We utilise a unique, extensive cross-sectional dataset covering 31,950 employees across the United Kingdom collected through the Britain's Healthiest Workplace, an annual online survey of organisations and their employees in the UK, in 2017 (see Section 5.3.2 for more information). Self-reported productivity, measured by the Work Productivity and Activity Impairment Questionnaire (Reilly et al., 1993) is used as the outcome variable; the determinants are evaluated using an advanced structural equation model (SEM), which combines the direct and indirect influences (e.g., path analysis) with factor analysis – a technique to reduce the dimensionality of highly correlated variables into lower dimensional latent space.

More specifically, in line with previous studies, we first develop separate models with a limited number of variables to evaluate productivity, each emphasising a different angle of either personal, job-related or workplace influences. The results, which are shown to be in line with the findings from the prior studies, allow us to assess the baseline influences. Second, we conflate all partial models to form a combined SEM framework in order to evaluate the most important influences and their path structure. Additionally, comparing the partial and combined models helps to make inference on the extent to which narrow-focused partial models are affected by the omitted-variable bias.

Given our limited control over workers' participation in the underlying survey, our results may be affected by a self-selection bias despite the large size of our dataset. In order to provide evidence that this is not a particular issue, we compared characteristics of the survey respondents to a representative sample of the working population in the UK using data from the Health Survey for England (UK Government Statistical Service, 2016) across a multitude of variables, including age, gender, ethnicity and bmi. The results, presented in Tables 5.3 and 5.4 in the Appendix, show that both samples are similar in their characteristics and estimated influences are directionally equivalent. Further information on this and other potential limitations is provided in Section 5.5.2.

5.2 Existing research

Employee productivity at the workplace is a measure encompassing both efficiency (time or other resources required for completing a task) and effectiveness (the degree to which objectives are achieved and/or targeted problems are solved). Research focus is often on relative productivity loss, e.g. a comparison of an individual's performance to an optimal or past performance levels or to that of other employees (see e.g. Anitha, 2014; Ford et al., 2011). Our study follows this direction and analyses self-reported productivity loss compared to an optimal state. One common way to evaluate productivity loss is through absenteeism and presenteeism (e.g., the share of time that an employee did not work or worked with a limited efficiency when compared to their contract or expectations). Below we discuss the most common individual and organisational factors associated with absenteeism and presenteeism.

Lifestyle, physical and mental well-being

Health assessment includes factors such as diseases, biometric indicators, life satisfaction, anxiety, depression or fatigue, and is substantially affected by one's lifestyle (e.g., physical activity, nutrition, alcohol use, smoking, sleeping patterns or other wellness behaviours) (World Health Organization, 1946). On the other hand, one's lifestyle depends on his or her health; this inherently creates two layers of effects in which both health and lifestyle affect productivity but also each other.

Some of the studies showing the negative effects of poor physical health include Gates et al. (2008) and Lal et al. (2012) who analyse obesity; Hex et al. (2012) and Tunceli et al. (2005) who look specifically at individuals with diabetes; or Hedge and Ray (2004) and Martimo et al. (2009) who target musculoskeletal conditions. Similarly, a number of mental health indicators have been used as productivity determinants. For instance, Merrill et al. (2012) show the importance of personal problems, financial concerns and depression, while Boles et al. (2004), Tarafdar et al. (2007) and Zelenski et al. (2008) found a positive correlation between indicators of happiness and productivity. Finally, lifestyle indicators have then been evaluated (e.g., see Brown et al., 2011, who look at physical activity and psycho-social health; Bouchery et al. (2011) and Frone (2006), who look at the burden of alcohol consumption; or Hafner et al. (2016) and Rosekind et al. (2010), who estimate the impact of insufficient sleep). All of the risk factors have been shown to have statistically significant effect on productivity.

Job attitude and characteristics

Job attitude is a set of feelings toward, beliefs about, and attachment to one's job. Research shows that it is mainly determined by job characteristics (Jex and Britt, 2014), yet it may also be affected by a worker's characteristics or emotional moods (Judge and Kammeyer-Mueller, 2012). The determinants of job attitudes have been studied e.g. by Akhtar et al. (2015), Bakker et al. (2007) and Hakanen et al. (2005). Moreover, job characteristics may also have an impact on lifestyle, as well as physical and mental health, in turn affecting productivity indirectly and highlighting the need to be considered simultaneously.

Job attitude can be measured by job satisfaction or employee engagement. Work engagement has received particular attention in the empirical literature (e.g., Anitha, 2014, Demerouti and Cropanzano, 2010, Rongen et al., 2014, Salanova et al., 2005, Xanthopoulou et al., 2009) and has been shown to have strong causal influence on workplace productivity. However, as we discuss further in our study, this may be partially due to omission of other relevant factors in the analysis. The strong influence of job satisfaction and other job characteristics, such as work-related stress, on productivity has been shown by e.g. AbuAlRub (2004), Judge and Kammeyer-Mueller (2008), Judge and Kammeyer-Mueller (2012), and Staufenbiel and König (2010).

Workplace characteristics

Workplace and organisational characteristics represent the broader attitude of an employer and its management toward its employees. Examples include company values, support from management, well-being offerings, fairness in treatment and appraisal or open and honest communication. Again, such factors are generally beyond an individual's control although he or she may be affected by attitude toward job and workplace.

The influence of workplace and organisational factors have been investigated e.g. by Kuoppala et al. (2008), Lewis and Malecha (2011), Patterson et al. (2005), Pereira et al. (2015) and Shanock and Eisenberger (2006), who provide a systematic literature review investigating the effect of on-site workplace health and well-being interventions on employee productivity, showing that organisations with better well-being offer see lower productivity losses.

5.3 Analytical approach

5.3.1 Method of analysis

Many empirical studies presented in the literature review focus on a limited number of factors when analysing influences on workplace productivity loss; this risks misinterpretation of results due to the omitted variable bias. In this study, we use integrated SEMs to simultaneously estimate the complex network of influences of physical and mental health, lifestyle, personal and family factors, and job and workplace characteristics on relative workplace productivity loss. SEM is a theory-driven data analytical approach for evaluation of *a priory* specified hypotheses about causal relations among measured and/or latent variables (Jahanshahi et al., 2015; Mueller et al., 2010). SEMs allow systematic decomposition of the complex network of influences, where the effects of each variable can be examined in turn; the framework is thus particularly useful in evaluating productivity determinants.

The analysis is done in two steps. First, highly correlated influences, which are difficult to model as separate explanatory variables are grouped to construct distinct latent variables such as *lifestyle*, *mental health* and *physical health*; exploratory factor analysis (EFA) is used to investigate how the latent variables are formed and manifested into the observed data space. Second, causal links between the constructed factors and directly observed variables are specified in a structural model. Here, both direct and indirect (mediated through other variables) impacts can be modelled to create a network of effects on productivity. Capturing commonality across explanatory variables by creating latent variable indicators also helps to avoid potential measurement errors and endogeneity issues (Litwin and Shiovitz-Ezra, 2006).

In what follows, we first develop three separate SEMs, namely *personal*, *job*, and *workplace* models, based on the conceptual structures suggested in the literature (refer to section 5.2). This involves employing factor analysis to construct a set of latent variables (factors) to measure the main conceptual elements (e.g., mental health or job attitudes), followed by developing separate SEM frameworks, one for each individual model, to test influences of the constructed latent variables alongside standalone-observed variables on productivity. The individual models can be used to directly compare our findings using a limited set of variables against those reported in the prior literature and build a base for comparison against the full model.

Second, we combine all individual models into a single combined SEM framework, reducing the omitted variable bias and allowing to account for additional interrelations across variables. Consequently, we can postulate the relative importance of influences and highlight those with the most significant effect on productivity loss, as well as any differences compared to the individual models. The theoretical foundations of our model are based on Anitha (2014), Bakker and Demerouti (2008) and Miraglia and Johns (2016), who construct various individual- or workplace-related models. Their analysis suggest that personal resources, job demands and job resources, which are estimated independently, affect employee's health and job attitudes.

5.3.2 Data

We use the data collected through the 2017 Britain's Healthiest Workplace survey of organisations and their employees in the UK. The survey is open to all organisations in the UK with more than 20 employees from any industrial sector; participating organisations self-select to the survey and distribute the survey links to their employees. There is no fee for participation nor a selection process for participants. All employees aged 18+ are allowed to complete the survey, yet their participation is voluntary and results are anonymised. The survey covers personal, social, lifestyle, job and workplace areas. Since its inception in 2013, more than 370 organisations and 124,000 individual employees participated in the study.

Our data consists of the entire 2017 cross-sectional dataset of 31,950 employee responses across all 173 participating organisations. The sectoral breakdown of the organisations and their respondents is provided in Table 5.5 in the Appendix. After excluding responses with missing data, the final dataset consists of 29,928 individuals. With more than 90 indicators per individual in the original dataset, each variable was carefully considered for inclusion in the study based on the intuition, statistical tests of wide range of models, and the prior literature, eventually limiting the number of included variables to 36 plus six controls. The variables were allocated to the three theoretical frameworks discussed above: the *personal*, *job* and *workplace*. Each individual model thus consists of variables intuitively related to each other (e.g., diet, alcohol consumption, smoking and sleep patterns; or job satisfaction, job-related stress, isolation and safety at the workplace) that have also been proven interlinked in the previous studies.

The full list of variables is presented in Table 5.1 with their descriptive statistics reported in Table 5.6 and Table 5.7 in the Appendix. Most of the variables represent a single question in the survey, while several variables represent composite indices – a combination of multiple questions – created and validated in the prior literature. For instance, mental well-being is measured using the Kessler Psychological Distress Scale (Kessler et al., 2002), whereas work engagement is measured using the Utrecht Work Engagement Scale (Schaufeli et al., 2006). Our main outcome variable, relative employee-level productivity loss, is a self-reported variable captured using the Work Productivity and Activity Impairment questionnaire (Reilly et al., 1993). The list of composite variables and their structure is shown in Table 5.8.

In order to simplify interpretation of results, we transformed the variables where appropriate so that, for all variables, higher values represent the preferable outcomes. For instance, the question on feeling isolated at workplace, originally on a 0 (never) to 4 (always) scale was transformed to 0 (always) to 4 (never) scale. Productivity is measured relative to the maximum potential individual performance at the workplace and is reported on a [0; 100%] scale,

Table 5.1: List and categorization of variables used in the analysis

Model	Category	Variable	Scale
Personal	*Lifestyle*	Physical exercise	Minutes per week
		Consumption of fruits and vegetables	Portions per day
		Consumption of dietary fats and oils	Portions per day
		Consumption of trans-unsaturated fatty acids	Portions per day
		Consumption of low-fat dairy products	Portions per day
		Alcohol consumption	Units per week[a]
		Smoking	Smoker/Nonsmoker
		Sleep length	Hours per day
	Mental health	Self-assessment of mental health	Poor-Excellent
		Kessler Psychological Distress Scale (K6)[b]	0-24[a]
		Life satisfaction	0-10
		Financial concerns	A lot; A little; None
	Physical health	Self-assessment of physical health	Poor-Excellent
		BMI	kg/m^2 [a]
		Number of musculoskeletal health conditions	0-9[a]
		Inability to work due to musculoskeletal health	Yes/No
		Number of chronic conditions	0-16[a]
		Fatigue	Always-Never
Job	*Job characteristics*	Job satisfaction	0-10
		Level of work-related stress[b]	0-7[a]
		Isolation at workplace	Always-Never
		Safety at workplace	Never-Always
	Work patterns	Possibility to work from home	No/Yes
		Possibility to work flexible hours	No/Yes
		Work commuting time	Minutes per day (one way)[a]
Workplace	*Support from organization*	Support to be physically active	Disagree-Agree
		Support to eat healthy diet	Disagree-Agree
		Support to live tobacco free	Disagree-Agree
		Support to manage stress at work	Disagree-Agree
		Support when unwell	Disagree-Agree
		Importance of health and well-being	Disagree-Agree
	Support from managers	Manager cares about well-being	Disagree-Agree
		Manager is encouraging	Disagree-Agree
		Openness to discuss mental health problems	Disagree-Agree
All		Work engagement[b]	0-6 (continuous)
		Productivity[b]	0%-100%

Notes: For all variables, higher values represent preferable outcomes. For individuals with no self-reported absenteeism and presenteeism, the productivity estimate is at 100%.

[a] Converted to a positive scale; all values subtracted from the theoretical maximum or the highest observed value.

[b] Composite index, refer to Table 5.8 for more information.

where 100% equals maximum productivity and lower values represent presence of self-reported absenteeism and/or presenteeism. The analysis was done in Stata 15 (StataCorp., 2017).

5.4 Analysis

5.4.1 Factor analysis

Given the high level of interrelation among variables in our dataset, they cannot be treated as independent; this prompts us to construct latent variables (factors) to represent the conceptual content of the interrelated indicators. We use EFA to establish associations among variables and create variable clusters defining composite, latent variables that are better capable of representing the pattern of influences than any of the constituents (Jahanshahi et al., 2015).

We performed EFA for each variable category presented in Table 5.1 to classify the associated variables into an optimal number of factors. We examined goodness of fit for the constructed factors iteratively, starting with simple models with no covariance structure between the factor indicators' measurement errors and moving toward more complex models where correlations between some or all of the measurement errors are controlled for. In each step, the Comparative Fit Index (CFI) and difference in the χ^2 statistic in relation to the associated difference in the degrees of freedom are used to assess suitability of the model (Hoyle, 1995). The final constructed factors with the best goodness of fit indices are then used in the SEM frameworks to analyse the influences on productivity loss. Additional information on the procedure and results are summarised in Tables 5.9-5.11 in the Appendix.

Most categories in Table 5.1 can be represented by a single latent variable. For instance, *mental health* consists of four observed indicators: mental health self-assessment, Kessler Psychological Distress Scale, life satisfaction and measure of financial concerns. On the contrary, *lifestyle* variables, which show little inter-correlation, were found unfit for constructing common latent variables and are therefore considered as separate observed independent variables in the analysis. Through factor analysis, we eventually reduced dimensionality of our data space to 19 variables (consisting of 7 factors, 6 observed variables and 6 control variables - age, gender, ethnicity, education, income and job position). In the SEM diagrams presented further (see Figures 5.1-5.4), the variables are represented as follows: individual independent variables (boxes) and latent variables (ellipses) used in the final models are shown with white background; variables forming each latent variable are shown with dark background. We discuss each of these models in turn in the following sections.

5.4.2 Individual models of workplace productivity

In this section we analyse the influences on workplace productivity loss. First, we develop three individual SEMs broadly based on the frameworks established in the literature. Subsequently, we combine the three models into a single framework in order to account for potential interrelations.

For each individual model, we tested various SEM structures with different directional effects in order to examine the one with the best fit to the data. The AIC and BIC measures were used to determine model fits. Throughout the paper, only the statistically significant influences ($p < 0.01$) in the optimal models are reported in the path diagrams.

Personal model - physical and mental well-being, lifestyle

The path analysis for the *personal* model is depicted in Figure 5.1. All coefficients are standardised so that they can be directly comparable. In addition to the direct effects, such as that of mental health on productivity (with the coefficient of 0.296), one major advantage of SEM is the estimation of indirect influences, which are quantified by multiplying the coefficients along the SEM paths. In our reported results, all indirect effects are standardised after being estimated from multiplication of direct influences. The total or combined effects are then calculated by adding up the direct as well as all indirect effects. The full list of direct, indirect, and combined effects and comparisons with the combined model are provided in Table 5.2. For instance, as shown in the personal model column, the indirect effect of mental health on productivity via physical health and work engagement is 0.124.

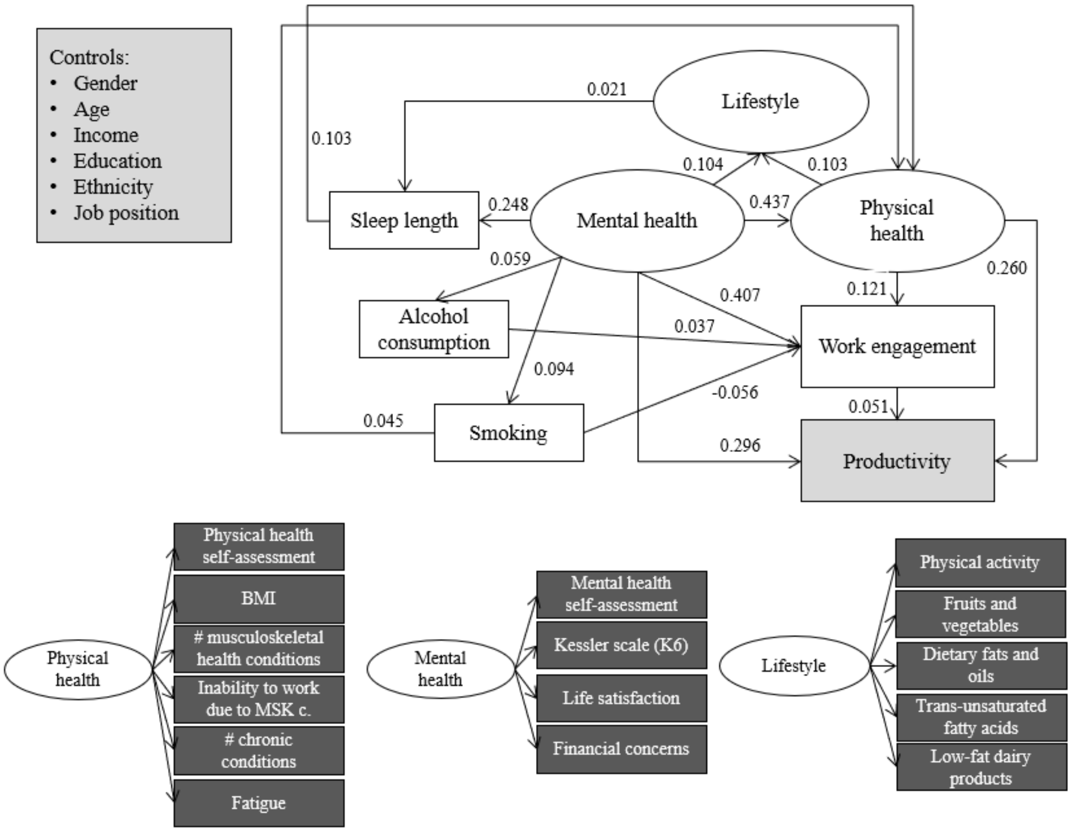
Mental and physical health have the strongest direct influences on workplace productivity. Additionally, mental health has a strong indirect effect mainly mediated through physical health (86% of total indirect effect). This can be calculated using the combined effect of 0.441, which is the sum of the direct effect (0.296) and all indirect effects (0.145), compared to the indirect effects mediated through mental health (0.124, see Table 5.2 for more information). Other influences are negligible, with only work engagement having statistically significant direct effect on productivity. All pathway coefficients, except for the one between smoking and work engagement, are positive, meaning that better health and lifestyle generally increase work engagement and productivity. Most of the control variables do not have statistically significant effect on productivity (refer to Table 5.12 in the Appendix for full results).

To compare our results with the prior literature, we developed a model with only work engagement as an explanatory variable in addition to the full set of controls (e.g., the effects of lifestyle, mental health and physical health are disregarded). The estimated standardised coefficient of 0.267 (see Table A10 in the Appendix) is in line with the overall findings from previous studies (refer e.g. to Demerouti and Cropanzano, 2010, Salanova et al., 2005, Xanthopoulou et al., 2009). However, after including lifestyle and health variables in the model, as shown in Figure 5.1, the influence of work engagement becomes negligible, suggesting that mental and physical health are in fact the major influences on productivity loss and it is their effects which are captured by work engagement when they are excluded from the model.

Job model - attitudes towards workplace

The *job* model is depicted in Figure 5.2. Commuting time is statistically significant though it has a small impact on productivity and all other variables (note that higher values represent shorter commuting time). Work patterns also have relatively small impact on both work engagement and productivity. On the other hand, the effect of job characteristics – both direct and indirect – is substantially bigger and positive, meaning that employees facing less stress at work and those more satisfied with their job are, on average, more productive. While this confirms previous findings of e.g. AbuAlRub (2004), Judge and Kammeyer-Mueller (2008) and Judge and Kammeyer-Mueller (2012), we will see later that the direct effect decreases by more than 50% once other variables are introduced. Regarding work engagement, its effect on productivity is higher than that in the personal model, yet it is relatively small compared to that of job characteristics.

Figure 5.1: Personal model.



Note: The diagram represents the model with the best fit to the observed data. All coefficients are standardised and represent change (in standard deviations) in a dependent variable per standard deviation increase in the predictor variable. Only coefficients with significant direct or indirect influence at <0.001 level are shown. Variables with dark background represent indicators associated with latent variables.

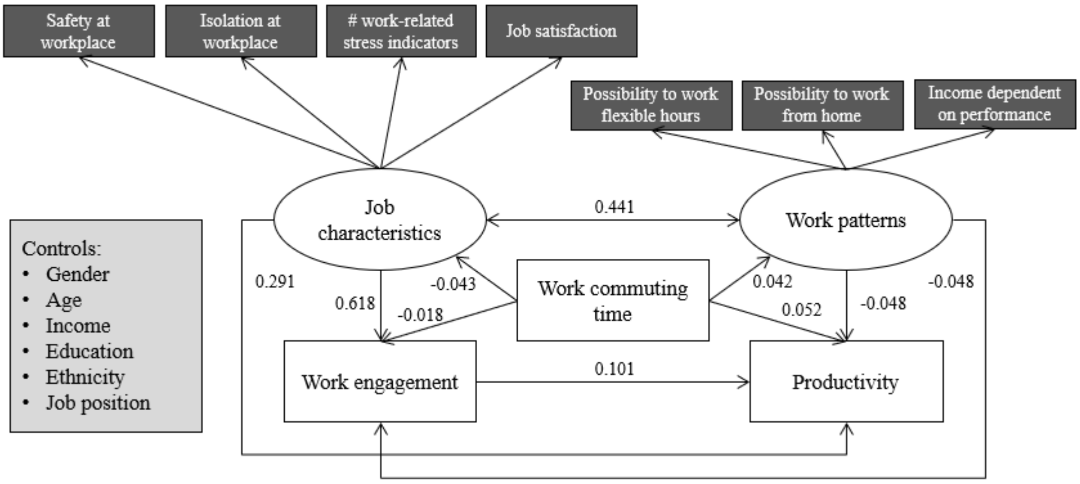
Workplace model - workplace and organisational characteristics

In line with what was suggested in the previous literature (e.g., Kuoppala et al., 2008, Lewis and Malecha, 2011), the support from an organisation and its managers are both statistically significant predictors of work engagement and productivity (refer to Figure 5.3). Both factors also affect productivity indirectly, through work engagement. Note that the pathway coefficient between work engagement and productivity is twice as high than in the previous models and generally more in line with the simple model presented in Table 5.13. The results thus again suggest that there are other unobserved effects affecting the results and that such simple models fail to properly capture the actual pathway of effects. Influences of control variables are in line with the previous models with gender, age and income being statistically significant predictors of all four dependent variables.

5.4.3 The combined model of workplace productivity

By integrating our findings from the individual models we developed a joint, comprehensive model of workplace productivity to determine the relative importance of influences. This is again done iteratively; the individual models are linked in one combined SEM framework and

Figure 5.2: Job model.



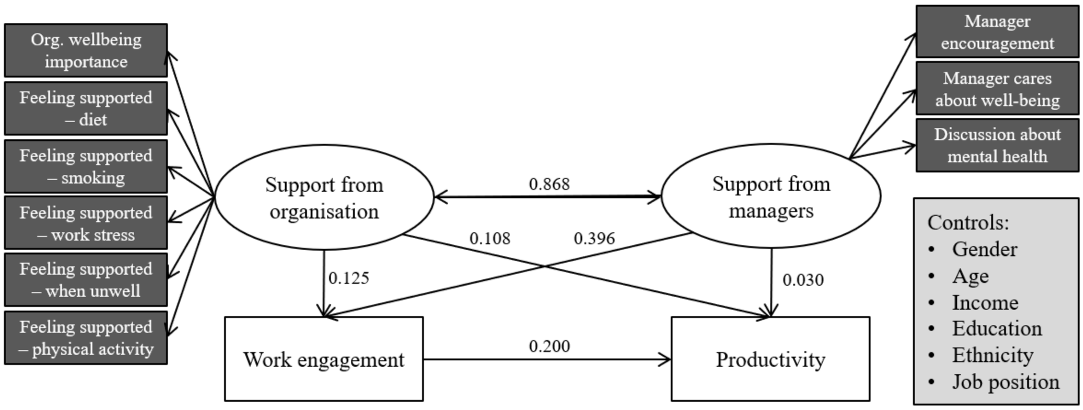
Note: The diagram represents the model with the best fit to the observed data. All coefficients are standardised and represent change (in standard deviations) in a dependent variable per standard deviation increase in the predictor variable. Only coefficients with significant direct or indirect influence at <0.001 level are shown. Variables with dark background represent indicators associated with latent variables.

an optimal model is found after testing alternative model structures and comparing the AIC and BIC values. That is, we took all statistically significant direct and indirect influences, keeping previously discovered pathway of effects. We then added all possible new links and tested both the significance of influences and the goodness of fit of the combined models in order to choose the one best describing our data. For instance, smoking was identified as a co-determinant of physical health, which in turn affects work engagement and, both directly and indirectly, productivity. Equally, work patterns affect work engagement and productivity in the second individual model. In the combined model, we further tested the relationship between smoking and work patterns, physical health and work patterns, and whether work engagement remains a statistically significant determinant of productivity when additional variables are included. The analysis showed that none of the new pathways (including the work engagement-productivity link) were statistically significant and were therefore not included in the final model. The resulting model is illustrated in Figure 5.4 and the direct and indirect influences on productivity are presented in Table 5.2. The full regression results are then presented in Table 5.14 in the Appendix.

The results show that, once all the factors established in the three individual models are combined, the most important influences on workplace productivity are: mental health, physical health, job characteristics and support from organisations, all of which are indeed also major influences highlighted in the separate individual models. Of these, mental health stands out as the most important determinant. On the other hand, working patterns show relatively small influence on workplace productivity, suggesting that the way employees work is no longer a key factor.

As in the individual models, most of the indirect effects (93%) in the model are mediated through mental and/or physical health. For instance, more than 50% of the influence of job characteristics, the second most important productivity determinant, is mediated through mental

Figure 5.3: Workplace model.



Note: The diagram represents the model with the best fit to the observed data. All coefficients are standardised and represent change (in standard deviations) in a dependent variable per standard deviation increase in the predictor variable. Only coefficients with significant direct or indirect influence at <0.001 level are shown. Variables with dark background represent indicators associated with latent variables.

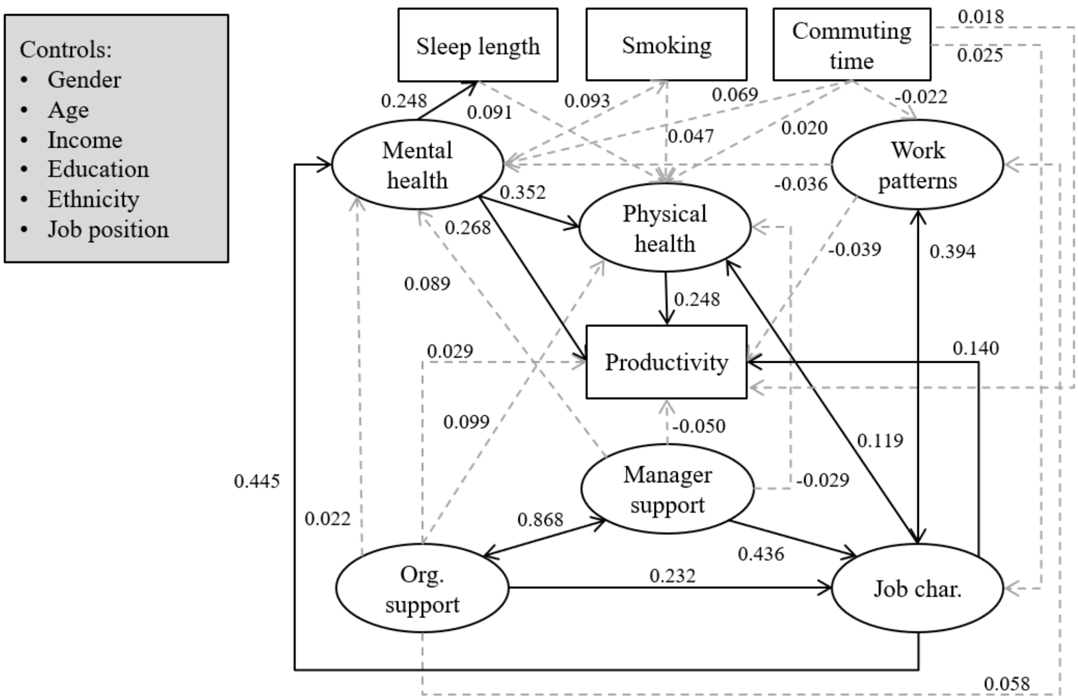
health. Second to mental health, physical health has the strongest direct effect on productivity; it also acts as a mediating factor specifically for the indirect influences of mental health and job characteristics.

Note that majority of pathway coefficients are smaller in size in the combined model compared to the individual models. This is in line with our expectations as the simpler models tend to overestimate the observable influences by capturing some of the effects of omitted variables. For instance, the direct effect of mental health is 9% weaker when compared to the individual model; for physical health, the difference is 7% and then substantially greater for all other factors (e.g., 52% for job characteristics or 73% for support from organisation). These findings highlight the potential misinterpretation of influences when only parts of the causal paths are modelled.

The benefit of a more inclusive combined model can be better perceived by examining the effect of work engagement, which appears as a significant productivity determinant in the individual models but completely lost its significance in the combined model. The effect of work engagement was strongest in the job and workplace models, where it additionally served as a mediating variable for job characteristics and for support from organisation and managers. For the combined model, however, the role of work engagement has been diminished and is replaced with a more complex path structure. In the combined model, support from organisation and managers affects job characteristics, which in turn has a direct influence on productivity, but it also exhibits a significant indirect influence through mental and physical health. This suggests that, arguably, the simpler individual models have overestimated the impact of work engagement by capturing the effects of other potentially important influences which were not included in the models.

Considering the four individual lifestyle variables – alcohol consumption, smoking, sleep length and commuting time — only commuting time is estimated to have statistically significant direct effect on productivity, while even the indirect effect of alcohol consumption is not significant when all other factors are included in the analysis. Looking at Table 5.12 in the

Figure 5.4: Combined model.



Note: The diagram represents model with the best fit to the observed data. Uncorrelated error variables are omitted for clarity of presentation. Solid black lines highlight pathway coefficients greater than 0.1. All the paths shown are statistically significant at <0.001 level.

Appendix, the influence of control variables remains remarkably consistent with those found in individual models. Gender, age, income and selected ethnicity and job position indicators have statistically significant influence on productivity. In particular, men, older employees and those with higher income tend to report higher productivity.

5.5 Discussion

5.5.1 Discussion and Conclusions

In this study, we present a novel insight into understanding employees' productivity by developing a new conceptual model augmenting simpler frameworks assessed in the prior literature. This is possible through exploiting granularity of the 2017 Britain's Healthiest Workplace survey, which provide detailed information on a large set of socioeconomic and workplace characteristics, as well as various personal and institutional variables for more than 30,000 employees.

Our principal findings are threefold. First, our results show that mental health, physical health, job characteristics and support from organisations are the most important determinants of employees' productivity. This highlights a strong case for promoting workplace interventions aimed at improving employees' wellbeing and the overall organisational, work and management culture.

Second, our study shows that the network of influences affecting employees' productivity is more complex than what hitherto presented in the literature. Disentangling the pathway of influences, we show that a large proportion of effects that support from the organisation

Table 5.2: Direct and indirect influences on productivity

Direct influence	**Indirect influence**	**Personal model**	**Job model**	**Workplace model**	**Overall model**
Work engagement		0.051	0.101	0.200	ns
Mental health		0.296	-	-	0.268
	MH ->PH ->Prod	0.124	-	-	0.087
	Other pathways	0.021	-	-	0.007
Combined		**0.441**	**-**	**-**	**0.363**
Physical health		0.260	-	-	0.248
	All pathways	0.006	-	-	-
Combined		0.266	**-**	**-**	**0.248**
Lifestyle		ns	-	-	ns
	All pathways	0.001	-	-	ns
Combined		**0.001**	**-**	**-**	ns
Work patterns		-	-0.048	-	-0.039
	All pathways	-	-0.005	-	-0.013
Combined		**-**	**-0.053**	**-**	**-0.052**
Job characteristics		-	0.291	-	0.140
	JC ->MH ->Prod	-	-	-	0.156
	Other pathways	-	0.0390	-	0.014
Combined		**-**	**0.330**	**-**	**0.310**
Manager support		-	-	0.030[a]	-0.050
	MS ->JC ->Prod	-	-	-	0.135
	Other pathways	-	-	0.194	0.025
Combined		**-**	**-**	**0.224**	**0.110**
Org. Support		-	-	0.108	0.029[a]
	OS ->JC ->Prod	-	-	-	0.190
	Other pathways	-	-	0.025	0.008
Combined		**-**	**-**	**0.133**	**0.226**
Smoking		ns	-	-	ns
	All pathways	0.009	-	-	0.012
Combined		**0.009**	**-**	**-**	**0.012**
Alcohol		ns	-	-	ns
	All pathways	0.002	-	-	ns
Combined		**0.002**	**-**	**-**	ns
Sleep length		ns	-	-	ns
	All pathways	0.027	-	-	0.023
Combined		**0.027**	**-**	**-**	**0.023**
Commuting time		-	0.052	-	0.018
	All pathways	-	0.014	-	0.039
Combined		**-**	**0.066**	**-**	**0.057**

Notes: [a] Significant at the 0.01 level. All other reported results statistically significant at the <0.001 level. ns = not significant. Only selected indirect pathways shown. MH = mental health, PH = physical health, Prod = productivity, JC = Job characteristics, MS = manager support, OS = Organization support. For all variables, higher values represent preferable outcomes. The indirect influences are quantified by multiplying the coefficients along the SEM paths.

and managers, as well as workplace conditions and attitudes more generally, have on workplace productivity are mediated through mental and physical health. This highlights the need for a more tailored strategy to improve employees' well-being. Indeed, employers typically focus on addressing the symptoms of poor mental and physical health through investing in comprehensive medical benefit packages as well as employees' assistance programs. Our study suggests that it is equally or even more important to address the source of such problems through supportive management, promoting more inclusive work atmosphere and improving job satisfaction in a healthy work environment.

Third, from the technical perspective, our study shows that the simple individual models carry the risk of overestimating influences as a result of neglecting important direct and indirect influences. For instance, even though work engagement appears as a strong predictor of workplace productivity in the individual models, inclusion of other variables such as health, job and workplace characteristics reduce its explanatory power a negligible amount. Similar studies aimed at assessing productivity or associated employee or workplace factors should therefore carefully design the evaluation framework to minimise the potential omitted variable bias.

5.5.2 Limitations and their mitigation

Despite using a very comprehensive dataset, the present data and analytical approach have their limitations. In particular, the participation rates per organisation are unknown as the full lists of eligible employees were not disclosed.

We have carried out extensive tests to understand and tackle the associated potential limitations. First, given that our results may be affected by a self-selection bias, we compared characteristics of the survey respondents to a representative sample of the UK working population from the Health Survey for England (UK Government Statistical Service, 2016) across a multitude of variables, including age, gender, ethnicity and BMI. The results, presented in Table 5.3 in the Appendix, show that both samples are similar in their characteristics. Additionally, we run two equivalent regressions with life satisfaction as the dependent variable using both samples to compare the influences. The results of this test, shown in Table 5.4, show that the estimated influences are similar, with the same direction of effects and level of significance. The only exception is ethnicity; our dataset contains 10 percentage points more white individuals and proportionally less blacks, Asians and individuals of mixed ethnicity. Consequently, white ethnicity appears as a statistically significant variable in the regression using the study dataset, but it is reported as insignificant in the representative dataset (although with a positive coefficient in both cases). Given that ethnicity has rarely appeared as a statistically significant variable in the main SEM results, we argue that the outcomes are representative of the general working population in the UK.

Second, measurement errors in our study are controlled for using latent variables that capture commonality across the correlated indicators. However, a separate potential issue with self-reported variables, such as those in our dataset, is that some variables may be consistently under- or over-stated as a result of psychological biases. To control for this, we modelled correlations among error terms in the exploratory factor analysis and, where statistically significant, we included them in the final SEMs.

Third, to control for a possible endogeneity bias and structural ambiguity, we estimated numerous model structure with pathways in opposite directions to check which model structure would fit the data best and used that for our final estimates.

Finally, our main outcome variable – productivity loss assessed using the Work Productivity and Activity Impairment questionnaire (Reilly et al., 1993) – is self-reported and thus prone to biases as documented by Gardner et al. (2016). Notwithstanding that, self-reported relative productivity loss assessments are extensively used in the literature (e.g., Nnoaham et al., 2011 and Wahlqvist et al., 2002). It will be useful for future studies to examine alternative survey designs to come out with the best approach for recording productivity metrics which can minimise the potential biases in assessment of physical and mental health influences.

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Appendix

Table 5.3: Analysis of representativeness - descriptive statistics

	BHW[a]		HSE[b]	
	Mean	# obs	Mean	# obs
Gender (% male)	0.5	29,928	0.5	6,546
Age (years)	39.1	29,928	41.7	4,751
Ethnicity (white)	93%	29,928	83%	6,475
Ethnicity (Asian)	4%	29,928	10%	6,475
Ethnicity (black)	1%	29,928	4%	6,475
Ethnicity (mixed)	2%	29,928	3%	6,475
BMI	26.1	29,928	25.2	5,262
Alcohol (units per week)	11.3	29,928	10.2	4,820
% current smokers	10%	29,928	13%	6,546
Life satisfaction (1 = low - 4 = very high)	2.7	29,928	2.9	4,310

[a] Britain's Healthiest Workplace dataset (i.e. the main dataset used in this study).
[b] Health Survey for England dataset.

Table 5.4: Analysis of representativeness - regression

	BHW[a]		HSE[b]	
Constant	2.835	***	3.137	***
	(0.047)		(0.131)	
Gender	-0.008		0.005	
	(0.010)		(0.028)	
Age	0.006	***	0.003	**
	(0.000)		(0.001)	
Ethnicity (white)	0.169	***	0.061	
	(0.039)		(0.111)	
Ethnicity (Asian)	0.054		-0.052	
	(0.045)		(0.119)	
Ethnicity (black)	-0.013		-0.017	
	(0.056)		(0.131)	
BMI	-0.017	***	-0.012	***
	(0.001)		(0.003)	
Alcohol (units per week)	-0.001	**	-0.001	*
	(0.000)		(0.001)	
% current smokers	-0.245	***	-0.173	***
	(0.016)		(0.037)	

[a] Britain's Healthiest Workplace dataset (i.e. the main dataset used in this study).
[b] Health Survey for England dataset.
Note: Life satisfaction as the dependent variable.

Table 5.5: Descriptive statistics - organizations

Industrial sector	Organizations (count)	Responses (by organization) Total	Mean	Median	Min	Max
Agriculture, forestry and fishing	0	0	-	-	-	-
Mining and quarrying	2	560	280.0	280	25	535
Manufacturing	26	2,598	99.9	62	18	328
Electricity, gas, air	2	99	49.5	50	34	65
Water supply, sewerage	1	771	771.0	771	771	771
Construction	14	5,133	366.6	243	26	1,447
Wholesale and retail trade	7	1,648	235.4	136	25	593
Transportation and storage	12	3,340	278.3	169	39	812
Accommodation and food services	3	269	89.7	94	62	113
Information and communication	12	2,565	213.8	90	21	716
Financial and insurance activities	28	5,853	209.0	130	46	940
Professional activities	23	2,778	120.8	87	17	416
Administrative and support services	5	843	168.6	191	17	251
Public administration and defence	5	404	80.8	57	19	168
Education	8	825	103.1	73	29	321
Human health and social work	21	3,484	165.9	153	19	668
Arts, entertainment and recreation	4	380	95.0	77	48	178
Other service activities	3	359	119.7	131	62	166
Activities of households as employers	0	0	-	-	-	-
Extraterritorial organizations	1	41	41.0	41	41	41
Total	**177**	**31,950**	**180.2**	**114**	**17**	**1,447**

Note: The sectoral names were shortened for presentation purposes; the classification follows the UK Standard Industry Classification (SIC) 2007.

Table 5.6: Descriptive statistics - variables

Variable	Scale	Mean (unadj.)	Std. (dev.)	Med.	Min	Max	Mean (adj.[a])
Smoking	Smoker/Nonsmoker	0.37	0.48	0	0	1	0.63
Alcohol consumption	Units per week	11.26	13.37	7	0	140	128.74
Exercise	Minutes per week[b]	296.32	294.72	230	0	4,200	
Fruits & vegetables	Portions per day	4.94	2.42	5	0	40	
Sleep length	Hours per day	6.99	0.94	7	1	20	
Dietary fats and oils	Portions per day	1.65	1.03	2	0	5	3.35
Trans-unsaturated fatty acids	Portions per day	1.33	1.20	1	0	7	5.67
Low-fat dairy products	Portions per day	3.97	1.58	4	1	6	
Mental health self-assessment	Poor-excellent	2.96	0.89	3	0	4	
Psychological distress	0-24	4.68	4.09	4	0	24	19.32
Life satisfaction	0-10	6.92	1.81	7	0	10	
Financial concerns	A lot; A little; None	0.56	0.63	0	0	2	1.44
Physical health self-assessment	0-4	1.07	0.79	1	0	4	2.93
BMI	kg/m^2	20.66	5.12	19.8	0	79.9	59.26
# musculoskeletal health cond.	0-9	2.09	1.84	2	0	9	6.91
# chronic conditions	0-16	0.38	0.70	0	10	0	15.62
MSK unable to work	Yes/No	0.15	0.35	1	0	0	0.85
Fatigue	Always-Never	1.72	0.99	2	0	4	2.28
Job satisfaction	0-10	4.22	1.48	5	0	6	
Work stress	0-7	6.05	1.20	6	0	7	
Flexible hours	No/Yes	0.56	0.50	1	0	1	
Home work	No/Yes	0.52	0.50	1	0	1	
Isolation	Always-Never	0.83	0.95	1	0	4	3.17
Safety	Never-Always	3.60	0.65	4	0	4	
Commuting time	Min/day (one way)	41.49	29.96	35	0	180	138.51
Support - physical activity	Disagree-Agree	3.19	1.01	3	1	5	
Support - diet	Disagree-Agree	3.08	0.99	3	1	5	
Support - smoking	Disagree-Agree	3.09	0.93	3	1	5	
Support - stress	Disagree-Agree	3.02	0.99	3	1	5	
Support - unwell	Disagree-Agree	3.58	0.90	4	1	5	
Manager encouragement	Disagree-Agree	3.83	0.95	4	1	5	
Manager well-being	Disagree-Agree	3.86	0.92	4	1	5	
Well-being imp. for the org.	Disagree-Agree	3.43	1.07	4	1	5	
Discussion with line manager	Disagree-Agree	3.09	1.26	3	1	5	
Discussion with HR rep.	Disagree-Agree	2.87	1.21	3	1	5	
Discussion with colleague	Disagree-Agree	3.05	1.17	3	1	5	
Work engagement	0-6 (continuous)	3.62	0.92	3.7	0	6	
Productivity loss	0%-100%	0.12	0.20	0	0	1	0.88

[a] Adjusted, where appropriate, so that for all variables, higher values represent preferable outcomes.
[b] Moderate-intensity physical activity; each minute of vigorous-intensity physical activity is counted as two minutes of moderate-intensity physical activity.
n = 29,928

Table 5.7: Descriptive statistics - controls

Variable	Mean (unadjusted)	Std. dev.	Min	Max
Gender	0.50	0.50	0	1
Age	39.15	11.26	18	82
Education - none or primary (baseline)	0.00	0.07	0	1
Education - First cycle of secondary	0.08	0.28	0	1
Education - Second cycle of secondary	0.13	0.33	0	1
Education - Post-secondary (not university level)	0.19	0.39	0	1
Education - Undergraduate	0.36	0.48	0	1
Education - Postgraduate	0.21	0.41	0	1
Education - Ph. D.	0.02	0.14	0	1
Ethnicity - white (baseline)	0.92	0.28	0	1
Ethnicity - Asian	0.04	0.20	0	1
Ethnicity - Black	0.01	0.12	0	1
Ethnicity - Mixed	0.02	0.12	0	1
Ethnicity - Other or not specified	0.01	0.12	0	1
Job - Manager	0.25	0.43	0	1
Job - Profession	0.35	0.48	0	1
Job - Technician or junior professional	0.14	0.35	0	1
Job - Clerical support worker	0.14	0.34	0	1
Job - Service worker	0.02	0.15	0	1
Job - Sales worker	0.03	0.16	0	1
Job - Manual labor worker	0.01	0.12	0	1
Job - Other or not specified (baseline)	0.06	0.24	0	1
Annual income (GBP)	43,925	29,194	5,000	150,000

n = 29,928

Table 5.8: Composite variables used in the questionnaire

Scale	Question
Kessler Psych. Distress Scale (K6)[a] (0 - None of the time; 4 - All of the time)	During the last 30 days, about how often did you feel: 1. …nervous? 2. …hopeless? 3. …restless or fidgety? 4. …that everything was an effort? 5. …so depressed that nothing could cheer you up? 6. …worthless?
HSE Management Standards[b] (0 - Never; 4 - Always)	1. I have a choice in deciding what I do at work. 2. I have unrealistic time pressures. 3. I am clear what my duties and responsibilities are. 4. I receive the respect at work I deserve from my colleagues. 5. Staff are always consulted about change at work. 6. Relationships at work are strained. 7. I am subject to bullying at work.
Utrecht Work Engagement Scale[c] (0 - Never; 6 - Always)	1. At my work, I feel bursting with energy 2. At my job, I feel strong and vigorous 3. I am enthusiastic about my job 4. My job inspires me 5. When I get up in the morning, I feel like going to work 6. I feel happy when I am working intensely 7. I am proud of the work that I do 8. I am immersed in my work 9. I get carried away when I am working
Work Productivity and Activity Impairment[d] (General Health Questionnaire)	1. During the past seven days, how many hours did you actually work? 2. During the past seven days, how many hours did you miss from work because of health problems? 3. During the past seven days, how much did your health problems (physical and/or mental) affect your productivity while you were working?

[a] Source: Kessler et al. (2002). Scores for all questions were summed up, forming a 0-24 scale.
[b] Selected questions from UK Government Statistical Service (2016). Employees are considered at stress in given indicator if they select 3 or 4 in negatively-oriented questions (no. 2, 6, 7) and 0 or 1 in positively-oriented questions (no. 1, 3, 4, 5).
[c] Source: Schaufeli et al. (2006). Scores for all questions were averaged.
[d] Source: Reilly et al. (1993). Productivity loss is calculated as $l = a/(a+w) + (1 - a/(a+w)) * p/10$, where w is the number of hours worked (Q1), a is a measure of absenteeism (Q2) and p is measure of presenteeism (Q3). Q3 is on scale 0–10.

Table 5.9: Personal model - standardized factor loadings and statistics

Latent constructs and indicators	Model 1	Model 2	Model 3
	Factor loadings		
Mental health			
Mental health self-assessment	0.783	0.655	-
Kessler scale (K6)	0.818	0.684	-
Life satisfaction	0.683	0.802	-
Financial concerns	0.418	0.464	-
Covariance: MH SA–Kessler scale	-	0.369	-
CFI	0.978	0.997	-
Physical health			
Physical health self-assessment	0.628	0.529	0.455
BMI	0.390	0.248	0.199
Fatigue	0.427	0.469	0.446
# chronic conditions	0.440	0.433	0.372
# musculoskeletal health conditions	0.488	0.551	0.617
Inability to work due to MSK cond.	0.399	0.436	0.448
Covariance: PH SA–BMI	-	0.269	0.302
Covariance: PH SA–# MSK	-	-	-0.032
Covariance: PH SA–fatigue	-	-	0.090
Covariance: PH SA–# chronic c.	-	-	0.130
Covariance: BMI–# chronic c.	-	-	0.118
CFI	0.875	0.959	0.995
Lifestyle			
Physical activity	0.306	0.303	0.217
Fruits and vegetables	0.462	0.460	0.391
Dietary fats and oils	0.392	0.389	0.423
Trans-unsaturated fatty acids	0.448	0.453	0.482
Low-fat dairy products	0.290	0.296	0.315
Smoking	0.069	-	-
Alcohol consumption	0.039	-	-
Sleep length	0.118	-	-
Covariance: exercise–fruits	-	-	0.134
CFI	-	0.910	0.970
Sample size	29,928	29,928	29,928

PH SA = Physical activity self-assessment, CFI = Comparative fit index.
For all variables, higher values represent preferable outcomes.

Table 5.10: Job model – standardized factor loadings

Latent constructs and indicators	Model 1	Model 2	Model 3
		Factor loadings	
Job characteristics			
Job satisfaction	0.711	0.713	0.713
Level of work-related stress	0.738	0.744	0.744
Isolation at workplace	0.570	0.558	0.558
Safety at workplace	0.383	0.361	0.360
Work patterns			
Possibility to work flexible hours	0.509	0.588	0.586
Possibility to work from home	0.714	0.605	0.606
Commuting time	-0.138	0.063	-
Covariances: Job characteristics–Work patterns	0.283	0.338	0.340
Isolation–Safety	-	0.103	0.103
Isolation–Work from home	-	-0.121	-0.129
Commuting time–Flexible hours	-	-0.051	-
Commuting time–Work from home	-	-0.219	-
CFI	0.949	0.984	0.985
Sample size	29,928	29,928	29,928

CFI = Comparative fit index. For all variables, higher values represent preferable outcomes.

Table 5.11: Workplace model – standardized factor loadings

Latent constructs and indicators	Model 1	Model 2	Model 3
	Factor loadings		
Openness to discussion about mental health			
Discussion with line manager	0.841	-	-
Discussion with HR representative	0.781	-	-
Discussion with colleague	0.695	-	-
Support from organization			
Support - physical activity	-	0.769	0.640
Support - diet	-	0.798	0.659
Support - smoking	-	0.644	0.553
Support - stress	-	0.749	0.830
Support - when unwell	-	0.581	0.628
Wellbeing importance for the organisation	-	0.533	0.565
Support from managers			
Openness to discussion about mental health	-	0.446	0.578
Manager encouragement	-	0.833	0.609
Manager well-being	-	0.906	0.667
Covariances: Organization support–Manager support	-	0.515	0.739
Support PA–Support diet	-		0.471
Support PA–Support smoking	-	-	0.220
Support diet–Support smoking	-	-	0.320
Support diet–Support unwell	-	-	-0.012
Support stress–Support unwell	-	-	0.028
Support unwell–Manager encouragement	-	-	0.143
Support unwell–Manager well-being	-	-	0.251
Man. encouragement–Man. well-being	-	-	0.595
CFI	-	0.914	0.992
Sample size	29,928	29,928	29,928

CFI = Comparative fit index. For all variables, higher values represent positive outcomes.

Table 5.12: Direct and indirect influences of control variables on productivity

Direct influence	**Indirect influence**	**Personal model**	**Job model**	**Workplace model**	**Overall model**
Gender - Male		0.049*	0.077*	0.075*	0.051*
	All pathways	-	-0.022*	-0.019*	-
Combined		0.056*	0.055*	0.056*	0.056*
Age		0.066*	0.073*	0.071*	0.069*
	All pathways	-	-	-	-
Combined		0.071*	0.068*	0.071*	0.071*
Education - First cycle of secondary		0.065	-	-	0.063
	All pathways	-0.033	-	-	-0.031
Combined		-	-	-	-
Education - Second cycle of secondary		-	-	-	-
	All pathways	-0.041	-	-	-0.041
Combined		-	-	-	-
Education - Post-secondary		-	-	-	-
	All pathways	-0.053	-	-	-0.054
Combined		-	-	-	-
Education - Undergraduate		-	-	-	-
Education - Postgraduate or Ph.D.		-	-	-	-
Ethnicity - Asian		-0.024*	-0.035*	-0.040*	-0.023*
	All pathways	-0.009		0.007*	-0.010
Combined		-0.033	-0.033	-0.033	-0.033
Ethnicity - Black		-	-	-	-
Ethnicity - Mixed		-	-	-	-
	All pathways	-0.010	-	-	-0.010*
Combined		-	-	-	-
Ethnicity - Other or not specified		-0.025*	-0.026*	-0.032*	-0.022*
	All pathways	-0.010	-0.009*	-	-0.013*
Combined		-0.035*	-0.035*	-0.035*	-0.035*
Job - Manager		-	-	-0.031	-
	All pathways	-	0.012	0.020*	-
Combined		-	-	-	-
Job - Professional		-	-	-	-
Job - Technician or junior professional		-	-	-	-
	All pathways	-	-0.011	-0.011*	-
Combined		-	-	-	-
Job - Clerical support worker		-	-	-	-
	All pathways	-	-	-0.011	-
Combined		-	-	-	-
Job - Service worker		-	-	-	-
Job - Sales worker		-0.019	-0.020	-0.021	-0.018
	All pathways	-	-0.007	-0.006	-0.010
Combined		-0.028*	-0.027*	-0.028*	-0.028*
Job - Manual labor worker		-	-	-	-
	All pathways	-	-0.012*	-0.013*	-
Combined		-	-	-	-
Annual income (GBP)		-	0.038*	0.028*	-
	All pathways	0.073*	0.029*	0.031*	0.066*
Combined		0.058*	0.067*	0.058*	0.058*

Notes: * statistically significant at the <0.001 level. All other reported results statistically significant at the 0.01 level. ns = not significant. For all variables, higher values represent preferable outcomes. No or primary education, white ethnicity and other or not specified job category are used as baseline.

Table 5.13: Results of a SEM model with work engagement and controls only. Explained variable: productivity.

Variable	Std. Coef.
Work engagement	0.267***
Gender - Male	0.074***
Age	0.066***
Education - First cycle of secondary	0.046
Education - Second cycle of secondary	0.034
Education - Post-secondary (not university level)	0.030
Education - Undergraduate	0.057
Education - Postgraduate	0.041
Education - Ph. D.	0.011
Ethnicity - Asian	-0.043***
Ethnicity - Black	-0.011
Ethnicity - Mixed	-0.006
Ethnicity - Other or not specified	-0.034***
Job - Manager	-0.035**
Job - Profession	-0.003
Job - Technician or junior professional	0.004
Job - Clerical support worker	0.029**
Job - Service worker	-0.001
Job - Sales worker	-0.025***
Job - Manual labor worker	0.003
Annual income (GBP)	0.033***

**$P < 0.01$, ***$P < 0.001$.

Table 5.14: Detailed SEM results - Combined model

Explained variable	**Explanatory variable**	**Standardised coefficient**	**Std. err. + significance**
Productivity	Mental health	0.268	(0.006)***
	Commuting time	0.018	(0.005)***
	Physical health	0.248	(0.006)***
	Job characteristics	0.140	(0.008)***
	Manager support	-0.050	(0.010)***
	Organisation support	0.029	(0.010)*
	Work patterns	-0.039	(0.006)***
	Gender	0.051	(0.005)***
	Age	0.069	(0.006)***
	Education - First cycle of secondary	0.063	(0.021)*
	Education - Second cycle of secondary	0.058	(0.025)*
	Education - Post-secondary (not uni.)	0.068	(0.029)*
	Education - Undergraduate	0.078	(0.035)*
	Education - Postgraduate	0.061	(0.030)*
	Education - Ph.D.	0.020	(0.011)
	Ethnicity - Asian	-0.023	(0.005)***
	Ethnicity - Black	-0.007	(0.005)
	Ethnicity - Mixed	0.004	(0.005)
	Ethnicity - Other	-0.022	(0.005)***
	Job - Manager	-0.019	(0.010)
	Job - Professional	-0.010	(0.011)
	Job - Technician or junior professional	-0.002	(0.008)
	Job - Clerical support worker	0.008	(0.008)
	Job - Service worker	0.002	(0.006)
	Job - Sales worker	-0.018	(0.006)*
	Job - Manual labour worker	0.001	(0.005)
	Income	-0.007	(0.007)
	Constant	4.114	(0.141)***
Work engagement	Smoking	-0.046	(0.004)***
	Mental health	0.180	(0.005)***
	Alcohol consumption	0.032	(0.005)***
	Commuting time	-0.031	(0.004)***
	Physical health	0.038	(0.005)***
	Job characteristics	0.393	(0.006)***
	Manager support	0.181	(0.009)***
	Organisation support	0.011	(0.009)
	Work patterns	-0.051	(0.005)***
	Gender	-0.030	(0.005)***
	Age	0.016	(0.005)*
	Education - First cycle of secondary	-0.030	(0.018)
	Education - Second cycle of secondary	-0.038	(0.021)
	Education - Post-secondary (not uni.)	-0.023	(0.025)
	Education - Undergraduate	-0.071	(0.031)*
	Education - Postgraduate	-0.034	(0.026)
	Education - Ph.D.	-0.003	(0.010)

	Ethnicity - Asian	0.042	(0.004)***
	Ethnicity - Black	0.014	(0.004)*
	Ethnicity - Mixed	0.009	(0.004)*
	Ethnicity - Other	0.011	(0.004)*
	Job - Manager	0.063	(0.009)***
	Job - Professional	-0.021	(0.010)*
	Job - Technician or junior professional	-0.040	(0.007)***
	Job - Clerical support worker	-0.070	(0.007)***
	Job - Service worker	0.014	(0.005)*
	Job - Sales worker	0.005	(0.005)
	Job - Manual labour worker	-0.007	(0.005)
	Income	0.017	(0.006)*
	Constant	3.646	(0.133)***
	Mental health	0.059	(0.006)***
	Gender	-0.160	(0.006)***
	Age	-0.004	(0.006)
	Education - First cycle of secondary	-0.035	(0.023)
	Education - Second cycle of secondary	-0.025	(0.028)
	Education - Post-secondary (not uni.)	-0.022	(0.032)
	Education - Undergraduate	-0.007	(0.040)
	Education - Postgraduate	0.022	(0.034)
	Education - Ph.D.	0.022	(0.013)
	Ethnicity - Asian	0.107	(0.006)***
	Ethnicity - Black	0.054	(0.006)***
Mental health	Ethnicity - Mixed	0.023	(0.006)***
	Ethnicity - Other	0.043	(0.006)***
	Job - Manager	-0.017	(0.012)
	Job - Professional	0.018	(0.012)
	Job - Technician or junior professional	0.000	(0.009)
	Job - Clerical support worker	0.015	(0.009)
	Job - Service worker	0.017	(0.006)*
	Job - Sales worker	-0.011	(0.007)
	Job - Manual labour worker	-0.006	(0.006)
	Income	-0.105	(0.008)***
	Constant	11.602	(0.150)***
	Mental health	0.118	(0.007)***
	Physical health	0.107	(0.006)***
	Job characteristics	-0.085	(0.008)***
	Manager support	0.071	(0.007)***
	Gender	-0.142	(0.006)***
	Age	0.053	(0.006)***
	Education - First cycle of secondary	0.035	(0.023)
	Education - Second cycle of secondary	0.067	(0.028)*
	Education - Post-secondary (not uni.)	0.105	(0.032)*
	Education - Undergraduate	0.159	(0.040)***
	Education - Postgraduate	0.141	(0.034)***
	Education - Ph.D.	0.054	(0.013)***
Lifestyle	Ethnicity - Asian	-0.043	(0.006)***
	Ethnicity - Black	-0.032	(0.006)***

	Ethnicity - Mixed	0.010	(0.006)
	Ethnicity - Other	-0.004	(0.006)
	Job - Manager	0.021	(0.012)
	Job - Professional	0.006	(0.012)
	Job - Technician or junior professional	0.009	(0.009)
	Job - Clerical support worker	-0.010	(0.009)
	Job - Service worker	-0.001	(0.006)
	Job - Sales worker	-0.007	(0.007)
	Job - Manual labour worker	-0.007	(0.006)
	Income	0.084	(0.008)***
	Constant	-1.765	(0.146)***
Physical health	Smoking	0.047	(0.005)***
	Mental health	0.352	(0.006)***
	Sleep	0.091	(0.005)***
	Commuting time	0.020	(0.005)***
	Job characteristics	0.119	(0.007)***
	Manager support	-0.029	(0.010)*
	Organisation support	0.099	(0.010)***
	Gender	0.094	(0.005)***
	Age	-0.108	(0.006)***
	Education - First cycle of secondary	-0.041	(0.021)*
	Education - Second cycle of secondary	-0.061	(0.025)*
	Education - Post-secondary (not uni.)	-0.081	(0.029)*
	Education - Undergraduate	-0.062	(0.035)
	Education - Postgraduate	-0.045	(0.030)
	Education - Ph.D.	-0.014	(0.011)
	Ethnicity - Asian	0.002	(0.005)
	Ethnicity - Black	0.017	(0.005)*
	Ethnicity - Mixed	-0.010	(0.005)
	Ethnicity - Other	0.000	(0.005)
	Job - Manager	-0.003	(0.010)
	Job - Professional	-0.016	(0.011)
	Job - Technician or junior professional	-0.008	(0.008)
	Job - Clerical support worker	0.016	(0.008)
	Job - Service worker	-0.007	(0.006)
	Job - Sales worker	0.008	(0.006)
	Job - Manual labour worker	-0.015	(0.006)*
	Income	0.025	(0.007)***
	Constant	-0.820	(0.145)***
Job characteristics	Commuting time	0.025	(0.004)***
	Manager support	0.436	(0.009)***
	Organisation support	0.232	(0.009)***
	Gender	-0.022	(0.005)***
	Age	0.004	(0.005)
	Education - First cycle of secondary	-0.024	(0.018)
	Education - Second cycle of secondary	-0.038	(0.021)
	Education - Post-secondary (not uni.)	-0.048	(0.025)
	Education - Undergraduate	-0.068	(0.031)*
	Education - Postgraduate	-0.048	(0.026)

	Education - Ph.D.	-0.022	(0.010)*
	Ethnicity - Asian	0.011	(0.004)*
	Ethnicity - Black	0.002	(0.004)
	Ethnicity - Mixed	0.002	(0.004)
	Ethnicity - Other	-0.015	(0.004)*
	Job - Manager	0.036	(0.009)***
	Job - Professional	0.007	(0.010)
	Job - Technician or junior professional	-0.006	(0.007)
	Job - Clerical support worker	-0.020	(0.007)*
	Job - Service worker	-0.011	(0.005)*
	Job - Sales worker	-0.001	(0.005)
	Job - Manual labour worker	-0.010	(0.005)*
	Income	0.074	(0.006)***
	Constant	-1.273	(0.120)***
Manager support	Organisation support	0.868	(0.001)***
	Gender	-0.017	(0.003)***
	Age	-0.018	(0.003)***
	Education - First cycle of secondary	0.007	(0.012)
	Education - Second cycle of secondary	0.005	(0.014)
	Education - Post-secondary (not uni.)	0.003	(0.017)
	Education - Undergraduate	0.001	(0.020)
	Education - Postgraduate	-0.007	(0.017)
	Education - Ph.D.	-0.002	(0.007)
	Ethnicity - Asian	-0.009	(0.003)*
	Ethnicity - Black	-0.002	(0.003)
	Ethnicity - Mixed	-0.002	(0.003)
	Ethnicity - Other	0.003	(0.003)
	Job - Manager	0.018	(0.006)*
	Job - Professional	-0.008	(0.006)
	Job - Technician or junior professional	-0.009	(0.005)
	Job - Clerical support worker	-0.010	(0.005)*
	Job - Service worker	-0.005	(0.003)
	Job - Sales worker	0.006	(0.003)
	Job - Manual labour worker	-0.021	(0.003)***
	Income	-0.024	(0.004)***
	Constant	0.500	(0.075)***
Organisation support	Gender	-0.040	(0.006)***
	Age	-0.023	(0.006)***
	Education - First cycle of secondary	-0.003	(0.024)
	Education - Second cycle of secondary	0.020	(0.028)
	Education - Post-secondary (not uni.)	0.014	(0.033)
	Education - Undergraduate	0.050	(0.041)
	Education - Postgraduate	0.049	(0.035)
	Education - Ph.D.	0.006	(0.013)
	Ethnicity - Asian	-0.002	(0.006)
	Ethnicity - Black	0.010	(0.006)
	Ethnicity - Mixed	-0.011	(0.006)
	Ethnicity - Other	-0.019	(0.006)*
	Job - Manager	0.016	(0.012)

	Job - Professional	0.007	(0.013)
	Job - Technician or junior professional	-0.004	(0.010)
	Job - Clerical support worker	0.024	(0.010)*
	Job - Service worker	-0.019	(0.007)*
	Job - Sales worker	-0.033	(0.007)***
	Job - Manual labour worker	-0.044	(0.006)***
	Income	0.093	(0.008)***
	Constant	-1.575	(0.150)***
Commuting time	Gender	-0.003	(0.006)
	Age	0.016	(0.006)*
	Education - First cycle of secondary	-0.003	(0.023)
	Education - Second cycle of secondary	-0.023	(0.028)
	Education - Post-secondary (not uni.)	-0.009	(0.033)
	Education - Undergraduate	-0.012	(0.040)
	Education - Postgraduate	0.011	(0.034)
	Education - Ph.D.	0.014	(0.013)
	Ethnicity - Asian	-0.042	(0.006)***
	Ethnicity - Black	-0.039	(0.006)***
	Ethnicity - Mixed	-0.015	(0.006)*
	Ethnicity - Other	-0.023	(0.006)***
	Job - Manager	-0.026	(0.012)*
	Job - Professional	0.024	(0.012)
	Job - Technician or junior professional	-0.009	(0.009)
	Job - Clerical support worker	-0.004	(0.009)
	Job - Service worker	0.009	(0.006)
	Job - Sales worker	-0.020	(0.007)*
	Job - Manual labour worker	0.036	(0.006)***
	Income	-0.225	(0.008)***
	Constant	8.515	(0.145)***
Work pattenrs	Commuting time	-0.022	(0.005)***
	Job characteristics	0.394	(0.006)***
	Organisation support	0.058	(0.006)***
	Gender	-0.009	(0.005)
	Age	-0.005	(0.005)
	Education - First cycle of secondary	0.002	(0.020)
	Education - Second cycle of secondary	0.025	(0.023)
	Education - Post-secondary (not uni.)	0.032	(0.027)
	Education - Undergraduate	0.081	(0.034)*
	Education - Postgraduate	0.079	(0.029)*
	Education - Ph.D.	0.035	(0.011)*
	Ethnicity - Asian	0.015	(0.005)*
	Ethnicity - Black	0.004	(0.005)
	Ethnicity - Mixed	-0.001	(0.005)
	Ethnicity - Other	0.005	(0.005)
	Job - Manager	0.125	(0.010)***
	Job - Professional	0.120	(0.010)***
	Job - Technician or junior professional	0.030	(0.008)***
	Job - Clerical support worker	-0.031	(0.008)***
	Job - Service worker	-0.042	(0.005)***

	Job - Sales worker	-0.001	(0.006)
	Job - Manual labour worker	-0.033	(0.005)***
	Income	0.168	(0.007)***
	Constant	-3.068	(0.130)***
Alcohol consumption	Commuting time	0.069	(0.005)***
	Job characteristics	0.445	(0.007)***
	Manager support	0.089	(0.010)***
	Organisation support	0.022	(0.010)*
	Work patterns	-0.036	(0.006)***
	Gender	0.003	(0.005)
	Age	0.104	(0.005)***
	Education - First cycle of secondary	-0.039	(0.020)
	Education - Second cycle of secondary	-0.048	(0.024)*
	Education - Post-secondary (not uni.)	-0.059	(0.028)*
	Education - Undergraduate	-0.066	(0.034)
	Education - Postgraduate	-0.057	(0.029)
	Education - Ph.D.	-0.016	(0.011)
	Ethnicity - Asian	-0.024	(0.005)***
	Ethnicity - Black	-0.007	(0.005)
	Ethnicity - Mixed	-0.013	(0.005)*
	Ethnicity - Other	-0.006	(0.005)
	Job - Manager	-0.001	(0.010)
	Job - Professional	0.012	(0.011)
	Job - Technician or junior professional	0.001	(0.008)
	Job - Clerical support worker	-0.005	(0.008)
	Job - Service worker	0.013	(0.006)*
	Job - Sales worker	-0.010	(0.006)
	Job - Manual labour worker	0.022	(0.005)***
	Income	0.112	(0.007)***
	Constant	-2.496	(0.135)***
Smoking	Mental health	0.093	(0.006)***
	Gender	-0.006	(0.006)
	Age	-0.038	(0.006)***
	Education - First cycle of secondary	0.036	(0.024)
	Education - Second cycle of secondary	0.097	(0.028)*
	Education - Post-secondary (not uni.)	0.106	(0.033)*
	Education - Undergraduate	0.237	(0.040)***
	Education - Postgraduate	0.216	(0.034)***
	Education - Ph.D.	0.090	(0.013)***
	Ethnicity - Asian	0.026	(0.006)***
	Ethnicity - Black	0.015	(0.006)*
	Ethnicity - Mixed	-0.012	(0.006)*
	Ethnicity - Other	0.006	(0.006)
	Job - Manager	-0.019	(0.012)
	Job - Professional	0.059	(0.012)***
	Job - Technician or junior professional	0.022	(0.010)*
	Job - Clerical support worker	0.024	(0.009)*
	Job - Service worker	-0.008	(0.007)
	Job - Sales worker	-0.016	(0.007)*

	Job - Manual labour worker	-0.004	(0.006)
	Income	0.009	(0.008)
	Constant	0.835	(0.150)***
Sleep	Mental health	0.248	(0.006)***
	Lifestyle	0.022	(0.006)***
	Gender	-0.069	(0.006)***
	Age	-0.145	(0.006)***
	Education - First cycle of secondary	0.004	(0.023)
	Education - Second cycle of secondary	0.011	(0.027)
	Education - Post-secondary (not uni.)	0.017	(0.032)
	Education - Undergraduate	0.047	(0.039)
	Education - Postgraduate	0.048	(0.034)
	Education - Ph.D.	0.020	(0.013)
	Ethnicity - Asian	-0.031	(0.006)***
	Ethnicity - Black	-0.038	(0.006)***
	Ethnicity - Mixed	-0.001	(0.006)
	Ethnicity - Other	-0.012	(0.006)*
	Job - Manager	0.005	(0.011)
	Job - Professional	0.016	(0.012)
	Job - Technician or junior professional	0.019	(0.009)*
	Job - Clerical support worker	0.009	(0.009)
	Job - Service worker	0.005	(0.006)
	Job - Sales worker	0.019	(0.007)*
	Job - Manual labour worker	-0.012	(0.006)
	Income	-0.036	(0.008)***
	Constant	8.527	(0.148)***

Notes: Statistical significance *** p<0.001, ** p<0.01, * p<0.05.

Chapter 6

Conclusion

This thesis consists of four chapters encompassing topics of labour force and its productivity, with results ranging from the macroeconomic impacts of population ageing to individual-level factors behind workplace productivity loss, and methods from micro-simulation modelling to regression analysis. The overarching goal of the study is to use innovative research techniques to assess, in a quantifiable and understandable way, the risks and opportunities associated with human labour in order to prompt a response from stakeholders across the economic spectrum that may lead to improved outcomes from the society as a whole.

In Chapters 2 and 3, I focus on the case of the Czech Republic, an exemplary country with ageing and slowly shrinking population facing long-term prospect of increasing pressure on public finances as a result of progressive shifts in the old-age dependency ratio. The analysis in Chapter 2, done using simulation of an overlapping generations model coded in MATLAB, shows that, conditional on a continuous economic growth, the adverse demographic changes may not necessarily lead to lower real pensions while keeping pension budget balanced in the existing PAY-GO scheme. At the same time, this is only at the cost of a growing disparity between pre-retirement earnings and pension benefits. To avoid that, pension indexation must follow nominal wages completely; this would almost certainly lead to explosive pension budget deficits in absence of an increase in social security taxation or retirement age. A transition to a well-designed multi-pillar pension scheme may provide a feasible solution in this regard, resulting in reasonable retirement benefits without an excessive cost of transition. A similar model used in Chapter 3 shows that, on the positive side, the ageing population would hold comparatively higher savings, promoting capital accumulation in the economy, and demand more goods and services, leading to higher output of the economy as a whole. At the same time, the decreasing labour supply would lead to higher equilibrium wages and cost of production, which will force firms to substitute some of the labour input in their production for capital, increasing the average capital/labour ratio by 10% by 2050.

In Chapter 4, we analyse the long-term effects of later high school starting times in the US in order to highlight the substantial estimated losses associated with insufficient sleep across the population. The hypothetical scenario, assuming a state-wide universal shift in school start times to 8.30 a.m. considered the benefits of higher academic performance of students and reduced car crash rates with a range of possible costs from \$150 per student per year to \$700 per student per year with additional upfront one-off infrastructure investment of \$110,000 per school. Despite the high assumed costs, the benefit–cost projections suggest that delaying school start times is a cost-effective, population-level strategy, which could have a significant impact on public health and the US economy.

Lastly, Chapter 5 provides new insights into the determinants of labour productivity loss using detailed information on personal and job-related factors from 31,500 individuals in the UK. The study accents the importance of physical and mental health in today's work environment as more than 84% of the direct effects on productivity loss were associated with either one or both of the factors in addition to 93% of the indirect influences are mediated through them. The study also shows that the network of influences affecting employees' productivity is more complex than what hitherto presented in the literature, highlighting the need for a more tailored strategy to improve employees' well-being and, from the technical perspective, showing that one must consider the entire spectrum of associated factors in the analysis to prevent unwanted biases from affecting the results.

Appendix A

Responses to Referees

I am grateful to all the referees for their comments and useful suggestions in their referee reports. Following is the full list of comments and my responses to them. The comments from referees are presented in *italics*, my responses are typeset in the normal font.

A.1 Doc. Ing. Ondřej Schneider MPhil., Ph.D.

A.1.1 First paper

1. *I would appreciate if Martin incorporated and quoted works by his predecessor in this noble endeavour, namely David Marek's dissertation*

   I have added more text about David Marek's dissertation (Marek, 2007) and additional citation of the version published in a refereed journal (Marek, 2008), as well as his later brief assessment of the Czech pension system for the European Commission (Marek, 2005).

2. *I find the presentation of results in tables 2.2-2.5 rather challenging for a reader. Similarly, the figure 2.2 would be much easier to comprehend if wages preceded pensions and "value" were better defined. Martin compensates these omissions by a very clear presentation of calibration parameters in table 2.1. and very careful discussion of parameters' sensitivity.*

   Thank you, I have kept the table structure to maintain consistency with the published version of the paper, but added further explanatory text in Section 2.5.1 to better introduce the tables and what they represent. I have also rewritten the notes accompanying each table, with extra information in Table 2.3 to provide better introduction.

3. *Table 2.7 presents Martin's estimates of market imperfections and their impact on final pensions, which I find very interesting and honest thing to do. Perhaps, it would be interesting to provide an rationale for using the parameters comparing them to the market data, when available (cost of annuity, for example).*

   The works of e.g. Krueger and Kubler (2006), Murthi et al. (2001), OECD (2017) and Sluchynsky (2015) report that efficiency of private pension systems, measured by total operating costs vs assets managed, varies considerably across countries, ranging from 0.1% to 1.5% p.a. of assets under management. In the Czech Republic, the average operating costs are as high as 1.3%. Fees charged to plan members to cover such costs vary correspondingly. Since it is impossible to predict what the actual cost to members could be in a state-run pension fund, the chapter uses the upper bound estimate of 1.5% to show the potential range of effects. Similarly, the average cost of transforming pension fund balance into an annuity varies and depends on the particular life tables used for its calculation. The 10% cost used in the study again corresponds to an upper bound estimate presented in the literature to outline the full range of effects. Additional explanation was added to Section 2.4.4.

   For financial market crash, the study considers a 40% reduction in asset value, which broadly reflects the average drop in individual account balances across all pension funds in Chile in 2008.

A.1.2 Second paper

1. *As the modelling is concerned, I find it interesting that while in the previous model, households utility was derived from consumption and from bequests (equation 2.5, page 13), here bequests do not play any role (equation 3.2, page 42). I do not think it would change the results in any significant way, but I wonder why Martin chose a different approach.*

Exclusion of bequests from the model indeed plays a negligible role in the overall results because the results report changes against a baseline and there are no particular changes to bequests-related parameters in any of the modelled scenarios. The reason for omission was purely practical: a full simulation of the baseline OLG model from Chapter 2 can take multiple days and adding the CGE components in Chapter 3 increase the computational requirements further. Given the virtually nonexistent effect on the results, bequests were therefore omitted to reduce model's complexity.

2. *I also miss a similar calibration table as in the previous chapter, as now I have to scramble to find the parameters in the text on page 45.*

   Good point, thank you. I have added the table to Section 3.3.4 (Table 3.1).

3. *I recommend to discuss simulation results (section 3.4) in more detail, as the text provides little intuition. Why, for example, interest rate declines so little (from 3.5% to 3.36%) and savings increase so little (by 0.8%)? These are minuscule changes compared with the massive demographic shifts.*

   As explained in Section 3.4.1, these are results of many effects supporting or offsetting each other. For example, the savings profile in 2019 (see Figure 3.2) shows a large proportion of savings associated with the cohort aged 58-62, which is going to retire by 2035 and start to consume majority of its wealth accumulated prior to that point. This, as well as the lower number of individuals aged 30-45 in 2035, offsets the overall trend to save more. Additional explanation has been added throughout Section 3.4. The results have slightly changed as a result of model redevelopment (see the next comment).

4. *On the other hand, Martin's estimates of sectoral effects are surprisingly confident (-6% for agriculture, but only -2% for electricity…). How much confidence does he have in these specific numbers?*

   Given the feedback from all referees, I have reconsidered the model specifications and study's purpose. The model now works with a closed economy to be consistent with those presented in Chapters 2 and 4, the set of equations determining sectoral demand for goods and services has been corrected, and the study now focuses more on the positive/negative effects of migration, although the sectoral effects are still modelled in the same way. The results for the agricultural sector are now more in line with the other sectors. Overall, the aggregate results have not substantially changed.

A.1.3 Third paper

1. *The text is slightly less crisp and explicit in this section, as for someone not familiar with the US school system, school buses and widespread driving by high school students may find Martin arguments confusing. It would be helpful, for example, to specify whether the study looks at high school students (who can drive from age of 16) or all students (who are often bused to their schools).*

   As discussed in Section 4.1, the study looks, in principle, at both middle and high schools, although most of the effects are associated with high school students, as correctly pointed out by the referee. Equally, the education attainment parameters (Sabia et al., 2017) refer to high school graduation and college attendance rates. Additional information was included in Section 4.3 to avoid confusion.

2. *Crucially, Martin spends surprisingly little time on explaining the link between the school start times and car crashes or, even more importantly, students lifetime earnings. These estimates, however, are the driving force of the model and the whole paper and thus would benefit from a thorough discussion. Are we really sure that academic grades determine lifetime productivity (page 67)? Should not we at least mention the signaling theory stipulating that the education serves rather limited role in future productivity of employees? Then, of course, I would be interested in a discussion of linearity of the insufficient sleep time effects on academic performance (page 69).*

   This is a very good point, thank you. Indeed, these are critical assumptions behind the model's results and are now better explained in Section 4.2.1.

   For various reasons, particularly the ability to drive from the age of 16 (with Learners Permit available from the age of 14 in some states), popularity of car transport in the US, good healthcare and generally low mortality rates associated with natural causes of death in the 10-19 age group, car crashes are a major cause of death among teenagers. Specifically, for the US population aged 15-19, transport injuries constitute 28.8% of all deaths, with car accidents being the most prevalent, covering 79.4% of all such deaths (Roth et al., 2018). To be fair, the absolute number of deaths is still relatively low, but it is not an insignificant factor in the broader picture. To assess changes in the mortality rates, we rely solely on the prior studies (Danner and Phillips, 2008, Tefft, 2014) and use their lower-bound estimates to obtain a conservative estimate of the beneficial effects of longer sleep.

   Most of the positive effect in the model comes from higher productivity. Here, we rely on the human capital theory, suggesting that higher education contributes to the economy by increasing the potential productivity of graduates, i.e. that individuals with higher educational attainment would generally be more productive. We proxy the productivity gap by looking at the average earnings of individuals with primary, secondary and tertiary education (by gender, ethnicity and state). On the other hand, the signalling theory suggests that higher education contributes to economic performance by enabling employers to differentiate potential employees who will, on average, be more productive from those who will be less productive. In this case, the role of better education would be rather limited. The theories are sometimes considered mutually exclusive to a large extent; for instance, Gerber and Cheung (2008) consider the following reasons for the observable income disparity: universities increase human capital, graduates signal their status to employers, university students garner more valuable social capital, and university graduates have enjoyed advantages such as family affluence or ability that generate more favourable outcomes. However, as argued e.g. by Marginson (2019) and Pericles Rospigliosi et al. (2014), the links between education and work are complex, context-bound, varying by country, field of study, occupation or industry, and the individual avenues of effect may be supporting, rather than contradicting each other. That is, universities may increase individual's productivity potential *and* get them a better job through employer signalling.

   Hence, I believe that the assumption of increased productivity due to additional sleep is reasonable although the particular parameter value may be contested. Note also that the benefits of longer sleep for teenagers may go beyond educational attainment as the brain functionality is develops at that stage of life and longer sleep may increase one's long-term productivity and performance regardless of change in educational attainment.

3. *Then, of course, I would be interested in a discussion of linearity of the insufficient sleep time effects on academic performance (page 69).*

   Here we must unfortunately rely on the admittedly limited empirical evidence from the prior literature. That being said, the relationship is not linear but rather quadratic with decreasing marginal returns of additional sleep as described in Equations 4.7-4.8.

4. *As for the results, they are quite intuitive once we accept the model assumptions. I only struggle to understand why car crashes improve with a one-year lag (page 73).*

   The one-year lag is a consequence of the cohort-component model (see Eq. 4.1), which considers that population in period $t+1$ will be comparatively larger due to fewer deaths in period t. This is mainly a notation issue; some of the effects would likely be visible in the first period. This is now better explained in the text.

A.1.4 Fourth paper

1. *Given the number of factors (roughly 40) there must have been issues of multicolinearity that Martin briefly addresses on page 97, but I would appreciate a more formal presentation of regression results (there are numerous tables in the appendix, but they mostly cover descriptive statistics).*

   Good point, thank you. The detailed results for the combined model are presented in Table 5.14. I did not report detailed results for the other models as the tables are very long. The potential issues with multicollinearity are solved through use of latent factor variables, which combine highly correlated variables in a single construct and use that in the subsequent modelling instead (see Tables 5.9-5.11).

A.2 Erez Yerushalmi, Ph.D.

A.2.1 Overall comments

Note that in UK Business Schools and Economic Departments, these journals are not considered high ranking. Rather, I think that these journals are more suitable in - for example - medical schools, inter-disciplinary departments, sociology /education departments etc. (In the UK, there is a clear list of journal rankings for economics/business that follow the Chartered Association of Business School (CABS).) Martin's strategy may have been to publish quickly (and probably work in the private sector). With some additional work and refinement, I believe that these papers could have been published in higher-ranking journals in Economics and Business (2 or 3* CABS).*

The publication strategy varied by paper. For the first study, published in the *Czech Journal of Economics and Finance*, I believed that publication in a Czech journal is appropriate given the sole focus of the study on the Czech pension system and did not consider foreign journals. For the third study, published in *Sleep Health*, the aim was to publish in an American journal (as its focus is on the US) with good reach to practitioners and policy-makers in the area. I believe that this was one of the reasons why the study contributed to the recent change in the school starting times in California. For the last study, published in *Journal of Occupational and Environmental Health Medicine*, the reasoning was similar; the journal has excellent reach to the academic and professional base that may be interested in the findings. The choice was also partially determined by Vitality (an insurance company in the UK that provided the data).

A.2.2 First paper

1. *The paper is already published. In my opinion, with a bit more editing, this paper could have been published in a 2* or 3* economics/business journal (i.e., a higher ranking journal targeted for economics).*

   Thank you, I chose Czech Journal of Economics and Finance principally to increase the chance that the policy-oriented study would be read by the relevant academics and policy-makers in the Czech Republic as all papers in the journal are publicly available free of charge and it is a Czech journal.

2. *I would have explained the figures and tables more carefully to help the reader (i.e., add a bit more text). E.g., it would have been useful to have more text in Table 2.2, so that readers will learn how to interpret the following tables, which have similar information.*

   Good point, thank you. I have added further explanatory text in Section 2.5.1 to introduce the tables and what they represent, as well as text throughout Section 2.5 for easier understanding of the figures. I have also rewritten the notes accompanying each table, with extra information in Table 2.3 (which was Table 2.2 in the original version of the dissertation as per the referee's comment).

3. *There are many scenarios being analysed in this paper. The clarity of the paper could have been improved by explaining the scenarios more carefully, making it easier for the reader to comprehend. I think this is the biggest weakness of this paper.*

Agreed, thank you for the comment. Section 2.4.4 has been rewritten to be in line with how the simulation results are presented and Table 2.2 has been added to summarise all changing parameters and their ranges.

4. *I would have liked a better explanation of the demographics model. Is this a cohort-component model? What is the model?*

   It is indeed a cohort-component model with the essentially same structure as the one described in Eq. 4.1. This is now explained in Section 2.4, with Eq. 2.19 added to the description.

A.2.3 Second paper

1. *I'm confused starting around section 3.3.1, and the paragraph before it. How is income obtained? How is efficient labour obtained? Is efficient labour a function of hours available, population size, other? This section would benefit from more clarity.*

   Income and efficient labour parameters/distribution are obtained directly from CSO (2018), as outlined in Figure 3.5, using the assumption that workers' productivity can be roughly proxied by their wage. Hence, each population subgroup is associated with its average wage in the Czech Republic in 2017 and the overall efficient labour is a combination of the average wage and the number of individuals in the population subgroup. That is, e.g. the difference in the amount of efficient labour supplied by professionals vs junior professionals in manufacturing can be approximated by multiplying the average wage and the number of workers in those two subgroups. Hours worked are not considered in the equation as they are, on average, implicitly reflected in the wage difference. This is now better explained in Section 3.3.

2. *Income is also a function of the wage. Wage changes according to demand for labor. Therefore, income changes. Here it seems that income is exogenous in the model. Is wage fixed across time?*

   No, the sector-specific equilibrium wage is endogenous and evolves over time according to Eq. 3.11 and 3.13. More specifically, consider Eq. 3.1: $I_{s,z,t} = (1-\tau)\, e_{s,z} w_{z,t}$. Here, income is a function of a baseline wage parameter $e_{s,e,o,p}$, set to their real-world level in 2017 as per above for each subgroup, and a scaling equilibrium wage multiplier $w_{e,o,p,t}$ set to one initially. That is, the total income is set to the real-world level for each subgroup in $t = 1$. From $t = 2$, income varies with $w_{e,o,p,t}$ (which fluctuates around one), which is determined by labour supply-demand interaction (Eq. 3.11) and sectoral labour supply (Eq. 3.13). Note that there is no inflation assumed in the model, all changes are therefore to the real wage. This is now better explained in the text.

3. *Equation 3.1 is unclear. Is $e_{s,z}$ efficient labor?*

   Yes, this has been updated in the text.

4. *Eq 3.4 and 3.5. Can you explain this a bit more carefully? How is savings obtained in this model? Is savings exogenous and different for different income groups?*

   This is a very good point, thank you. Savings are determined endogenously within the model; as defined in Eq. 3.4, all non-consumed income (sum of earnings and value of assets saved in the previous period plus any interest on them) is saved in interest-bearing assets each period. Since income $I_{s,z,t}$ is determined endogenously and varies by population subgroup (see above) and consumption is inherently determined by income (see Eq. 3.2), savings indeed vary by population subgroup as well. This is now better explained in the text.

5. *Eq. 3.7 and 3.8 need to be explained carefully. At the moment, I don't understand them and they seem to be wrong. Eq. 3.8: why do you multiply a price term in the CES function?*

   I think that σ_d is not the income elasticity of demand. Is it? I think it should be σ_a, the elasticity of substitution between domestic goods and foreign imports given by the Armington equation in Eq 3.8.

   Eq. 3.7 is intended to be the demand function for Q. But which one, domestic, foreign, or the composite. The demand functions are unclear to me. The price indexes are unclear to me. After looking at this part of the model more carefully, I am a bit 'suspicious' that something is wrong.

   It might be that income elasticity in your model is equal to 1 because you are using constant returns to scale (CRS) functions? Is your SAM balanced, or not? If not, than you might not be using CRS functions, whereby the income elasticity of demand could be higher or lower than 1. Yet, these should be substitution elasticities because you are using a constant elasticity of substitution (CES) function (Eq 3.8).

   Why do you say that σ_d is the income elasticity? Can you prove this mathematically? Overall, Equation 3.7 and Eq 3.8 are unclear to me. The paragraph below these equations that explain them seem to me wrong. Needs to be checked carefully.

   Thank you very much for the detailed analysis and comments. There were indeed two errors in Eq. 3.7 and 3.8, which refer to household demand for sectoral, regional and imported goods, a result of the intra-temporal cost minimisation problem. Firstly, Eq. 3.8 should indeed not contain the price terms P^d and P^f. This was implemented correctly in the simulation model but described wrongly in the text. Secondly, σ_d is indeed not the income elasticity of demand. Following Eq. A.34 in Lecca et al. (2013), the parameter's purpose was to create a link between changes in consumption of the composite good, as determined by Eq. 3.2, and sectoral consumption. However, this was not done correctly as a substitution elasticity should have been used instead, as per the referee's comments.

   Upon reflection, and in line with other suggestions from the referees and the dissertation pre-defence committee, I have altered the model as follows. Since elasticity of demand is not essential for the model *per se* but it is important to track changes in consumption patterns with age, I follow Fehr et al. (2014) and use a CES function to determine sectoral consumption as a function of overall consumption and include the age-specific parameters $\kappa_{s,p}$ explicitly in the model description (see Eq. 3.7). Correspondingly, demand for sectoral goods and services can be described using Eq. 3.9. The model description and simulation results have been updated accordingly.

   In line with the other comments, the study's overall scope is now more aimed at assessment of migration on the Czech economy as a whole and the text throughout the study has been changed to better reflect this and provide better motivation for the three modelled scenarios. Finally, the model now considers the Czech economy to be closed in line with the other studies presented in Chapters 2 and 4.

To reflect on the other comment, the underlying SAM is balanced in period $t = 1$ as it is taken, in its unchanged form, directly from the Global Trade Analysis Project database (Aguiar et al., 2016). It then remains balanced in the subsequent periods as all of its components are proportionally increased/reduced following the changes in the underlying OLG model.

6. *The model is complex (as is expected). To help the reader, maybe it would have been helpful to include a flow chart of the model.*

   With the foreign sector removed and the details of the solution method presented in the Appendix, I believe that the model flowchart is no longer needed.

7. *Scenarios are clear. However, could be useful to add the motivation for choosing them?*

   Motivation to consider such scenarios and reasoning behind the particular choice was added to Section 3.3.5.

8. *P. 47, second paragraph after Sec 3.4.1. How is savings chosen in this model. Is this exogenous and depends on the income of the specific individual? Savings is not really explained in the model. I think this relates to Eq 3.4 and 3.5, but I'm not sure. Is this part of the OLG feature? Maybe worth expanding here a bit, or expand around Eq 3.4, 3.5?*

   Savings are subgroup-specific and endogenously determined in the model. This is now better explained in Section 3.3.1 as per another comment above.

9. *Section 3.4.2: What is the significance of your results? What is the story? You present your results in Table 3.3 and supply the text. But I am unsure about the significance. Why do we care? What are the policy implications? Motivation behind these results are necessary to make the paper more interesting.*

   This is now better discussed throughout Chapter 3: the Czech economy is projected to face a substantial reduction in its effective labour supply and changes in aggregate as well as sectoral demand patterns, leading to lower economic growth, increase in unit labour costs and lower competitiveness of the economy as a whole. This can be offset through replacement migration, yet the migration patterns would need to significantly change for going forward in order to achieve this.

10. *Other thoughts: Any reason why you model Czech citizens immigrating or emigrating to the country rather than others nationalities? Is this just to give a scenario or is there a real policy reason behind this?*

    The emigration scenario considers foreign-born citizens (rather than Czechs) to leave the Czech Republic. The immigration scenario considers only Czech citizens to provide a good policy-related reason (Brexit) and also because immigration of foreign nationals to the Czech Republic is generally very low. This is now better explained in Section 3.3.5.

11. *I understand that the main conclusion is that Agriculture would be hit. However, the paper doesn't really give a feeling of urgency because it lacks a clear motivation. Is there a more urgent story to 'take home' with us? We need a bit more of: "Why do we care?"*

This has been rewritten in the text and is now positioned around the possibility to offset the inherent demographic changes using replacement migration.

A.2.4 Third paper

1. *Eq. 4.9 compacts all previous equations. Is this exogenous to the model? Is this done in Excel or Matlab? Would have been nice to know.*

   Yes, this is exogenous to the model and works only with empirical data from US Bureau of Economic Analysis (2016). The resulting parameters, calculated in Excel, are inputs in the main model, coded in MATLAB.

2. *Second paragraph in section 4.2.2. I would simply change the wordings: "The economy has three sectors - households, firms and government – which continuously . . . ." Instead, I would change this to agents and not sectors. Firms could represent sectors/industries.*

   Thank you, this has been updated.

3. *Why did you decide to use an OLG model for this paper? Was it necessary?*

   Not in particular; we had the model readily available from my previous work (the first paper presented in the dissertation) and there are no obvious downsides of using the model. On the contrary, the model considers a variety of microeconomic factors related to ageing and therefore arguably provides more precise estimates.

4. *Why did you add the ability for agents to move between income groups (eq. 4.10). What is the reason/purpose for this? I understand that it doesn't actually change the their wage distribution (end of page 70). So what was the purpose?*

   This was a feature of the underlying model (as prepared for the previous study). It does not change the aggregate results in any way, so it was easiest to kept it in.

5. *P. 71, you wrote $I_{a,z,t}$. Shouldn't it be $I_{s,z,t}$?*

   Indeed, thank you for the observation. This has been fixed.

6. *End of page 72. Why did you choose the cost as a perpetuity rather than a one-off cost? What is the reason?*

   We consider both an upfront investment and a cost in perpetuity in different scenarios. This is done to provide a better overview of the potential impacts.

7. *In Figure 4.2: what is, for example, Normal (1) and Normal (2)? It was not properly defined (I think).*

   Good point, thank you. The scenarios are now better described in Section 4.2.3 and throughout the tables and figures with results. In addition, Table 4.6 now properly describes the costs in the 'Very high' scenario as a \$330,000 one-off investment and \$500 annual costs rather than \$220,000 and \$350 as before.

A.2.5 Fourth paper

1. *Would have been useful to have a summary/literature review that compares results from other papers with the main results from this paper. This would have given a better feel to what the results actually mean.*

   As discussed throughout Section 5.4, the results are generally in line with the prior literature, particularly when looking at the three individual models in which most of the explained variables are highly statistically significant and work engagement is a major factor in determining productivity losses (see e.g. Demerouti and Cropanzano, 2010, Salanova et al., 2005, Xanthopoulou et al., 2009, Kuoppala et al., 2008, Lewis and Malecha, 2011). What is different – and more important – is the decrease in importance of work engagement and, to lesser extent, lifestyle factors once all of the variables are considered at the same time in the overall model discussed in Section 5.4.3.

2. *The paper gives the reader an indication of the important elements of workplace productivity (e.g., mental health, physical health, organizational support are the most important elements). However, what do these values mean? Can we use them as inputs into other types of models (e.g., as inputs into a similar model as you did in your labor efficiency paper 3 (Chapter 4))? Bottom line, besides understanding the importance of each variable within this framework, how do I use these results for other models?*

   Indeed, we could use the findings in other models. In many economic models, productivity changes over time refer principally to technological improvements. However, the data from Britain's Healthiest Workplace survey analysed in Chapter 4 show that employees are inherently not perfectly productive due to various reasons unrelated to technology and that their workplace productivity could be affected by improving particularly their physical and mental health, regardless of technology improvements. We can therefore consider various individual-, workplace- or state-wide interventions affecting employee health and how these may in turn affect productivity and output of the firms and economy as a whole.

A.3 Ing. Kamil Dybczak, Ph.D

A.3.1 Adopted research strategy

1. ***Why additional heterogeneity beyond age?*** *Although, the extension of the OLG model by heterogeneous agents is a remarkable achievement, Chapter 2 does not really explain how such an extension improves the analysis (more uncertainty, larger precautionary savings?). In addition, Chapter 2 presents rather aggregated results, which in my view, could have been achieved without extending the OLG model by additional heterogeneity. Although, Figures 2.2 and 2.5 present wages, income and pension benefits for twelve income groups, a true distributional analysis seems to be missing. For example, it would be interesting to see a comparison of distributions of pensioners over 12 categories under alternative pension schemes (or in the initial and final steady state).*

   Thank you for the valuable suggestion. While I agree that the results presented in Tables 2.2-2.7 could be obtained using a model with homogeneous agents without a substantial impact on the conclusions, I believe that modelling intra-generational differences among households is crucial for a proper assessment of the effects. In particular, the existing Czech pension system is highly redistributive (see Section 2.3.1), the implied consumption and savings behaviour in the model is therefore very different for households whose pension/wage ratio is near 100% compared to those with a pension/wage ratio of 25%. In contrast, the two alternative pension schemes are less redistributive but and also contain various safety nets for the poorest, again affecting agents' behaviour in the model. We can see this in Figure 2.5, which compares average pensions for the 12 income groups across the three alternative pension schemes. The subgroup analysis is also reported in Figures 2.6 and 2.7, which highlight the difference in pensions and their structure for the average household and for households in the lowest income group.

   I have also added an overview distribution of agents by income group in the first and last period of their lives (see Figure 2.9) and, as per another comment below, also a transition matrix used to approximate the idiosyncratic shocks to agents' income over time (see Table 2.9). The corresponding modelling process is described in Section 2.4. Note that because pensions are determined by prior earnings (unfunded systems) or contributions to pension funds (funded systems), distribution of pensioners across the 12 income groups does in fact not change by pension scheme and broadly follows that shown in Figure 2.9, i.e. there will always be approx. 2% of agents in the lowest-income group, etc. What changes, however, is their actual pension as described in Figure 2.5, thus I believe that reporting on the results is sufficient.

2. ***Open or closed economy?*** *Modelling a closed or an open economy has significant implications for simulation outcomes (see for example Domeij and Floden (2004): "Population Ageing and International Capital Flows." CEPR Discussion Papers 4644). In a closed economy, domestic financial markets clear every period and the domestic interest rate is affected by supply of and demand for funds, i.e. the size of households' savings and firms'/government's demand for resources to finance investment and deficits. This contrasts with an open economy model, where the world interest rate is set exogenously and the excess of supply of domestic savings results in capital outflows from a domestic economy*

to the rest of the world and a resulting surplus in the current account of the balance of payments (excess of demand for funds would result in capital flows in the opposite direction). While Chapters 2 and 4 rest on closed-economy assumptions, Chapter 3 assumes an open economy model. Is there any specific reason? For example, is the introduction of an external block critical for the analysis of migration flows in Chapter 3?

This is an excellent point, thank you. I believe that introduction of an external block in Chapters 2 and 4 would not significantly affect the results as all of the results are reported in comparison to the baseline scenario; opening the economy would affect each scenario individually, but the differential impact would likely be minimal. In fact, the same applies to some extent for Chapter 3 as well. The external block is not critical for analysis of migration flows and has been removed during redevelopment of the study (see responses in Section A.2.3 above) for simplicity and in order to maintain better consistency with the other chapters.

3. ***Why a CGE model?*** *What is the main focus of Chapter 3? Is it migration, sectoral analysis or a combination of the two? If it is migration, could this issue be analyzed without introducing the CGE model?*

   It is a combination of the two: migration is considered a means to offsetting the ongoing (unstoppable) demographic changes in the Czech Republic, but sectoral analysis is the way of representing the impacts. The CGE component of the combined model is not critical for the analysis but I wanted to add it to see the implications. The motivation and conclusions are now better articulated in the study.

4. ***Bequest motive*** *Depending on parametrization of the model, bequest motive extends households' planning horizons and thus has consequences for the impact of policy reforms in the model. As such, the thesis should, at least briefly, elaborate on why the bequest motive has been introduced only in Chapter 2 and not in Chapters 3 and 4.*

   Agreed, this is a good point. This is now explained in Chapter 1. The reason for exclusion of the bequest motive was to lower the computational demands of the simulation models as is not essential for analysis in the two models.

5. ***Anticipated or unanticipated reforms*** *The analysis of a pension reform (Chapter 2) assumes a reform is implemented in period 2. It seems a reform comes as a surprise (an unanticipated shock) to the agents. In reality, however, agents are well aware of future developments in retirement age for several years ahead and the same argument applies (probably even more) in case of a structural pension reform. Thus, pre-announced future policies have implications for the current behavior of agents both in real life as well as in economic models. While I'm not requesting any changes in the simulations, it would be useful if the text recognizes these issues.*

   Thank you for the excellent suggestion. This is now addressed in Section 2.4.4.

A.3.2 Alternative scenarios

1. ***The extent of pension indexation*** *Chapter 2 (Table 2.2) quantifies the impact of population aging under the PAY-GO system when assuming a different degree of pension*

indexation. The chapter assumes three variants (full, 1/3 and none), and presents rather optimistic results in the last column of Table 2.2 (a cumulative budget surplus close to 300 percent of GDP in 2050 in a zero-indexation scenario). However, indexing wages more than fully to nominal wage seems to be more in line with the actual situation in many countries.

While I agree that no indexation beyond inflation (i.e. the 'None' scenario) is highly improbable, I believe that it is useful to have such an extreme scenario in the model to depict the full range of possible outcomes. Additionally, the baseline indexation (at the level of inflation plus one third of changes in real wages) is consistent with the development in the Czech Republic in the recent years (see Figure 2.1) and hence I believe that considering a maximum indexation at the level of nominal wages is appropriate and any indexation beyond that level is rather unrealistic in the current Czech setting.

2. ***Return on savings*** *In the same vein, Table 2.6 presents the impact of population aging on a multi-pillar and a fully funded pension schemes assuming a real rate of return on savings of 1, 3.5 and 6 percent. Given the global decline in rates of return over the past decade, secular stagnation, and the most recent developments in the financial sector (some of commercial banks have started charging negative nominal interest rates on long term deposits), the chapter may usefully present and discuss a scenario with zero or even negative rates of return.*

   While I agree that we may potentially see zero or even negative return on assets invested in pension funds in the future, I believe that the already wide range of returns assumed in the study gives a good overview of the potential implications for the two alternative pension schemes. Additionally, I believe that the example of long-term deposits with commercial banks is not fully adequate in this regard as the assets in multi-pillar and fully funded pension schemes would be invested in pension funds, which generally invest in stocks and bonds (and start to invest more and more in private equity, real estate, infrastructure, and various securities) and mostly achieved positive return on assets in the recent years, with the overall returns sometimes being as high as 8.3% (OECD, 2017). The assumed range for retirement asset returns is therefore not completely out of place.

3. ***Retirement age*** *On several occasions, Chapter 2 mentions that increasing retirement age to 67 years may not be feasible in reality. This is indeed true for physically demanding professions, nonetheless health standards and life expectancy have improved immensely over the past decades and these trends are expected to continue. To contain the impact of these trends on sustainability of pension funds, several countries (Germany, Portugal or Hungary, etc.) have linked developments in retirement age to life expectancy. It would be interesting to know by how many years the average retirement age would increase in case of the Czech Republic if such an approach is followed.*

   This is an excellent suggestion. This is now discussed in Section 2.6. '*On the other hand, countries such as Finland, Cyprus, Denmark, Estonia, Greece, Italy, the Netherlands, Portugal and Slovakia have linked statutory retirement age to life expectancy and are going to increase it as a result (Finish Centre for Pensions, 2019). For the Czech Republic, life expectancy is assumed to increase from the current 79.2 years to 82.8 years by 2040 and* *keep increasing beyond that, to 85.8 years by 2070 and more (United Nations, 2019). Hence, the statutory retirement age could increase further than to 67 years by 2042 as assumed in the model, perhaps to 69 years by 2070 to broadly match the further changes in life expectancy, keeping the statutory retirement age at approx. 0.8 of population life expectancy.'*

A.3.3 Model description

1. ***Government*** *OLG models are inherently general equilibrium models, where economic sectors are linked by macroeconomic identities, i.e. a model is closed. It seems that some of the identities have been skipped in some of the simulations. While this approach seems unavoidable to quantify the size of cumulative pension scheme deficits or surpluses in the long-run, it should be carefully described in the text or at least in the appendix. Nonetheless, in a closed model, pension system deficits/surpluses have to accumulate over time according to the following law of motion:*

$$D_{t+1} = D_t(1 + r_t) + E_t + R_t$$

where E_t and R_t represent government (pension fund in this case) non-interest expenditure and revenue, respectively. Dt represents a stock of public debt/assets. In addition, the following macro identity needs to hold every period.

$$A_t = K_t + D_t + NFA_t$$

In words, firm's capital Kt and government deficits Dt need to be financed each period either by domestic savings At or by an inflow of foreign capital NFAt (Change in net foreign assets). Since government deficits crowd out private investment and thus have a negative impact on economic growth, introducing this identity into the model has implications for model outcomes. None of these two identities would be necessary only in case if the pension fund is balanced each period. This does not seem to be the case for all scenarios as equation 2.13 allows for $<$ or $>$. The two above mentioned identities do not seem to appear in the model description or in the appendix.

   This is a very good point, thank you. The former identity is implicitly introduced in Equation 2.13 and the surrounding text, but I agree that it should have been more explicitly outlined in the model description. This is now added in the text in Section 2.4.2. The model assumes an exogenously given interest rate on government debt of 1% p.a.. This was previously discussed in Section 2.4.4 and is now merged with the new information in Section 2.4.2. The latter identity is only partially modelled in the study as the equality between firm's capital and domestic savings is required by Eq. 2.20, whereas the government debt is assumed to be fully covered by inflow of foreign capital. The referee is correct in saying that this affects model outcomes by disregarding the crowding out effect. This is now also explained in Section 2.4.2.

2. ***How does productivity enter the model?*** *While the thesis extensively refers to productivity, it is unclear how it enters the model. As a common practice in OLG models two types of productivity can be modelled. First, individuals' productivity varies with age and*

thus impacts the size of effective labor. Second, macroeconomic productivity often representing technological progress. Looking at the production function (equation 2.9), it seems technological progress is missing in the model (or is not described properly, at least). For example, Ω is defined as a constant representing technological advancement and there does not seem to be any labor–augmenting technology growth in the definition of N_t.

Thank you very much for the comment, which made me realise my mistake in the model description. Although the scaling constant representing macroeconomic technological advancement Ω is constant over time and varies by scenario (see Section 2.4.4), Eq. 2.9-2.11 and 2.22 incorrectly defined the associated model dynamics as constant over time. The correct representation should have been Ω^{t-1}, i.e. productivity due to technological progress increases over time as suggested by the referee. This was implemented correctly in the simulation model and has been fixed in the model description.

Individual's productivity enters the model through equation 2.4, implicitly assuming that individual's earnings are equivalent to the marginal product of their labour (see comment 2 in Section A.1.3 above), representing age- and skill-related productivity differentiation.

A.3.4 Interpretation of the results

1. ***The size of the impact of migration/emigration*** *It looks as the results among the three scenarios (Table 3.3) vary only to a very limited extent. Can we conclude that both inward and outward migration have no significant consequences for the Czech Republic?*

   Yes, that is correct, migration would need to be substantially higher in order to fully offset the negative consequences of the underlying demographic changes, as discussed in the chapter's conclusion.

2. ***The impact of aging on sectors*** *Chapter 3 quantifies the impact of aging on thirteen sectors of the Czech economy. Please, clarify if the sectoral analysis takes into account the expected migration flows or not.*

   It does, this is now better explained in the text.

3. *Second, the size of presented changes between now and 2050 (Table 3.1 and 3.2) appears rather small. For example, wages are expected to improve only marginally by 2.9 percent over the next 30 years.*

   Please note that for simplicity there is no inflation or long-term macroeconomic productivity improvement (as a result of technological advancement) assumed in the model, all of the changes are therefore only due to the inherent changes in the population structure. This is now better explained in the text

4. *Third, agriculture is the only sector that stands out from the sectoral analysis. Can further conclusions be derived from this analysis? Shall policymakers be concerned about the projected impact on agriculture?*

   The previous results for agriculture specifically were wrong as a result of incorrect model specification (see comment 5 in Section A.2.3 above) and are now more in line with the other industries.

5. ***The impact of later school start*** *Chapter 4 addresses an interesting issue and presents convincing results and conclusions. While the chapter discusses costs and necessary investment related to delayed school start, the estimated cumulative economic gains become positive immediately one year after the enforcement of this measure (Figure 4.1). Could we really expect that ½ hour of additional sleep could have an impact on the economy within one year? In the abstract of Chapter 4, it is said "...delaying school start times is a cost-effective population-level strategy, which could have a significant impact on public health and the US economy." While I'm not questioning this conclusion, it would be interesting to see a chart or a table presenting developments of main macro variables (growth, size of effective labor, labor productivity) under a baseline and the later school time start scenario.*

   Thank you for the comment. I agree that the beneficial impacts would likely take more time to fully propagate through the economy in reality. The estimated second-year impact is a direct implication of the cohort-component model, which assumes that sleeping more would have an immediate impact on the number of car accidents, and the relatively rigid nature of the OLG model, in which all individuals with at most a high school diploma would start working at the age of 18 (i.e. $s = 1$) – and their productivity would already be higher on average as more of them would finish high school. In addition, the model makes a simplifying assumption that students graduating in the first period would see 25% of the estimated effects of higher academic performance. The dynamics would be far more complex in reality, where more individuals would perhaps attempt to attend a university only to drop out later, the effect on students in their last year could be diminished because they would be too old or too far in the study programme to see meaningful effects, etc. Hence, I believe that what is more important is considering 5-, 10- or even 20-year changes to the economy as this is where we would truly expect the positive effects of higher human capital accumulation to show, whereas the short-term effects are merely a result of the model structure.

A.3.5 Some minor suggestions

1. *Given that the thesis does not discuss model's steady states (which is surprising), the description of the numerical algorithm seems unnecessary and could be easily skipped from the appendices and replaced by a reference to relevant literature.*

   The steady states are calibrated to represent the actual real-world situation in the given economy, hence I believe did not require further discussion. The appendices were included as per the published/submitted versions of the respective papers, as the editors/reviewers explicitly required more information on the solution mechanism.

2. ***Transition matrix*** – *Appendices to Chapter 2 and 3 could usefully present a transition matrix representing probabilities of switching between income categories as equation 2.3 does not provide a reader with the extent of uncertainty the agents are facing.*

   I believe that this refers to Chapters 2 and 4 instead, as the model in Chapter 3 works with heterogeneous agents but not idiosyncratic productivity shocks to income (this was not properly described in the text and has been corrected). The transition matrix used in

Chapter 2 is now reported in Table 2.9, the one used in Chapter 4 is effectively the same, just works with nine income groups instead of 12 and was omitted from reporting.

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