Essays on Human Capital, Productivity and Labour Market Flows

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Introduction

Employment opportunities and workers' careers are determined by various factors. For example, technological advancement, trade or change in tastes lead to re-shaping of industries, altering the mix of resources which are used in production, and fundamentally changing the employment composition in the medium to long run. To gain a better understanding of the importance of these processes, it is crucial to study individual careers and their determinants. Workers' outcomes on the labour market depend, among other things, on their human capital and the opportunities they have to advance their careers. Given this framework, this dissertation consists of three papers in the field of Labour Economics focusing on productivity growth, cross-sectoral employment shifts, labour market flows, the accumulation of human capital and its social efficiency. Each chapter deals with a different facet of these topics. Chapter 1 presents an empirical investigation on employment growth at the sectoral level and cross-sectoral labour shifts, comparing the majority of European Union member countries. Chapters 2 and 3, on the other hand, take a microeconomic approach which centres around the decisions of firms, studying how these decisions affect the labour market and workers' careers. In particular, chapter 2 zooms in to study employment decisions at the firm-level via a theoretical model whereas chapter 3 deals with the social efficiency of firms' decisions in a similar context to the one presented in chapter 2.

Employment shifts across different economic sectors and their underlying causes are an area of great interest for social scientists. While there are various factors contributing to cross-sectoral labour flows, in chapter 1 of the dissertation, one particular channel that affects employment is explored—R&D investment. This is an empirical study on the interaction between labour productivity, sectoral employment and R&D investments. Some of the seminal contributions on employment movement between sectors date back to Clark (1957) and Baumol (1967). Clark (1957) offers a demand-based explanation of the observed employment shifts away from manufacturing towards the services by arguing that as income per capita increases, demand for services rises as well. Baumol (1967, 2001) offers an alternative explanation by arguing that employment in service sectors expands because of differential productivity growth between manufacturing and services. Chapter 1 of this dissertation makes use of recent sectoral-level data from the OECD and ILOSTAT covering EU member countries. First, we document a quantitatively large and uniform cross-sectoral employment shift away from manufacturing sectors to service sectors. There is, however, a large heterogeneity with respect to the levels of employment in services and manufacturing among countries.

Next, we perform a shift-share decomposition of labour productivity for 22 of the EU member countries and find a slowdown of average annual labour productivity growth in most of them. Within-sector productivity growth contributes the most to overall productivity increase for most of the countries in the sample. However, our analysis suggests that employment is expanding in industries with lower productivity which has a negative effect on productivity growth. Further, some qualitative differences with respect to the effect of labour reallocation on total productivity growth between older and newer EU member countries emerge. More specifically, in most of the newer EU member countries there are productivity gains associated with cross-sectoral labour shifts but the effect is quantitatively small.

Having presented the overview of sectoral employment patterns in the majority of EU countries, we explore how innovation, proxied by R&D expenditure, is associated with sectoral employment. It is well documented in the empirical literature that R&D investment has a significant impact on employment. However, at the firm level, empirical studies deliver mixed results on whether or not innovation has a labour-saving effect or it causes employment growth. Overall, product innovations have been found to lead to employment growth (for example, Bogliacino and Vivarelli (2012); Crespi et al. (2019); Harrison et al. (2014)). Results with respect to process innovation, characterized by reduction in the amount of input factors required for production, are, on the other hand, less clear-cut (Dosi and Mohnen, 2018). We use sectoral-level data which does not allow us to differentiate between product or process innovation, but instead we can study the net correlation between R&D investment and sectoral level employment. We find that there is a large degree of heterogeneity among different sectors with respect to the relationship between R&D and employment. Moreover, for some sectors, we also find qualitative differences between the older and the newer EU member countries in the sample. Overall, higher R&D investment is associated with higher employment in high-technology manufacturing and service sectors. For low- to medium-technology manufacturing sectors we find generally a negative and significant relationship between the two, while for low- or medium-technology service sectors the results are predominantly insignificant.

In chapter 2 a theoretical model of optimal promotion timing is developed. The analysis is done at the firm level and looks into the effect of firm competition and human capital accumulation on workers' careers. Firms have hierarchical structures, with junior and senior positions and promotions are modelled in a framework of human capital accumulation, following Gibbons and Waldman (1999). Workers start their professional careers on the lower hierarchical level and begin accumulating human capital. Firms, on the other hand, choose the level of human capital which is required for promoting junior workers. Workers who are eligible for promotion but cannot be promoted because the senior position in their firm is taken begin on-the-job search. Hence, the model studies upward mobility in workers' careers via promotions and job-to-job transitions under one theoretical framework. Further, integrating firms' internal labour markets in the larger labour market allows us to characterize the general equilibrium effects of firms' choices.

We find that firms' competition exhibits strategic complementarity in promotion choices such that the promotion time that an entering firm chooses is increasing in the average promotion timing of the incumbent firms. Immediate promotions are not optimal because firms are forward looking and expect higher profits if they let their junior workers gain human capital first. Waiting very long before promoting is also not optimal since the foregone profits associated with keeping a worker with high human capital on the lower hierarchical level increase. Further, the fraction of senior workers and the senior vacancy-filling rate are decreasing in the promotion cut-off that firms choose while the opposite holds for the fraction of junior workers and the junior job-filling rate.

In the benchmark model we assume that workers are homogeneous with respect to ability and that firms have the same hierarchical structure. We relax these assumptions in two extensions of the model and characterize how firms optimally alter their promotion strategies. The first extension introduces worker skill heterogeneity such that there are low and high skill workers in the economy. In this framework firms respond by promoting high skill workers much faster then the low skill ones. This result of the model is also supported by empirical evidence (for example, Baker et al. (1994)). Furthermore, there is strategic substitutability between the promotion thresholds that firms set for the two types of workers. If for some exogenous reasons firms have to decrease the human capital requirement for promoting high skill workers, they respond by increasing the promotion requirement of low skill workers and vice versa. Finally, the extended model with worker skill heterogeneity predicts that a higher fraction of high-skill workers in the economy is associated with later promotion timing for both skill groups.

In the second extension of the benchmark model we incorporate firm heterogeneity by introducing pyramidal firms as a fraction of all active firms in the market. The pyramidal firms have more positions at the lower hierarchical level while the firms assumed in the benchmark model have a vertical structure with the same number of positions on each layer. The results show that pyramidal firms choose higher human capital requirement for promotion compared to their vertical, smaller competitors. Higher probability that pyramidal firms have their senior position filled together with higher probability that in case the senior position becomes vacant they might have a junior worker eligible for promotion, contribute to the result. Furthermore, this implies that in the market with heterogeneous firms and endogenous promotion decisions, workers employed in the larger, pyramidal firms will have on average higher human capital. This generates endogenously a firm size wage gap which is a stylized fact reported in numerous empirical studies (for example, Lallemand et al. (2007); Main and Reilly (1993); Oi and Idson (1999); Oosterbeek and Van Praag (1995)). Further, the extended model suggests that the firm size wage gap is increasing in the hierarchical level which is also empirically supported in Fox (2009).

In the third chapter of the dissertation we analyse the efficiency of firms' promotion choices in frictional labour market with hierarchical firms. This study deals with the question of whether or not workers gain the "right" amount of human capital before being promoted in a context of strategic interaction between firms. Optimality of human capital accumulation is viewed from total output maximizing perspective. The study is, thus, related to human capital theory (Becker, 1962) assuming an imperfect labour market and contributes to the literature which identifies externalities that potentially distort human capital accumulation (for example, Acemoglu (1997); Mincer and Leighton (1980); Stevens (2001)).

The results show that firms choose a promotion requirement that is too high compared to the socially optimal benchmark. This leads to an output loss which stems from an allocative inefficiency in the economy. Even though under the optimal equilibrium workers have on average lower human capital, they are allocated more efficiently across the hierarchical levels. The positive effect of having higher professional employment and higher stock of senior workers, compared to the decentralized equilibrium outweighs the negative effect of lower average human capital. A switch from the decentralized to the socially optimal equilibrium is then associated with approximately 5% welfare gain. When a firm chooses to increase its promotion requirement it creates a negative externality on all other firms by reducing the pool of potential applicants to the high productivity senior positions. However, due to strategic complementarity of firms' promotion choices, other firms respond by also increasing their promotion requirement. Hence, the negative externality is not internalized which leads to an inefficient general equilibrium outcome.

Next in the model, the assumption of fixed firm entry is relaxed and the equilibrium stock of firms is determined via a free entry condition and the model parameters are assumed such as to satisfy the Hosios (1990) conditions. The Hosios conditions states that in a search and matching model, the decentralized equilibrium is generally not efficient unless the elasticity of the matching function with respect to unemployment equals the workers' bargaining power parameter. We find that the Hosios conditions do not deliver a constrained efficient outcome in a labour market with hierarchical firms and endogenous promotion decisions. More specifically, firm entry is downward biased which exacerbates the allocative inefficiency in the economy. In this setting switching to the socially optimal equilibrium is associated with 10% welfare increase, where the addition gain compared the fixed firm entry scenario comes from a firm entry effect. Next, it is shown that the socially efficient and decentralized equilibrium could coincide under the free entry condition provided that a larger fraction of the match output is retained by junior worker while a smaller fraction of the match output accrues to senior workers compared to the traditional Hosios value. This implies that firms are not adequately compensated for creating the high productivity, senior level jobs and that firm profits are suppressed which leads to under-entry. Finally, we show that the welfare maximizing pair of promotion cut-off and output sharing rule is such that higher fraction of output goes to workers compared to firms, the promotion requirement is lower than in the decentralized equilibrium, but higher compared to the centralized equilibrium when the Hosios conditions are satisfies.

The dissertation is organized as follows: the first chapter presents an Empirical Analysis of Sectoral Employment Shifts and the Role of R&D. The second chapter discusses the Optimal Promotions of Competing Firms in a Frictional Labour Market with Organizational Hierarchies and the third chapter elaborates on the Social Optimum in a Model with Hierarchical Firms and Endogenous Promotion Time. Each chapter contains an independent research paper.

Contributions

Two of the chapters in this dissertation are co-authored. Chapter 1 is a joint work with Prof. Dr. Herbert Dawid[1]. My contribution was in collecting the data, writing the literature review and executing the shift-share and regression analyses. Chapter 2 is co-authored with Prof. Dr. Herbert Dawid and J.-Prof. Dr. Anna Zaharieva[2]. The work was distributed equally among the authors.

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Chapter 1

Empirical Analysis of Sectoral Employment Shifts and the Role of R&D[1]

1.1 Introduction

In recent decades EU member countries have experienced an increase in employment in service-related jobs at the expense of manufacturing and agricultural employment. Possible reasons for such structural change that are explored in the literature include demand and supply side explanations, as well as relative productivity arguments. Clark (1957) argues that labour reallocation away from manufacturing is primarily caused by demand shifts. An opposite view is presented by Baumol (2001). In a model with two economic sector with different productivity growth, the author shows that labour tends to move to the "stagnant" sector in order to keep relative output in the two sectors constant. However, such employment reallocation does not contributing to productivity growth because the costs in the sector with slow productivity growth rises. The increasing cost burden due to such productivity lag is referred to as "Baumol's cost disease hypothesis". More recently, Goos and Manning (2007) conclude that the employment polarization observed in many countries which is characterized by simultaneous increase in the highest and lowest paying jobs at the expense of those in the middle in the wage distribution, is a corroboration of Baumol's hypothesis.

In this study we document decreasing average annual labour productivity growth in most EU member countries in our sample over the last 20-25 years. Further, the findings suggest that labour reallocation between different sectors has had a small but negative contribution to overall productivity growth, especially in older EU member countries. We then proceed by examining closer the relationship between R&D investment, as one channel that has impact on labour productivity, and employment on the sectoral level. Here, we contribute to the rich empirical literature which widely identifies significant relationship between innovation and employment where most studies are conducted at the firm-level. We conduct the analysis at the sectoral level, aiming to identify net effects of R&D expenditure on sectoral employment.

Depending on the considered type of innovation activity (process or product), empirical

[1] This chapter is co-authored with Prof. Dr. Herbert Dawid.

evaluations of the effects of innovations on employment deliver mixed results[2]. A product innovation might require a new method of production or new input mix. Intuitively it is plausible that a new product will create employment opportunities in the innovating firm. However, it is less clear whether the general equilibrium effects of this innovation will increase or decrease labour inputs, since new products might drive out existing products from the market (Katsoulacos, 1984). Here, the degree of product differentiation matters in so far as to whether new products substitute existing ones or act as complements.

On the other hand, successful process innovation reduces production costs by decreasing the amount of required production factors. This could mean that less labour input is required for producing one unit of output. Hence, process innovation is likely to have a negative effect on employment growth or a direct displacement effect in the short run. However, since process innovation translates into lower production costs, if it also leads to lower prices, there might be a boost in demand and growth in employment (Harrison et al., 2014).

Further, innovation is also likely to affect employment levels in other firms in the supply chain. Assuming that a successful innovation increases output, then it is likely that the innovating firm will increase its demand for intermediate goods and services (Peters, 2004). Moreover, firms' innovation competition can lead to various strategic effects which impact firms' market share (for example, Dawid et al. (2010)). All of these effects are in turn also very likely to influence firms' employment decisions.

There is a rich empirical literature on the estimation of the effects of different innovation types on employment at the firm level. For instance, using data on UK manufacturing firms for the period 1976-1982, Van Reenen (1997) finds that product and process innovation have opposite effects on employment. However, the product innovation coefficient is estimated to be quantitatively large and highly significant while the process innovation one is insignificant. In a comparative study between Australia and Britain of the determinants of employment growth, Blanchflower and Burgess (1998) find that process innovation (measured as the establishments which report the introduction of new technology in the last three years) is associated with approx. 2.5% increase in yearly employment growth in the UK. However, the result is found to be sensitive to the inclusion of establishment size controls. For Australia, the authors report that this effect is 1.5% per year. A different result is obtained by Brouwer et al. (1993) who use data on Dutch manufacturing firms covering the period 1983-1988 and find that growth of R&D intensity is associated with employment reduction. However, the authors find that firms who invested in product innovation and specifically directed R&D activities towards ICT experienced employment growth. Further, Klette and Førre (1998) compare the rates of job creation between plants which are part of firms that invest in R&D and such that do not and find no difference in job creation between the two groups. The authors use data on Norwegian manufacturing plants covering the period 1982-1992.

More recent empirical studies find a job creation effect of R&D (Bogliacino and Vivarelli (2012); Bogliacino et al. (2012); Bogliacino (2014); Hall et al. (2008); Harrison et al. (2014)). Harrison et al. (2014), for example, use Community Innovation Surveys (CIS) data for Germany, France, Spain and the UK and find that both in services and manufacturing, product

[2]Literature surveys can be found in Spiezia and Vivarelli (2002) and Dosi and Mohnen (2018) for the most recent contributions on the topic.

innovation is positively associated with employment growth in innovating firms. The negative effect of process innovation is found to be small in German and UK manufacturing or null in Spanish manufacturing and the service sectors of all studied countries. Overall the positive employment effects associated with product innovation outweigh the outcomes of process innovation. Hall et al. (2008) find similar trends for Italian manufacturing firms for the period 1995-2003. The authors estimate no effect of process innovation on employment growth and a positive one of product innovation in innovating firms. Using German panel data covering manufacturing firms in the period 1982-2002, Lachenmaier and Rottmann (2011) find that both product and process innovation have a positive impact on employment where the effect of process innovation is estimated to be higher. Using data on French manufacturing firms for the period 1984-1991, Greenan and Guellec (2000) also find that at the firm level, both process and product innovation are associated with job creation. However, process innovation reduces employment for competing firms and therefore at the sectoral level only product innovation leads to higher employment. Antonucci and Pianta (2002), on the other hand, find using EU Community Innovation Survey data covering eight countries in the periods 1990-1992 and 1994-1996 that process and product innovation have had opposite impacts on employment. However, the estimated impact of product innovation on the rate of change of employment, although positive, is quantitatively smaller and not statistically significant while the effect of process innovation is estimated to be negative and only weakly significant. Crespi et al. (2019) use micro data from innovations surveys, covering the manufacturing sectors in Argentina, Chile, Costa Rica and Uruguay. They find that product innovation increases demand and has a positive, significant effect on employment in all countries. With respect to process innovation, the results are mostly insignificant. Similarly, using data on Spanish manufacturing firms for the period 2004-2012, Calvino (2018) finds that product innovation has a positive effect on employment growth and these effects are stronger for the firms at the top and at the bottom of the conditional employment distribution, while in the case of process innovation is positively associated with employment growth only at the bottom of the conditional distribution.

Further, Peters (2004) finds that effects of process innovation may differ between manufacturing and service firms in Germany. More specifically, using survey data covering the period 1998-2000, the author finds that process innovation is associated with reduction of employment in manufacturing firms but no such effect is found for service firms. Possible explanations for why this might be the case are, on the one hand, that distinguishing clearly between process and product innovation in the services is not as straight-forward. Alternatively, service firms tend to be smaller and have less market power which leads to more of the benefits from innovation to be passed on to customers. On the other hand, sales growth that can be attributed to successful product innovation is found to have a one-to-one correspondence with employment growth in innovating manufacturing and service firms. Bogliacino et al. (2012) use a dataset encompassing 677 EU companies over the period 1990-2008. The authors find a positive significant relationship between firm R&D expenditure and employment. However, the magnitude of the effect varies depending on which sector the firm operates in. The results suggest that the positive employment effect of R&D is strongest in high-tech manufacturing and the services but weaker for firms in other manufacturing sectors.

Overall, results at the firm level point at a positive effect of product innovation on employment while the results with respect to process innovation are less clear-cut. Moreover, results vary for different countries and time spans. In this analysis we look at the relationship between innovation and employment at an aggregate sectoral level covering a relatively large time span between 1995-2016. The aggregation we use is the two-digit level of ISIC, Rev.4 and the majority of EU member countries are included in the analysis. In this respect the analysis is closer to Bogliacino and Vivarelli (2012) who also investigate the job creation effect of R&D at a sectoral aggregation level. Using a panel of 15 European countries, over the period 1996-2005, the authors find that R&D expenditure has had a positive employment effect in manufacturing and that the employment gains seem to be concentrated in the high-tech sectors. The novelty of our paper is that we are able to study effects of R&D on employment at finer sectoral definitions and identify heterogeneity within low-, medium- and high-tech industries. Also we are able to add more service sectors for which R&D data has become available in the latest releases of the OECD ANBERD (Analytical Business Enterprise Research and Development) database. Given that we observe a persistent movement of employment away from agriculture and manufacturing into the service sectors, it is important to analyse the effects that innovation has on these sectors. Moreover, we include more Central and East European countries in the analysis which allows for a discussion of qualitative differences between older and newer EU member countries with respect to cross-sectoral employment shift patterns as well as correlation between innovation and employment.

Overall, the aim of this paper is twofold. On the one hand, we contribute to the literature on structural change by collecting recent empirical evidence on magnitude of employment shifts between manufacturing, services and agriculture for all EU member countries. Further, we explore whether the observed employment reallocation corresponds to labour productivity gains. Secondly, the paper contributes to the discussion on the effect of innovation activity, measured as R&D investment, on employment by examining OECD data. Given the aggregation of the data, we look at net effects of innovation, product or process, measured as sectoral R&D expenditures on employment. More specifically, the following questions are addressed:

i) How has the overall employment share of the manufacturing respectively the service sectors evolved over time in different European countries? Are there qualitative differences in the evolution between 'old' and 'new' EU member countries?

ii) How is the shift in employment shares related to (country-specific) changes in labour productivity? Does it contribute to a faster increase in total labour productivity?

iii) What is the impact of (country- and sector-specific) R&D expenditure on employment in a sector? Is there a systematic difference with respect to this impact between manufacturing and service sectors?

The motivation to explore these questions is twofold. First, it should help to identify the driving forces of the observed sectoral employment shifts. Second, and more importantly, gaining a better understanding of the role of R&D for employment and for sectoral shifts clearly has important implications for innovation policy. If certain sectors can be identified where increases in R&D investments tend to have particularly strong positive effects on

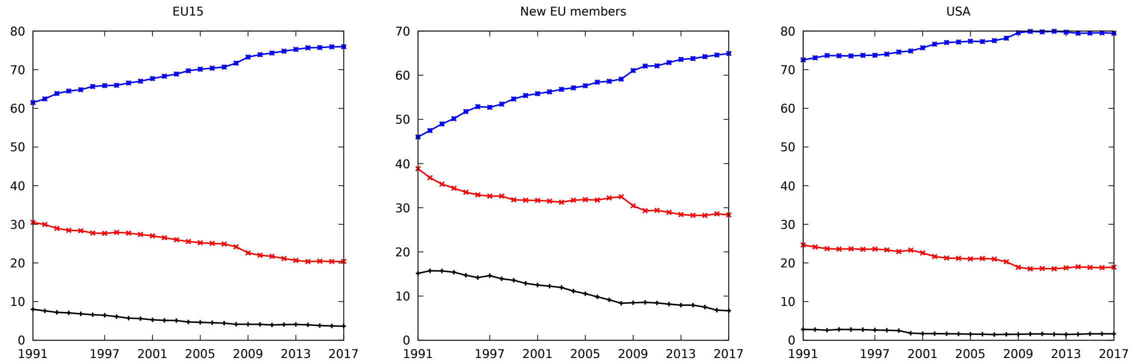


Figure 1.1: Employment in agriculture (black), services (blue) and industry (red) as percentage of total employment. Left panel: average over EU15 countries. Middle panel: average over rest of EU member countries. Right panel: USA. Data source: ILOSTAT database.

employment, then fostering investments in those sectors would not only have direct effects on productivity and international competitiveness in such sectors but would also contribute to positive second order effects through demand stimulation and human capital improvements, e.g. through learning by doing effects. Also, the analysis sheds light on the question in how far the observed shifts in employment might be desirable or at least necessary from the perspective of overall labour productivity increases.

From a methodological perspective, we combine pure a descriptive treatment of the time series data for different countries and sectors with a shift-share analysis (see e.g. Fagerberg (2000), Maudos et al. (2008) and OECD (2014)) which disentangles productivity dynamics into within-sector effects and changes that are driven by labour movements between sectors and pooled as well as sector-specific regressions analysing the relationship between R&D and employment. The rest of the paper is organized as follows: Section 1.2 presents data on general employment patterns in all EU member countries. In section 1.3 we test whether the observed cross-sectoral employment shifts are related to changes in labour productivity. Section 1.4 presents the results with respect to the correlation between sectoral employment and R&D investment and Section 1.5 concludes. Appendix A provides additional figures, while detailed description of the data is presented in Appendix B. Additional results and robustness checks are in Appendix C and further regression results are in Appendix D.

1.2 Country level evidence on shift between manufacturing and services: an aggregate perspective

We start our analysis with a purely descriptive treatment of the sectoral shifts of employment between industrial production and service from the early 90s until 2017 . Figure 1.1 depicts the development of the three main economic sectors (agriculture[3], industry[4] and services[5]) and the evolution of their employment shares for EU15 countries, the 13 newer EU members and the U.S. (Data source: ILOSTAT database). The figures for the two groups of EU

[3] Agricultural activities, forestry, hunting and fishing.

[4] Manufacturing, mining, construction, quarrying, public utilities (electricity, gas, and water).

[5] Communications, insurance, financing, real estate, business services, social, community and personal services, trade, hotels and restaurants.

countries are done by taking yearly averages. There is an evident cross-sectoral shift of labour between manufacturing and services. We can see that the share of workers employed in services has been steadily increasing everywhere over the considered periods. Moreover, the importance of the services is still on the rise, while employment in manufacturing and agriculture is decreasing. Also, it should be noted that, although the employment share of services in the U.S. is considerably above that in the EU, the speed of growth of the service sector in Europe seems larger than that in the U.S. In Figures 1.4 and 1.5 in Appendix A we show the breakdown of employment shares for each EU member country. It can be clearly seen that the employment share in the service sector in the new member countries is below that in most countries of the EU15. Qualitatively, all considered countries in the EU share the same upwards trend in the service sector share, however for some the new EU member countries, in particular those where in 1990 a substantial fraction of the work force was still employed in agriculture, the increase in the service sector share has been much more rapid than the average across the EU. Focusing however on the shift from manufacturing to service the patterns seem rather uniform across all considered countries.

1.3 Role of Productivity Differences: A Shift-Share Analysis

Having observed a clear pattern of an increasing employment share in service across all European countries and the U.S., we will now try to gain a better understanding of what is driving this phenomenon and how it differs between various sectors within service and manufacturing. As a first step we explore the question whether the shift in employment is an expression of changes of relative labour productivity across sectors, in a sense that workers move from sectors where their labour becomes (relatively) less productive to those with high labour productivity or faster labour productivity growth. Figure 1.2 shows the evolution of average labour productivity (measured in local currency in 2010 prices) in all manufacturing and business service sectors covering overall about 61% and 65.5% of total full-time employment equivalents in 2016 in Germany and Czech Republic, respectively, as representatives of old and new EU member countries. In both countries productivity is higher and also faster growing in the manufacturing sector with the exception of the earliest considered years for the Czech Republic where productivity in business service sectors is slightly above that of manufacturing. Putting this together with the insights from the previous section means that overall, workers tend to move towards less productive employment.

To further explore the relationship between employment shifts and productivity changes we carry out a shift-share decomposition of the change in labour productivity in 22 European countries. In particular, we use a shift-share decomposition equation of the following form:

$$\begin{aligned}\frac{P_{c,t+k}-P_{c,t}}{P_{c,t}} = & \underbrace{\frac{\sum_i (p_{c,i,t+n}-p_{c,i,t})l_{c,i,t}}{P_{c,t}}}_{\text{Within Effect}} + \underbrace{\frac{\sum_i (l_{c,i,t+n}-l_{c,i,t})p_{c,i,t}}{P_{c,t}}}_{\text{Static Shift Effect}} \\ & + \underbrace{\frac{\sum_i (p_{c,i,t+n}-p_{c,i,t})(l_{c,i,t+n}-l_{c,i,t})}{P_{c,t}}}_{\text{Dynamic Shift Effect}},\end{aligned} \tag{1.1}$$

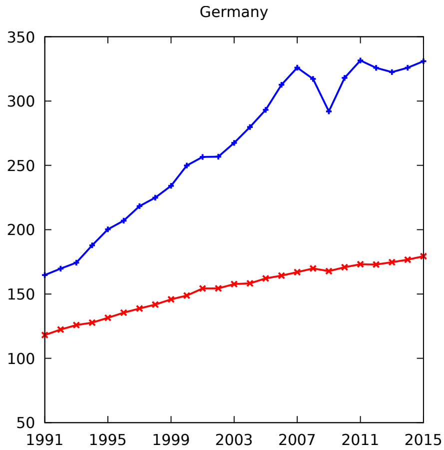


Figure 1.2: Average labour productivity in Germany (left panel) and the Czech Republic (right panel) in manufacturing (blue line) and business service (red line) sectors. Differences in the scale of the y-axis are due to measurement in national currencies.

where $p_{c,i,t}$ is the labour productivity in sector i in country c at time t and $l_{c,i,t} = \frac{L_{c,i,t}}{\sum_i L_{c,i,t}}$ is the employment share of sector i in country c with $L_{c,i,t}$ denoting total employment in sector i in country c at time t. Labour productivity in country c is calculated as a weighted sum of the productivity in the different sectors: $P_{c,t} = \sum_i p_{c,i,t} l_{c,i,t}$.

The *Within Effect* (WE) measures the contribution of the sectoral productivity growth on total productivity growth, assuming that labour input remains constant; the *Static Shift Effect* (SSE) measures the effect of labour mobility between different sectors on total productivity growth, assuming that productivity within each sector remains constant, and the *Dynamic Shift Effect* (DSE) measures the change in the share of labour in each sector, as well as the impact of labour reallocation between sectors with differential productivity growth rates on total productivity growth. Considering the time average of these effects for a given country and a given time window allows to examine whether the increase in labour productivity in a country is primarily driven by productivity increases within the different sector or by employment shifts to sectors that are already more productive or exhibit faster productivity growth. We calculate the shift-share decomposition relying on data from the OECD Structural Analysis (STAN) database. In particular, we take employment data on the sectoral level and calculate sector-specific labour productivity using production (gross product) volumes[6] and again full time equivalent employment at the sectoral level using this database. The considered time window generally spans the years 1990-2016 and is cut in 5-year periods for which the three different effects are calculated. For some countries, due to data restrictions only a subset of these periods could be covered.

Tables 1.1 and 1.2 show the results of the shift-share analysis for 22 EU countries. Tables 1.1 and 1.2 display the results for EU15 member countries, while the second part of table 1.2 shows the result for further 7 countries which became EU members during the 2004 enlargement. Apart from a few exception in Italy, Greece and Spain labour productivity has been growing in all countries in all the covered time intervals. Particularly, for the new

[6]For Estonia, Ireland, Lithuania, Spain and UK this variable is not available so output is measured in value added, national currency 2010 prices.

Table 1.1: Decomposition of Labour Productivity Growth: EU15 p.1

	Period	**LPG**[a]	**WE**[b]	**SSE**[c]	**DSE**[d]	**AALPGR**[e]
		percent	points	points	points	percent
Austria	1995–2001	17.16	18.56	−0.33	−1.08	2.68
	2001–2006	15.66	17.01	−0.42	−0.93	2.96
	2006–2011	3.96	4.56	−0.35	−0.25	0.80
	2011–2016	1.62	2.22	−0.48	−0.12	0.32
Belgium	1999–2005	4.06	7.80	−3.19	−0.59	0.67
	2005–2011	3.66	6.89	−2.11	−1.13	0.64
	2011–2016	1.35	3.51	−1.94	−0.22	0.28
Denmark	1990–1995	14.92	14.18	1.15	−0.41	2.83
	1995–2000	8.77	11.00	−1.31	−0.93	1.70
	2000–2005	11.11	13.42	−1.15	−1.16	2.14
	2005–2010	4.46	6.01	−0.13	−1.42	0.90
	2010–2015	5.81	6.61	−0.66	−0.15	1.14
Finland	1990–1996	23.70	22.64	1.72	−0.66	3.63
	1996–2001	13.97	12.28	1.65	0.04	2.66
	2001–2006	12.76	15.64	−1.52	−1.37	2.43
	2006–2011	1.37	5.10	−3.08	−0.65	0.33
	2011–2016	1.18	3.20	−1.91	−0.12	0.24
France	1990–1995	7.63	9.96	−1.47	−0.86	1.48
	1995–2000	11.03	13.04	−0.98	−1.02	2.12
	2000–2005	5.46	6.20	−0.29	−0.45	1.07
	2005–2010	2.15	4.81	−2.15	−0.50	0.45
	2010–2015	3.93	4.99	−0.76	−0.30	0.78
Germany	1991–1996	14.08	16.71	−0.34	−2.30	2.67
	1996–2001	15.30	14.80	1.14	−0.64	2.89
	2001–2006	9.67	11.60	−1.11	−0.83	1.87
	2006–2011	5.90	8.51	−1.92	−0.69	1.19
	2011–2015	1.95	1.81	0.19	−0.05	0.49
Greece	1995–2001	17.49	13.12	4.93	−0.56	2.74
	2001–2006	9.49	6.10	7.62	−4.24	1.87
	2006–2011	−9.10	−9.30	1.34	−1.13	−1.86
	2011–2016	0.34	2.10	−0.84	−0.92	0.07
Italy	1995–2000	11.17	10.21	1.59	−0.63	2.14
	2000–2005	2.31	3.35	−0.43	−0.62	0.46
	2005–2010	−1.73	−0.41	−0.83	−0.49	−0.29
	2010–2015	−2.25	0.46	−2.45	−0.26	−0.44
Ireland	1998–2002	13.16	8.52	5.04	−0.40	3.15
	2002–2006	4.63	6.13	0.09	−1.59	1.14
	2006–2010	13.55	0.75	12.81	−0.01	3.25
	2010–2014	16.06	15.81	0.23	0.01	3.96
Luxembourg	1995–2001	29.30	21.03	9.86	−1.54	4.42
	2001–2006	21.49	25.40	−1.86	−2.05	4.00
	2006–2011	4.89	6.19	−1.10	−0.20	1.10
	2011–2016	15.45	15.69	−0.83	0.59	2.98

[a] Labour Productivity Growth
[b] Within Effect
[c] Static Shift Effect
[d] Dynamic Shift Effect
[e] Average Annual Labour Productivity Growth Rate

Table 1.2: Decomposition of Labour Productivity Growth: EU15 p.2 and new EU member countries

	Period	LPG[a]	WE[b]	SSE[c]	DSE[d]	AALPGR[e]
		percent	points	points	points	percent
Netherlands	1995–2001	12.55	16.53	−3.27	−0.70	1.99
	2001–2006	6.92	11.09	−2.84	−1.33	1.35
	2006–2011	2.03	5.15	−2.58	−0.53	0.47
	2011–2016	5.83	7.34	−1.14	−0.37	1.14
Portugal	1995–2000	11.04	10.35	1.89	−1.21	2.12
	2000–2005	7.19	10.63	−1.72	−1.71	1.40
	2005–2010	6.44	6.78	0.17	−0.51	1.27
	2010–2015	1.26	0.09	1.24	−0.07	0.25
Spain	1995–2000	−0.26	−4.01	10.61	−6.86	−0.05
	2000–2005	0.86	−0.19	3.31	−2.25	0.17
	2005–2010	8.63	7.37	2.33	−1.07	1.67
	2010–2015	6.63	7.68	−0.49	−0.56	1.30
Sweden	1993–1995	5.03	4.56	0.40	0.06	2.48
	1995–2000	12.80	13.69	−0.62	−0.27	2.45
	2000–2005	11.54	12.85	−0.56	−0.75	2.21
	2005–2010	1.10	3.36	−1.73	−0.53	0.26
	2010–2015	4.06	7.04	−3.19	0.22	0.81
UK	1995–2001	11.37	9.38	2.37	−0.38	1.81
	2001–2006	9.90	8.66	2.84	−1.61	1.91
	2006–2011	0.99	0.45	1.24	−0.70	0.21
	2011–2016	1.85	2.20	−0.14	−0.20	0.37
New EU member countries						
Czech Republic	1993–1996	9.12	7.68	1.47	−0.03	2.97
	1996–2001	20.29	23.47	−1.27	−1.91	3.77
	2001–2006	28.83	27.80	1.70	−0.67	5.24
	2006–2011	6.75	7.82	−1.00	−0.07	1.42
	2011–2016	6.11	4.54	1.47	0.10	1.22
Estonia	2000–2005	29.28	34.53	−0.83	−4.42	5.14
	2005–2010	18.86	20.18	5.54	−6.85	3.58
	2010–2015	5.02	8.73	6.56	−10.26	1.01
Hungary	2010–2015	6.67	10.39	−2.07	−1.66	1.32
Lithuania	1995–2001	36.98	38.23	−0.56	−0.70	5.43
	2001–2006	33.45	32.17	8.61	−7.33	5.97
	2006–2011	19.20	15.65	9.83	−6.27	3.67
	2011–2016	5.49	6.41	0.17	−1.09	1.09
Poland	2000–2005	12.09	10.77	1.99	−0.66	2.36
	2005–2010	17.43	13.09	5.76	−1.41	3.30
	2010–2015	10.90	9.92	1.15	−0.17	2.10
Slovak Republic	1995–2000	28.83	25.83	4.34	−2.44	5.21
	2000–2005	11.89	13.13	1.17	−2.41	2.33
	2005–2010	18.79	20.97	−1.33	−0.85	3.71
	2010–2015	20.36	19.49	0.11	0.77	3.79
Slovenia	2000–2006	27.31	20.22	10.97	−3.88	4.13
	2006–2011	1.84	1.17	1.63	−0.95	0.53
	2011–2016	2.61	3.10	−0.23	−0.26	0.53

[a] Labour Productivity Growth
[b] Within Effect
[c] Static Shift Effect
[d] Dynamic Shift Effect
[e] Average Annual Labour Productivity Growth Rate

EU member countries growth rates of labour productivity have been substantial in the 1990s and early 2000s. However the shift-share analysis indicates that consistently throughout the considered time period and across countries the contribution of sectoral employment to that productivity increase is rather limited. For most considered EU15 member countries, both the static shift effect and the dynamic shift effects are negative in almost all periods, indicating that in these countries the employment shift has reduced the increase in labour productivity emerging from the evolution of productivity within the sectors. This negative static shift effect indicates that labour is shifting to industries with lower productivity or, put differently, that high productivity industries are contracting. This is further supported by the often negative dynamic shift effect. Exceptions are Ireland, for which the static shift effect is consistently positive and Greece, Spain and Portugal for which for the majority of the considered time intervals the SSE is also positive. However, the dynamic shift effect is predominantly negative also for those countries. For the new EU member countries in the sample the static shift effect tends to be positive, although much smaller than the within effect. This suggests that in the new EU member countries some productivity gains were made by workers moving to more productive sectors. However, also for these countries the dynamic shift effect is consistently negative, indicating that there is no systematic movement of workers to sectors in which the growth of labour productivity is above average.

Overall, these results imply that an increase in labour productivity in general does not correspond to an expansion of this sector in terms of employment, but they also suggest that in some countries, in particular new EU member countries, there seems to be a weak positive relationship between productivity growth and employment expansion. Generally speaking, these observations of course give little indication of the causal chains which are responsible for these relationships. For example, the underlying mechanism for a negative relationship between productivity and employment might be that due to productivity increases induced by technological change firms in a sector can reduce the workforce needed to satisfy demand. A similar negative relationship could however also emerges due to a reduction of the firm's output (e.g. because of demand contraction), leading to an elimination of old and less productive machines or less skilled labour from the production process. An analysis encompassing the different potential causal relationships between productivity increase and employment on a sectoral or even a firm level is beyond the scope of this manuscript. However, in the next section, we dig deeper into one particular channel influencing the relationship between productivity and employment, by exploring how sectoral employment depends on the level of R&D activities, and whether this relationship differs between manufacturing and service sectors.

1.4 Role of R&D: the share of employment in manufacturing

Our analysis of the relationship between R&D activity and employment relies on country and sector specific regressions. The largest sample contains 23 EU member countries: Austria, Belgium, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, UK, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Netherlands, Poland, Portugal, Slovak Republic, Slovenia and Sweden. However, because of data limitations our panel

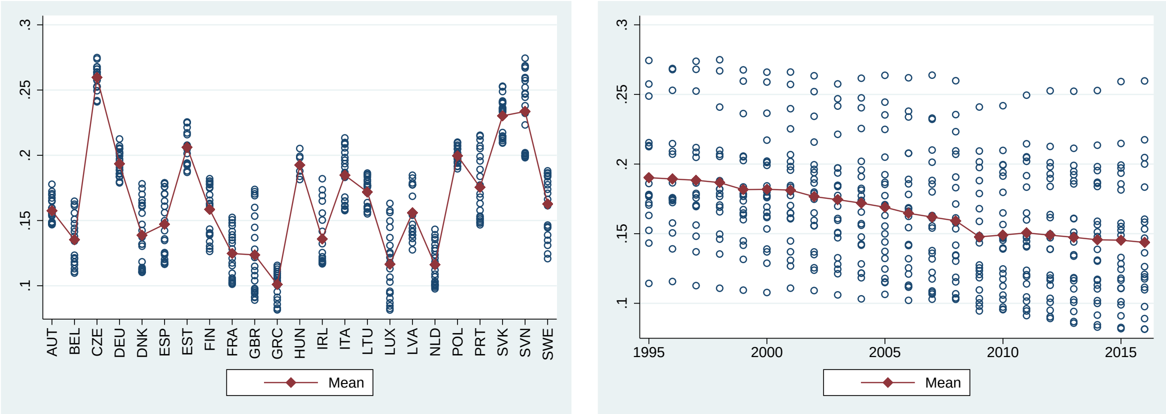


Figure 1.3: Share of manufacturing employment by country (left panel) and by year (right panel) in full time employment equivalents.

is unbalanced and some countries are dropped for some of the regression specifications[7].

First, we consider the decline of the manufacturing sector's employment share as a whole in the period 1995-2016. The Hausman test indicates that the use of a fixed-effects model is appropriate. However, diagnostic tests suggest that the errors are heteroskedastic and autocorrelated. Therefore, we estimate a robust fixed-effects (within) regression with Driscoll and Kraay standard errors. The regression equation has the following form:

$$sharemanu_{it} = \beta X'_{it} + \alpha_i + u_{it} \tag{1.2}$$

where β is the coefficient vector, X'_{it} is the vector of independent variables, α_i captures country fixed effects and u_{it} is the error term. Here i stands for the cross-sectional unit (i.e., the 23 countries) and t denotes time (1995-2016). The dependent variable **sharemanu** is defined as the full time equivalent employment in all manufacturing sectors as a share of full time equivalent total employment in country i. Figure 1.3, shows that, consistent with the evidence from Section 1.2, the share of labour employed in manufacturing sectors differs substantially between countries but exhibits a consistent downward trend over time.

We begin by estimating the relationship between gross domestic expenditure on R&D and the share of employment in manufacturing. There are various conceptual issues when trying to estimate relationship between R&D and other economic variables. On the one hand, not all R&D investments translate into successful product or process innovation or if it does there is an unknown time lag between the investment and the actual output from this investment. Also, knowledge spillovers between firms cannot be observed in the data which might distort estimation results (Chennells and Van Reenen, 2002). The last concern is not particularly relevant given the sectoral aggregation we use in the analysis. Regarding the first one, in our baseline estimations we use first lag of the R&D measures so that to keep as many observations as possible in the sample. However, we perform robustness checks by adding longer lag structure. This does not lead to qualitative changes in the relationship between R&D and employment, but might affect the significance level in some of the cases.

[7]Latvia was not included in the shift-share analysis because of lack of full time employment data on the two-digit industry level. However, we can include it for the baseline regression analysis in which we consider total manufacturing employment.

Table 1.3: Descriptive statistics

	All			***Old EU members***			***New EU members***		
	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs	Mean	Std.Dev.	Obs
Dependent variable									
manufacturing_share	0.17	0.05	498	0.14	0.04	329	0.21	0.04	169
manufacturing_share_FTEN	0.17	0.05	466	0.15	0.03	322	0.21	0.04	144
R&D measures									
GERD	1.56	0.83	487	1.88	0.81	314	0.97	0.48	173
businessRD	1.03	0.66	322	1.27	0.67	202	0.61	0.40	120
businessRD_manu	0.67	0.53	324	0.85	0.56	202	0.37	0.29	122
Controls									
lnempl	8.36	1.28	506	8.72	1.26	330	7.68	1.01	176
gdp/cap	32.37	13.98	506	38.87	12.72	330	20.18	5.51	176
gdpgrowth_l1	2.59	3.49	502	2.10	3.00	330	3.54	4.13	172
labcostgrowth	0.79	6.55	475	0.27	6.21	317	1.84	7.08	158
trade	0.66	0.53	436	0.64	0.43	304	0.72	0.70	132
EPL	2.42	0.67	362	2.43	0.73	273	2.41	0.47	89

Note: FTEN: full time employment equivalent; "GERD": gross domestic expenditure as % of GDP; "businessRD": total business R&D expenditure measured as a % of GDP; "businessRD_manu": business R&D expenditure in all manufacturing sectors as a % of GDP; lnempl: natural log of total employment; gdp/cap is devided by 1000; "labcostgrowth": annual change in unit labour cost in manufacturing (%); trade: value of imports plus exports divided by GDP; EPL: Employment Protection Legislation - measures the strictness of employment protection legislation.

The choice of explanatory variables is partially based on previous empirical studies which have focused on possible determinants of sectoral employment. In particular, higher GDP per capita has been found to be associated with higher employment in service sectors (Messina (2005), based on 27 OECD countries for the period (1970-1998), d'Agostino et al. (2006) for EU-15 (1970-2003)). Hence, we expect a negative correlation between GDP per capita and the employment share in manufacturing. On the other hand, different studies find different effects of higher employment regulations (EPL) on the expansion of the service sector. OECD (2000) and d'Agostino et al. (2006) find that on an aggregate level, higher employment protection hinders the expansion of the service sector. On the other hand, Messina (2005) does not find a significant relationship between the two. In addition, we control for demographic changes coming from, for example, migration which is captured in the total employment variable, and for changes in labour cost. Further, we account for the impact of international trade, which is controlled for by a trade openness measure widely used in empirical literature (see, for example, Alesina et al. (2000); Felbermayr et al. (2011); Frankel and Romer (1999)): nominal imports plus nominal exports divided by GDP (again in nominal terms). Keller and Utar (2016), for example, identify a significant impact of Chinese import competition on worker transitions between different sectors in Denmark. Specifically, using matched worker-firm data covering the period 1999-2009, the authors find that import competition explains 17% of the decline in manufacturing, middle-wage jobs. On the flip side, Dosi and Yu (2018) find that sales growth and exports growth is positively correlated with employment at the two-digit manufacturing sectors in China. Our main focus is, however, on the role of R&D

on sector specific employment growth. Table 1.3 provides descriptive statistics for the used variables in the regressions presented in tables 1.4, 1.11 and 1.12. Most of the data is collected from OECD, in particular we use the OECD STAN database for structural analysis (ISIC Rev. 4) for the employment and labour cost data. Further, we use the BTDIxE Bilateral trade by Industry and End-use (ISIC Rev. 4) database for data on value of imports and exports per industry. The data on business R&D expenditure is collected from the OECD ANBERD Analytical Business R&D database. Finally, additional control variables are collected from OECD annual national accounts statistics. More detailed data description can be found in Appendix B.

As can be inferred from figure 1.3 and table 1.3, newer EU member countries have on average a higher share of the working population employed in manufacturing sectors: 21% vs. 15% for EU15 member countries and lower R&D investments, where business R&D expenditures (which are measured as a fraction of countries' GDP) are almost half compared to older EU members. In table 1.4 the R&D measure used for these regressions is gross domestic expenditure on R&D, as a percentage of GDP (first lag). Quite strikingly, we consistently obtain a statistically significant coefficient for R&D expenditures, which means that, considering all manufacturing sectors, there is a negative correlation between the R&D investment in a country and the share of employment in manufacturing. Using alternative measures for aggregate R&D expenditure per country or using longer lags yields similar results for the relationship between the manufacturing share and R&D expenditure. This is displayed in table 1.11 in Appendix C where we used total business R&D expenditure in a country, measured in national currency, 2010 prices, divided by GDP, again in national currency, constant prices. Similarly to the specification in table 1.4, R&D expenditure is negatively, significantly correlated with share of manufacturing employment. Finally, in table 1.12 in Appendix C we include the second lag of gross domestic expenditure on R&D, as well as business R&D in total economy (first and second lag) and business R&D concentrated only in manufacturing sectors (again first and second lag). In all specification, we observe a negative and significant coefficient of R&D[8].

Apart from this, we obtain a positive correlation of the employment share in manufacturing with the growth rate of GDP as well as negative correlation with total employment and with GDP per capita. This latter result is consistent with the observation that in particular the new EU member countries are characterized by higher manufacturing shares but lower per capita GDP compared to the old EU member states. It is also consistent with the results of d'Agostino et al. (2006) who study the determinants of employment in the service sectors and establish a strong positive correlation between GDP per capita and the service sector's employment share. Further, labour cost growth in manufacturing is negatively correlated with the manufacturing employment share, but the relationship is insignificant in most of the specifications. On the other hand, we find no significant correlation between the employment protection index (EPL) and the manufacturing employment share. Also, this variable is missing for multiple years and countries and including it restricts our sample size. Therefore, it is excluded from the controls used in the regressions reported in table 1.12. Finally, we obtain

[8]Only when using the first lag of business R&D in manufacturing, the significance of the coefficient drops below the 1% level.

Table 1.4: Manufacturing share of employment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
GERD_L1	-0.036***	-0.029***	-0.022***	-0.014***	-0.014***	-0.013***	-0.011*
	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.005)
lnempl		-0.123***	-0.139***	-0.082***	-0.081***	-0.097***	-0.095**
		(0.020)	(0.013)	(0.011)	(0.011)	(0.010)	(0.029)
gdpgrowth_l1			0.002***	0.002***	0.002***	0.002***	0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
gdp/cap				-0.002***	-0.002***	-0.002**	-0.001*
				(0.000)	(0.000)	(0.000)	(0.001)
labcostgrowth					-0.009	-0.007	-0.023
					(0.009)	(0.011)	(0.013)
trade						-0.007	-0.011**
						(0.004)	(0.003)
EPL							0.001
							(0.007)
Constant	0.222***	1.248***	1.370***	0.935***	0.926***	1.067***	1.058***
	(0.007)	(0.165)	(0.106)	(0.092)	(0.090)	(0.078)	(0.218)
Observations	444	444	441	441	432	374	296
Within R^2	0.294	0.446	0.561	0.628	0.623	0.616	0.650
Num. of countries	23	23	23	23	23	20	20
Country FE	yes	yes	yes	yes	yes	yes	yes

Dependent variable: share of employment in manufacturing based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), Manufacturing [C]: ISIC 10-33. In specifications (6) and (7) Spain, Latvia and Lithuania are dropped due to missing data.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

a negative correlation between trade openness and the share of manufacturing employment. However, the significance of the result is not stable across the different regression specifications. Concerning the negative correlation between the manufacturing share and R&D, in principle this phenomenon is in accordance with our evidence from the previous sections that employment tends to move to sectors with lower growth rates of labour productivity. However, it should be noted that here we consider the whole manufacturing sector and it is not yet clear how R&D expenditure affects employment at more-narrowly defined sectoral levels. Furthermore, we should expect a large heterogeneity across manufacturing sectors with respect to the elasticity of employment with respect to R&D, which clearly limits the informativeness of such considerations on the aggregate level.

1.4.1 R&D expenditure and employment in manufacturing sectors

To address this shortcoming we now perform sector specific regressions. We begin by looking deeper at the country level heterogeneity with respect to distribution of business R&D expenditure between the different manufacturing sectors. Table 1.5 displays some summary statistics of business R&D expenditure. Since there are many missing observations for this

Table 1.5: Business R&D

Country	Business R&D	R&D manufacturing	Low-	Medium-	High-tech
	% of GDP	*share*	*distribution of R&D*		
	average 2010-2015				
Austria	2.04	62.87	7.14	14.85	78.01
Belgium	1.58	58.60	8.71	9.30	81.99
Czech Republic	0.95	52.24	7.95	13.00	79.05
Germany	1.92	85.90	3.24	6.72	90.04
Denmark	1.93	55.50	6.71	17.59	75.69
Spain	0.67	45.33	16.42	9.60	73.98
Estonia	0.93	37.82	60.04	4.37	35.59
Finland	2.31	73.00	7.52	4.18	88.30
France	1.43	50.44	8.76	11.57	79.67
UK	1.05	38.67	12.73	6.96	80.31
Greece	0.22	34.17	29.79	10.56	59.65
Hungary	0.86	51.02	7.45	6.77	86.11
Ireland	1.06	40.10	15.85	24.33	59.74
Italy	0.71	72.07	12.68	8.38	79.00
Lithuania	0.26	35.22	11.74	19.58	66.79
Netherlands	1.04	59.36	17.14	6.18	77.44
Poland	0.34	47.02	19.29	14.89	66.20
Portugal	0.65	38.32	32.24	16.86	51.14
Slovak Republic	0.31	62.43	6.18	12.49	80.68
Slovenia	1.77	68.21	9.96	8.06	82.15
Sweden	2.22	70.61	4.82	7.22	87.49

Note: All values are averages for 2010-2015, except for Greece where the time span is 2011-2015. Second column: business R&D expenditure as a % of GDP. Third column: share of business R&D expenditure allocated to manufacturing sectors. Fourth-Sixth columns: share of business R&D in manufacturing allocated to low-, medium- and high-tech manufacturing sectors, respectively.

variable, the table displays average values, spanning 2010-2015, for which years most observations are present. The second column shows business R&D as a percent of GDP per country. The highest value is Finland's: 2.31% followed by Sweden: 2.22% and Austria: 2.04%. For all other countries in the sample the average business R&D investment for the years 2010 to 2015 was below 2% of GDP. The lowest value is Greece's: 0.22%, followed by Slovak Republic: 0.31% and Poland: 0.34%. Column 3 of the table then looks at what share of this investment was done in the manufacturing sectors. Overall, for the majority of the countries the larger share of business R&D investment was allocated in manufacturing; exceptions are Spain, Estonia, UK, Greece, Ireland, Lithuania, Poland and Portugal. Finally, the last three columns of the table look how the R&D investment in manufacturing is distributed between low-, medium- and high-technology sectors. Low-tech manufacturing sectors are: "Food products, beverages and tobacco", "Textiles, wearing apparel, leather and related products", "Wood and paper products, and printing", "Coke and refined petroleum products" and "Fabricated metal products, except machinery and equipment"; medium-tech manufacturing sectors are: "Rubber and plastic products", "Other non-metallic mineral products", "Basic metals" and "Furniture; other manufacturing: repair and installation of machinery and equipment" and high-tech manufacturing sectors are: "Chemicals and chemical products", "Basic pharmaceutical products and pharmaceutical preparations", "Computer, electronic and optical products", "Electrical equipment", "Machinery and equipment n.e.c.", "Motor vehicles, trailers and semi-trailers" and "Other transport equipment". Most of R&D expenditure is concentrated in high-tech manufacturing industries which is expected since high-tech manufacturing industries are considered those with high R&D intensity. The taxonomy we use is based on the one proposed by Galindo-Rueda and Verger (2016). The authors group manufacturing and non-manufacturing industries in five categories according to their R&D intensities, where R&D intensity is measured as the ratio of R&D expenditure to gross value added. The low-tech specification here corresponds to the "Medium-low R&D intensity industries" in their classification; medium-tech corresponds to "Medium R&D intensity industries" and high-tech combines "Medium-high R&D intensity industries" and "High R&D intensity industries". While overall, majority of R&D expenditure is concentrated in high-tech industries, we observe a considerable variation among the countries in the sample regarding the distribution of R&D investment.

We next run sector-specific regressions to identify whether the overall negative, significant correlation between R&D and employment in manufacturing is preserved at the less aggregate level. The dependent variable in each case in the natural logarithm of total employment in a specific sector. As explanatory variables we include natural logarithm of sectoral business R&D expenditure[9]. Further, we include similar control variables as in the baseline regression, namely natural log of total employment and natural log of GDP per capita as well as GDP growth rate. Next we control for international trade by including log of the sector-specific trade openness measure. Finally, we include changes in hourly wages and salaries using OECD STAN database ("wage_growth" variable) but also include a change in unit cost variable ("labcostgrowth"), which is collected from the OECD Productivity and ULC by main economic activity database. Data on wages and salaries or total hours worked is missing for some sectors of some countries, so for those sectors, in order to not lose too many observations we control for changes in labour cost using the growth in unit labour cost control variable. The drawback of doing so is that it is defined for the whole manufacturing sector. More detailed description of the data can be found in Appendix B. Again, fixed effects (within) regressions with with Driscoll and Kraay standard errors are estimated.

Starting with low-tech manufacturing, table 1.13 in Appendix D presents the results for "Food products, beverages and tobacco". This sector accounted on average for 2.15% of total employment across the countries in the sample in 2015, where on average 1.9% of total employment in EU15 countries was in this sector compared to 2.6% for the newer EU member countries. In the first four columns, the dependent variable is natural log of total employment in the sector, while in the last four, it is natural log of full time equivalent employment. Differences between specifications (1) and (2); (5) and (6) is that we use the different controls capturing changes in labour costs. The coefficients for both variables are insignificant for this sector. Also, we divide the sample into EU15 and newer EU member countries (specifications (3) and (4); (7) and (8)) and re-run the regressions. Overall, R&D expenditure is positively correlated with employment in the "Food products, beverages and tobacco" sector. The result is significant at the 0.1% level when considering full-time equivalent employment and at the 1% level for the case of total sectoral employment. Interestingly, the significance level of the result is driven by the group of newer EU member countries, while we observe no

[9] Measured in national currency, 2010 prices, first lag.

Table 1.6: Manufacturing and innovation

Sector+Code	R&D[a]	N[b]	Countries	R^{2c}
Low-tech manufacturing				
Dependent variable: Total employment				
Food products, beverages and tobacco ISIC 10-12	0.053** (0.014)	262	19	0.590
Textiles, wearing apparel, leather and related products: ISIC 13-15	−0.048* (0.023)	233	18	0.663
Wood and paper products, and printing: ISIC 16-18	−0.034* (0.012)	249	18	0.326
Coke and refined petroleum products ISIC 19	0.035* (0.026)	157	14	0.330
Fabricated metal products, except machinery and equipment: ISIC 25	−0.034*** (0.026)	255	19	0.352
Dependent variable: Full time equivalent employment				
Food products, beverages and tobacco ISIC 10-12	0.061** (0.013)	248	19	0.591
Textiles, wearing apparel, leather and related products: ISIC 13-15	−0.055* (0.023)	233	18	0.661
Wood and paper products, and printing: ISIC 16-18	−0.039* (0.014)	235	18	0.335
Coke and refined petroleum products ISIC 19	0.028 (0.026)	157	14	0.352
Fabricated metal products, except machinery and equipment: ISIC 25	−0.028** (0.007)	179	15	0.441
Medium-tech manufacturing				
Dependent variable: Total employment				
Rubber and plastic products ISIC 22	−0.008 (0.019)	229	19	0.471
Other non-metallic mineral products ISIC 23	−0.042* (0.015)	237	19	0.343
Basic metals ISIC 24	0.036*** (0.009)	246	18	0.319
Furniture; other manufacturing; repair and installation of machinery and equipment: ISIC 31-33	−0.017* (0.006)	245	19	0.150
Dependent variable: Full time equivalent employment				
Rubber and plastic products ISIC 22	−0.026 (0.031)	163	15	0.453
Other non-metallic mineral products ISIC 23	−0.077*** (0.015)	171	15	0.334
Basic metals ISIC 24	0.030 (0.028)	170	14	0.306
Furniture; other manufacturing; repair and installation of machinery and equipment: ISIC 31-33	−0.033** (0.009)	231	19	0.175

[a] First Lag
[b] Number of observations
[c] Within R^2
Note: Dependent variables are in natural log. Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. The full regressions are displayed in tables 1.17 and 1.18 in Appendix D. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

significant correlation between R&D expenditure in this sector and employment in EU15 countries. Further, higher GDP per capita is associated with lower full time employment in “Food products, beverages and tobacco” but the highly significant result is driven by the newer EU member countries. Trade openness is negatively correlated with employment in this sector and for most of the specifications the coefficient is statistically significant.

Next, table 1.14 shows the result for employment in “Textiles, wearing apparel, leather and related products" as a second example of a low-tech manufacturing sector. In 2015 on average 1.04% of the workforce in the countries in the panel was employed in this sector, where this percentage is slightly lower if we consider only EU15 countries: 0.79% vs. 1.53% for EU15+ member countries. Here, R&D expenditure is negatively associated with sectoral employment and the result is significant at the 5% level for both full time equivalent and total employment. However, the negative, significant relationship seems to be caused by the EU15 countries, while for the rest of the sample the coefficient of R&D expenditure is positive, but insignificant. Further, the results indicate a not significant relationship between trade openness and employment in "Textiles, wearing apparel, leather and related products" but considering the sub-sample of newer EU member countries there is a positive correlation between the two, significant at the 5% level. On the other hand, hourly wage growth is associated with lower full time employment in the sector in the EU15 countries.

Table 1.6 summarizes the regression results with respect to the relationship between employment and R&D expenditure for low- and medium-tech manufacturing sectors. The full regression results for low-tech manufacturing sectors are presented in table 1.17 in Appendix D. On average, in 2015, the share of employment in low-tech manufacturing sectors was 6.3% of total employment. This breaks down into approximately 5.2% for EU15 countries (excluding Luxembourg) and 8.6% for the rest of the countries in the sample (excluding Estonia). We observe that for the majority of low-tech manufacturing sectors for which R&D expenditure is significantly correlated with employment, the sign of the coefficient is negative. The one exception is the sector "Food products, beverages and tobacco" discussed in more detail above. Increase in the unit cost of labour is mostly negatively correlated with employment where the result is highly significant only for the sector "Textiles, wearing apparel, leather and related products". The trade openness measure is also negatively correlated with sectoral employment for most of the low-tech manufacturing sectors. However, the coefficient is predominantly insignificant. Further, similarly to our baseline regression from the previous section we observe a negative, significant relationship between GDP per capita and sectoral employment in four out of the five low-tech manufacturing sectors. The only exception is "Fabricated metal products, except machinery and equipment" for which we obtain a statistically significant and positive coefficient. These results are in line with the overall conclusion from the previous section that R&D expenditure in manufacturing is associated with lower employment.

Next, we turn to the medium-tech manufacturing sectors. Tables 1.6 and 1.18 in Appendix D display results with respect to total employment and full time equivalent employment for all medium-tech manufacturing sectors. The average share of employment in these sectors in 2015 across the countries in the sample was 3.47% of total employment. In EU15 countries (excluding Luxembourg) the average in 2015 was 2.8% compared to 4.6% for the rest of the countries in the panel. We observe that for "Other non-metallic mineral products" and "Furniture; other manufacturing, repair and installation of machinery and equipment" there is a negative, significant relationship between R&D expenditure and employment for both total and full time equivalent employment specifications. For the sector "Basic metal" this relationship is positive and significant at the 0.1% level. However, this significance disappears when considering full-time employment which might be driven by the fact that the

Table 1.7: Manufacturing and innovation: part 2

Sector+Code	R&D[a]	N[b]	Countries	R^{2c}
High-tech manufacturing				
Dependent variable: Total employment				
Chemicals and chemical products ISIC 20	0.090** (0.026)	211	16	0.490
Basic pharmaceutical products and pharmaceutical preparations: ISIC 21	0.163** (0.044)	216	18	0.245
Computer, electronic and optical products ISIC 26	0.214** (0.073)	259	19	0.509
Electrical equipment ISIC 27	0.036 (0.024)	259	19	0.147
Machinery and equipment n.e.c. ISIC 28	0.024 (0.021)	259	19	0.160
Motor vehicles, trailers and semitrailers: ISIC 29	0.036* (0.015)	258	19	0.449
Other transport equipment, ISIC 30	−0.053* (0.025)	243	19	0.145
Dependent variable: Full time equivalent employment				
Chemicals and chemical products ISIC 20	0.076* (0.033)	197	16	0.417
Basic pharmaceutical products and pharmaceutical preparations: ISIC 21	0.093** (0.031)	199	18	0.462
Computer, electronic and optical products ISIC 26	0.198** (0.069)	245	19	0.520
Electrical equipment ISIC 27	0.015 (0.024)	245	19	0.102
Machinery and equipment n.e.c. ISIC 28	−0.007 (0.021)	245	19	0.127
Motor vehicles, trailers and semitrailers: ISIC 29	0.073** (0.021)	182	15	0.453
Other transport equipment, ISIC 30	−0.114** (0.039)	173	15	0.170

[a] First Lag
[b] Number of observations
[c] Within R^2
Note: Dependent variables are in natural log. Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. The full regressions are displayed in tables 1.19 in Appendix D. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

number of observations and countries in the panel for that regression is much smaller due to missing data. GDP per capita preservers its negative, significant correlation with sectoral employment for two out of the four medium-tech manufacturing sectors. Considering the sector "Rubber and plastic products" there is significant, positive correlation between the two. Next, trade openness is associated with lower employment in medium-tech service sector, however, the coefficient is mostly insignificant. Overall, the results for medium-tech manufacturing sectors with respect to the correlation between R&D expenditure and employment are also broadly in line with the conclusion from the previous section.

Last but not least, we run the sector-specific regressions for high-tech manufacturing sectors. Table 1.15 in Appendix D shows the results for "Computer, electronic and optical products" as a detailed example of one of the high-tech manufacturing sectors. In terms of employment, in 2015, approximately 0.56% of workers were employed in that sector. This percentage is slightly lower considering EU15 countries (excluding Luxembourg): 0.46% vs. 0.73% for the rest of the countries. We observe a positive and significant coefficient of R&D

expenditure in all regression specifications. Similarly to the overall results for manufacturing, higher GDP per capita is negatively correlated with employment in this sector and the coefficient is highly significant across most specifications. Unlike, the overall manufacturing results, however, trade openness is positively correlated with employment in "Computer, electronic and optical products" and the coefficient is significant at the 0.1% level. Finally, hourly wage growth is associated with lower employment in this sector in the newer EU member countries.

Further, table 1.16 in Appendix D displays result for "Motor vehicles, trailers and semi-trailers" as a second detailed example for high-tech manufacturing sector. Employment in this sector was on average 0.97% of total employment in 2015. This breaks down into 0.62% for EU15 countries (excluding Luxembourg) and 1.58% for the other eight EU member countries in the panel. Again we observe a significant relationship between R&D expenditure and employment if we consider the whole sample. The coefficient of R&D turns, however, insignificant in the case of total employment in EU15 countries. For newer EU member countries the coefficient is positive and significant at the 0.1% level, considering total employment and at the 1% level regarding full-time employment. Interestingly, higher GDP per capita is associated with higher employment in this sector in newer EU member countries, while there is no statistically significant relationship between the two considering EU15 countries. Higher trade openness is also associated with higher employment in "Motor vehicles, trailers and semi-trailers" in EU15+ countries.

The overall results for high-tech manufacturing sectors are displayed in table 1.7 and table 1.19 in Appendix D. These sectors employed on average 4.48% of the working force in 2015, where this percentage is slightly lower if we consider the group of EU15 countries (excluding Luxembourg): 3.76% vs. 5.92% for the rest of the countries (excluding Estonia). Out of the seven considered sectors there are four for which there is a positive significant relationship between R&D expenditure and employment and for one of them: "Other transport equipment" there is a significant negative relationship. The coefficient of growth in unit labour cost is negative, whenever significant while the results with respect to trade openness are mixed. For "Computer, electronic and optical products" and "Motor vehicles, trailers and semi-trailers" we observe a positive correlation between trade and employment, while for "Chemicals and chemical products" and "Basic pharmaceutical products and pharmaceutical preparation" this relationship is negative. For the other three high-tech manufacturing sectors the coefficient of trade is not statistically significant. GDP growth is positively correlated with employment in the high-tech manufacturing sectors whenever the coefficient is statistically significant. And finally, GDP per capita is negatively correlated with employment in most of the sectors. Exceptions are "Motor vehicles, trailers and semi-trailers", discussed in more detail above, and "Basic pharmaceutical products and pharmaceutical preparation".

Overall, the results with respect to the relationship between R&D expenditure as a proxy for innovation and employment in manufacturing are quite mixed and nuanced. Generally, we observe that higher R&D investment in high-tech manufacturing sectors is associated with higher employment in those sectors while the opposite is true for the low- and medium-tech sectors considered in the analysis. There are, however, exceptions in each group. These results might reflect the dominant innovation strategies, either product or process innovation, in each industry. In this respect, Antonucci and Pianta (2002), report that for firms in

“Textiles”, “Food, Beverages and Tobacco” and “Printing and Publishing” (according to ISIC Rev. 3) process innovations is the main source of innovation. All of those industries fall in the low-tech category which might be one explanation to why we often observe a negative correlation between R&D expenditure and employment in those sectors. On the other hand, Antonucci and Pianta (2002) find that for firms in “Machinery”, “Electrical and Communications Machinery” and “Transport”, which are high-tech industries, product innovation is the main source of innovation. This indicates that a positive employment effect of product innovations, as reported in many of the empirical firm-level studies, can also be observed at the sectoral level. One has to be, however, cautious in interpreting our result since we cannot claim causality. Moreover, the positive association between R&D in high-tech industries and employment is also reported in Bogliacino and Vivarelli (2012)[10]. The authors find, however, that R&D has a positive but insignificant effect on employment in low- and medium-tech industries. Further, our results indicate that there are qualitative difference between the older and newer EU member countries with respect to the relationship between R&D and employment in some sectors. Diving deeper into the types of innovation in Central and Eastern European firms might provide insight to why this is the case.

1.4.2 R&D expenditure and service sector employment

Next, we move to the service sectors and again use the taxonomy proposed by Galindo-Rueda and Verger (2016) to cluster the service sectors into three broad groups based on their R&D intensity. Galindo-Rueda and Verger (2016) point out that most service sectors exhibit low R&D intensity. However, “Scientific research and development” and “IT and other information services” are exceptions. What we call “high-tech service sectors” then corresponds to the high and medium-high R&D intensity non-manufacturing industries in their taxonomy. Our “medium-tech service sectors” correspond to the medium-low tier in their clustering, and the “low-tech service sectors” follows the low R&D intensity industries in their classification. Also, we include only the business service sectors[11]. While data on R&D expenditure is more scarce for the service sectors, it is important to understand the link between innovation and employment in them especially given that we observe substantial cross-sectoral shifts of labour towards the services.

Tables 1.20 and 1.21 in Appendix D present the results with respect to “Scientific research and development” and “Telecommunications” as examples of high and medium-tech service industries, respectively. On average, 0.52% of workers were employed in “Scientific research and development” in EU15 countries (excluding Luxembourg) in 2015, compared to 0.39% for the rest of the countries in the panel. As expected, the correlation between R&D expenditures and employment is positive and highly significant across all specifications. On the other hand, hourly wage growth and GDP per capita are negatively associated with employment in this sector when considering all countries in the sample. However, looking at the two groups of countries separately reveals conflicting results, such that the coefficient of wage growth is

[10]The authors group manufacturing and few service industries into the three categories: low-, medium-, and high-tech. So there are two service sectors included in their high-tech definition: ”Computer and related activities” and ”Research and Development”. The other two service sectors which they consider: ”Hotels and catering” and ”Other business activities” are grouped together with the medium-tech manufacturing sectors.

[11]Code: ISIC D45-82.

Table 1.8: Services and innovation

Sector+Code	R&D[a]	N[b]	Countries	R^{2c}
Medium-tech services				
Dependent variable: Total employment				
Telecommunications ISIC 61	−0.021 (0.011)	171	19	0.316
Professional, scientific and technical activities: ISIC 69-75	0.022** (0.008)	167	21	0.611
Dependent variable: Full time equivalent employment				
Telecommunications ISIC 61	−0.030** (0.011)	171	19	0.347
Professional, scientific and technical activities: ISIC 69-75	0.016* (0.008)	167	21	0.638
High-tech services				
Dependent variable: Total employment				
Scientific research and development: ISIC 72	0.195*** (0.027)	276	21	0.542
IT and other information services: ISIC 62-63	0.123** (0.027)	184	20	0.867
Dependent variable: Full time equivalent employment				
Scientific research and development: ISIC 72	0.205*** (0.023)	276	21	0.575
IT and other information services: ISIC 62-63	0.120** (0.026)	184	20	0.861

[a] First Lag
[b] Number of observations
[c] Within R^2
Note: Dependent variables are in natural log. Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. The full regressions are displayed in tables 1.22 in Appendix D. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

negative and significant at the 0.1% level for the sub-group of newer EU member countries, while it is positive and significant at the 1% level for EU15 countries.

For employment in "Telecommunications" we find a negative, significant correlation between R&D and full time employment but the significance disappears when considering the sub-sample of newer EU member countries. This sector employed, on average, 0.48% of workers in EU15 countries in 2015 compared to 0.56% for the rest of the countries in the panel. Hourly wage growth is negatively correlated with employment while higher GDP per capital is associated with higher employment in "Telecommunications". The results for high- and medium-tech service sectors are displayed in table 1.22 in Appendix D and a summary of the relationship between R&D expenditure and employment is shown in table 1.8. Overall, high tech service sectors employed on average 2.19% of workers across the countries in the panel. This average is slightly higher for EU15 countries (excluding Luxembourg): 2.26% vs. 2.07% for the newer EU member countries. Similarly to "Scientific research and development", also for the other high-tech service sector: "IT and other information services" we observe a highly significant, positive correlation between R&D and employment. Unlike "Scientific research and development", higher GDP per capita is associated with higher employment in "IT and other information services". For the medium-tech service industries the results are mixed. While full-time equivalent employment in "Telecommunications" is negatively correlated with R&D expenditure in that sector, we observe a significant, positive correlation between R&D

Table 1.9: Services and innovation: part 2

Sector+Code	R&D[a]	N[b]	Countries	R^{2c}
Low-tech services				
Dependent variable: Total employment				
Financial and insurance activities ISIC 64-66	−0.002 (0.003)	214	20	0.178
Audiovisual and broadcasting activities: ISIC 59-60	−0.008 (0.008)	72	13	0.345
Wholesale and retail trade, repair of motor vehicles and motorcycles: ISIC 45-47	0.007 (0.004)	251	21	0.710
Administrative and support service activities: ISIC 77-82	0.005 (0.004)	153	21	0.368
Transportation and storage ISIC 49-53	−0.003 (0.002)	191	20	0.329
Accommodation and food service activities: ISIC 55-56	0.015** (0.005)	123	16	0.370
Real estate activities ISIC 68	−0.005 (0.003)	109	17	0.199
Dependent variable: Full time equivalent employment				
Financial and insurance activities ISIC 64-66	−0.005 (0.004)	214	20	0.203
Audiovisual and broadcasting activities: ISIC 59-60	−0.008 (0.010)	72	13	0.340
Wholesale and retail trade, repair of motor vehicles and motorcycles: ISIC 45-47	−0.009 (0.005)	251	21	0.220
Administrative and support service activities: ISIC 77-82	0.001 (0.003)	153	21	0.380
Transportation and storage ISIC 49-53	0.003 (0.002)	191	20	0.118
Accommodation and food service activities: ISIC 55-56	0.010 (0.005)	123	16	0.344
Real estate activities ISIC 68	−0.006 (0.004)	109	17	0.147

[a] First Lag
[b] Number of observations
[c] Within R^2
Note: Dependent variables are in natural log. Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. The full regressions are displayed in tables 1.23 in Appendix D. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

and employment in “Professional, scientific and technical activities except scientific R&D” for both the total and full time equivalent employment specifications. “Professional, scientific and technical activities except scientific R&D” is quite a broad category which includes legal and accounting activities, architectural and engineering activities, advertising and market research. However, the R&D data is scarce at a more detailed level. Further, hourly wage growth exhibits a significant negative correlation with employment in high- and medium-tech service sectors for both total and full time employment, although as discussed above there are some differences between the two groups for “Scientific research and development”. On average medium-tech services accounted for approximately 6% of total employment in 2015 across the considered EU countries (excluding Luxembourg) which breaks down into 6.44% for EU15 and 5.21% for the rest of the countries in the panel.

Finally, the majority of service sectors fall into the low-tech category. Also, these sectors account for a large share of total employment where in 2015 on average across the countries in the panel, 34.8% of workers were employed in one of those sectors. For the group of EU15 countries employment in the low-tech service sectors was on average 36.2% compared to 32.2% for the newer EU member countries. The regression results are displayed in table 1.23 in Appendix D and table 1.9 shows a summary. With respect to the correlation between R&D expenditure and sectoral employment we find predominantly that the coefficient of R&D is not significant. The only exception is “Accommodation and food service activities”, but the significance of the result drops in the specification with full-time equivalent employment.

Overall, we find that for the majority of business service sectors, for which we establish significant correlation between R&D and employment, the corresponding coefficient is positive. However, for most of the business service sectors, the correlation is not statistically significant. In terms of differences between the two country groups in our panel, we find that for the high-tech service sectors there are no qualitative differences of the direction of the relationship between R&D expenditure and employment. Considering the medium-tech services, we find a negative but insignificant association between R&D expenditure and employment in Professional, scientific and technical activities, except scientific research and development for the newer EU member countries (result not shown here but available upon request). This implies that the overall result displayed in table 1.22 is driven by the EU15 countries. As for the low-tech service sectors, in five out of the seven, the sign and significance of the coefficient of R&D coincides between the two groups. Exception is “Financial and insurance activities”, but the result is not significant in all cases. Also, for “Accommodation and food service activities” the significance of the result with respect to total employment is due to the EU15 countries where for the rest of the countries in the panel the R&D coefficient is negative and insignificant.

1.4.3 R&D expenditure and employment in other non-manufacturing sectors

In the last step, we look into the few of the rest of the economic sectors and the correlation between R&D and employment. Table 1.24 in Appendix D displays the results for “Agriculture, forestry and fishing”, “Mining and quarrying”, “Electricity, gas and water supply; sewerage, waste management and remediation activities” and “Construction”, and table 1.10 shows a summary with respect to R&D expenditure. We obtain significant results for three out of those four sectors, where in “Agriculture, forestry and fishing” and “Construction”, R&D expenditure is negatively correlated with employment. On the other hand, for “Electricity, gas and water supply; sewerage, waste management and remediation activities” the R&D coefficient is positive and highly significant in both total and full time equivalent employment specifications. Out of those sectors, “Construction” employs the largest fraction of workers—on average 6.8% in 2015 across the countries in the panel.

1.5 Conclusion

The purpose of this study is to provide some empirical diagnostics of the relationship between R&D, productivity growth and employment on a sectoral level and to explore in how far these relationships differ qualitatively between manufacturing and service sectors or between EU15

Table 1.10: Other non-manufacturing sectors and innovation

Sector+Code	R&D[a]	N[b]	Countries	R^{2c}
Other non-manufacturing sectors				
Dependent variable: Total employment				
Agriculture, forestry and fishing ISIC 01-03	−0.026* (0.011)	260	21	0.701
Mining and quarrying ISIC 05-09	0.011 (0.016)	235	19	0.455
Electricity, gas and water supply; sewerage, waste management and remediation activities: ISIC 35-39	0.025*** (0.004)	247	20	0.278
Construction ISIC 41-43	−0.030* (0.014)	263	21	0.347
Dependent variable: Full time equivalent employment				
Agriculture, forestry and fishing ISIC 01-03	−0.042** (0.011)	260	21	0.708
Mining and quarrying ISIC 05-09	0.003 (0.017)	235	19	0.465
Electricity, gas and water supply; sewerage, waste management and remediation activities: ISIC 35-39	0.025*** (0.005)	247	20	0.233
Construction ISIC 41-43	−0.042** (0.014)	263	21	0.377

[a] First Lag
[b] Number of observations
[c] Within R^2
Note: Dependent variables are in natural log. Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. The full regressions are displayed in tables 1.24 in Appendix D. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

countries and countries that have joined the EU during or after the 2004 enlargement. As a first step, consistent with the literature, we have documented a clear and persistent movement of employment from manufacturing to service sectors in all EU countries. Second, we have shown that this shift of employment corresponds to a movement from sectors with higher and faster growing productivity to such with smaller and slower growing productivity. This holds particularly true for old EU member countries, whereas for new member countries some movement towards more productive sectors could be observed. Finally, we have shown that there is a negative correlation between the manufacturing share in employment and the gross domestic expenditure on R&D. The result is robust if R&D expenditure is instead measure by business R&D expenditure or by business R&D expenditure in manufacturing. It is also robust with respect to using a different lag structure. Higher GDP per capita is also associated with lower share of employment in the manufacturing sectors while higher GDP growth is related to higher manufacturing share of employment. On the other hand, our estimations suggest no significant effects of growth in unit labour cost or strictness of employment protection on the manufacturing employment share. Trade openness is also negatively correlated with the manufacturing employment share, although its coefficients is not always statistically significant.

In terms of absolute employment (rather than employment share) we find that for most high-tech manufacturing and service sectors an increase in R&D is associated with higher employment. The relationship is, however, reversed for most middle to low-tech manufacturing sectors. Moreover, splitting the sample into two groups—EU15 and EU15+ countries—reveals that for some sectors there are qualitative differences with respect to the relation of R&D

and sectoral employment in the two groups. On the other hand, we find no significant relationship between employment in low-tech business service sectors and R&D expenditure in those sectors while the results with respect to the medium-tech service sectors are mixed. A significant determinant of sectoral employment, across most specifications is GDP per capita, while GDP growth is significantly related with employment mostly for manufacturing industries. Further, growth in hourly wages is significantly, negative correlated with employment in all high- and medium-tech business service sectors. For the low-tech business services the coefficient of wage growth is significant in two out of the seven considered sectors. For majority of manufacturing industries, however, changes in labour cost are not significantly correlated with employment. Whenever, the coefficient of trade openness is significant in low- and medium-tech manufacturing sectors, it is negative. However, there are qualitative difference between the two country groups in the panel for some manufacturing sector with respect to this variable. On the other hand, in high-tech manufacturing the results for trade openness and its correlation with employment are mixed.

1.6 Appendix A: Additional figures

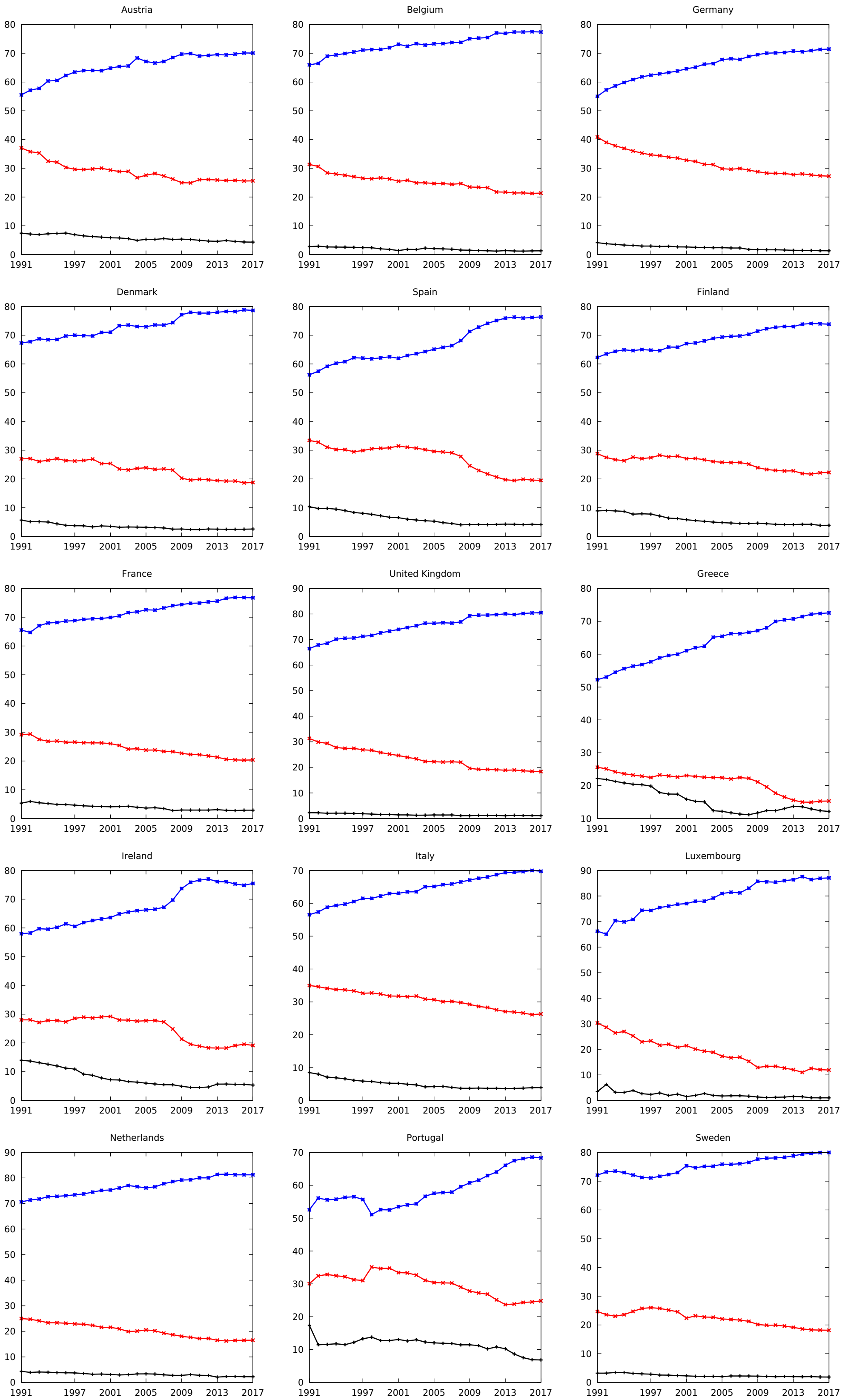


Figure 1.4: Employment in agriculture (black), services (blue) and industry (red) as percentage of total employment. Data source: ILOSTAT database.

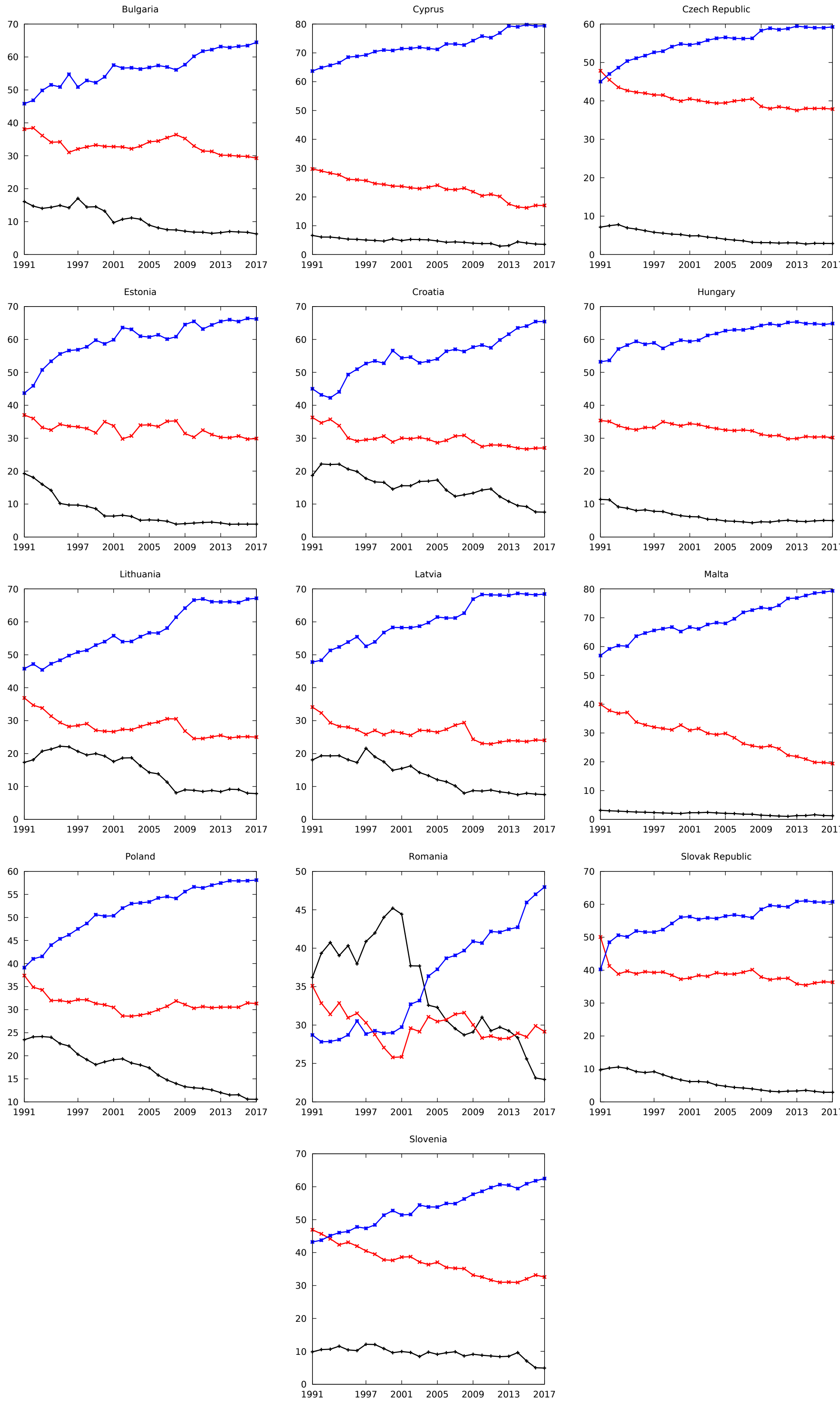


Figure 1.5: Employment in agriculture (black), services (blue) and industry (red) as percentage of total employment. Data source: ILOSTAT database.

1.7 Appendix B: Data description

- Share of manufacturing employment regressions
  - *GERDL1*: gross domestic expenditure on R&D, as a percentage of GDP, first lag, source: OECD Main Science and Technology Indicators (MSTI) dataset
  - *lntotalempl*: total employment (measured in number of workers, natural logarithm), source: OECD STAN dataset (ISIC Rev. 4)
  - *gdpgrowth_l1*: first lag of GDPgrowth rate, source: OECD annual national accounts statistics
  - *gdp/cap*: GDP per head, constant prices, constant PPPs, unit is thousands, 2010 base year. Source: OECD annual national accounts statistics
  - *labcostgrowth*: change in unit labour cost in manufacturing, percentage. Source: OECD annual national accounts statistics
  - *trade*: indicator for trade openness: nominal imports plus exports (unit: US dollars, thousands) divided by GDP (unit: national currency, current prices, millions). Source of imports, exports data: Bilateral Trade in Goods by Industry and End-use (BTDIxE), ISIC Rev. 4. Source of GDP data: OECD annual national accounts statistics
  - *EPL*: index of strictness of employment protection: individual and collective dismissals, Version 1
  - *businessRD_L2*: business investment in R&D, total economy, classification criteria: main activity, second lag in national currency, 2010 prices divided by GDP in national currency, 2010 prices. Unit: thousands. Source: OECD ANBERD dataset
  - *busiRD_manu_L2*: business investment in R&D in manufacturing, classification criteria: main activity, second lag in national currency, 2010 prices divided by GDP in national currency, 2010 prices. Unit: thousands. Source: OECD ANBERD dataset

- Sector specific regressions, additional variables
  - *RD_L1*: natural log of business R&D expenditure by industry, classification criteria: main activity, measured in national currency, 2010 prices, source: OECD Analytical Business Enterprise R&D (ANBERD) database
  - *wage_growth*: growth in hourly wages. Hourly wages are constructed by dividing the total wage bill in an industry by total hours worked in that industry. Source: OECD Database for Structural Analysis (STAN), ISIC Rev.4

1.8 Appendix C: Additional results and robustness checks

Table 1.11: Manufacturing share of employment by country and year

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
businessRD_l1	-0.004***	-0.003***	-0.003***	-0.002***	-0.002***	-0.002***	-0.001**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnempl		-0.091***	-0.119***	-0.059**	-0.050**	-0.056**	-0.083*
		(0.023)	(0.024)	(0.020)	(0.017)	(0.017)	(0.039)
gdpgrowth_l1			0.001***	0.002***	0.002***	0.001***	0.002***
			(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
gdp/cap				-0.001***	-0.002***	-0.001**	-0.000
				(0.000)	(0.000)	(0.000)	(0.001)
labcostgrowth					-0.014	-0.013	-0.031*
					(0.009)	(0.012)	(0.014)
trade						-0.014*	-0.017**
						(0.005)	(0.005)
EPL							0.010
							(0.008)
Constant	0.214***	0.995***	1.222***	0.751***	0.676***	0.724***	0.909**
	(0.006)	(0.202)	(0.203)	(0.171)	(0.151)	(0.141)	(0.301)
Observations	286	286	286	286	285	261	197
Within R^2	0.341	0.401	0.484	0.518	0.517	0.560	0.614
Num. of countries	21	21	21	21	21	19	19
Country FE	yes	yes	yes	yes	yes	yes	yes

Dependent variable: share of employment in manufacturing based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), Manufacturing [C]: D10T33. Luxembourg and Latvia are excluded due to lack of data on business R&D expenditures. In specification (6) and (7) Lithuania and Spain are dropped.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.12: Robustness checks

	(1)	(2)	(3)	(4)	(5)
GERD_perc_L2	-0.0129**				
	(0.0039)				
lnempl	-0.0994***	-0.0563**	-0.0591**	-0.0621**	-0.0576**
	(0.0098)	(0.0166)	(0.0169)	(0.0182)	(0.0181)
gdpgrowth_l1	0.0021***	0.0015***	0.0015***	0.0019***	0.0019***
	(0.0004)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
gdp/cap	-0.0015**	-0.0010**	-0.0008**	-0.0016***	-0.0015***
	(0.0004)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
labcostgrowth	-0.0055	-0.0130	-0.0167	-0.0221	-0.0258
	(0.0113)	(0.0125)	(0.0167)	(0.0125)	(0.0148)
trade	-0.0080	-0.0137*	-0.0168**	-0.0111	-0.0127*
	(0.0043)	(0.0054)	(0.0054)	(0.0060)	(0.0057)
businessRD_l1		-0.0022***			
		(0.0003)			
businessRD_l2			-0.0023***		
			(0.0003)		
businessRD_manu_l1				-0.0017*	
				(0.0006)	
businessRD_manu_l2					-0.0024***
					(0.0005)
Constant	1.0872***	0.7244***	0.7461***	0.7774***	0.7433***
	(0.0794)	(0.1414)	(0.1433)	(0.1558)	(0.1537)
Observations	371	261	244	262	246
Within R^2	0.623	0.560	0.573	0.504	0.525
Num. of countries	20	19	19	19	19
Country FE	yes	yes	yes	yes	yes

Dependent variable: share of employment in manufacturing based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), Manufacturing [C]: ICIS 10-33. (1) excludes Spain, Lithuania and Latvia. (2), (3), (4) and (5) additionally exclude Luxembourg.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

1.9 Appendix D: Sector specific regression results

Table 1.13: Employment in Food products, beverages and tobacco

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Food_bev_tobac_L1	0.053**	0.054***	-0.004	0.069***	0.061***	0.063***	-0.002	0.075***
	(0.014)	(0.013)	(0.005)	(0.017)	(0.013)	(0.013)	(0.010)	(0.016)
lnempl	1.227***	1.078***	0.399***	2.313***	1.000***	0.962***	0.084	2.571***
	(0.097)	(0.105)	(0.091)	(0.312)	(0.183)	(0.176)	(0.124)	(0.298)
gdpgrowth_l1	0.010***	0.009***	0.008***	0.005***	0.010***	0.009***	0.008***	0.005***
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)
ln_gdp/cap	-0.830***	-0.667***	-0.345**	-0.941***	-0.734***	-0.695***	-0.261	-1.064***
	(0.099)	(0.126)	(0.112)	(0.156)	(0.141)	(0.143)	(0.133)	(0.134)
ln_trade	-0.057	-0.090**	-0.027	-0.106*	-0.115***	-0.130***	-0.061**	-0.137**
	(0.030)	(0.029)	(0.021)	(0.045)	(0.024)	(0.028)	(0.020)	(0.038)
labcostgrowth	-0.124				-0.162			
	(0.069)				(0.090)			
wage_growth		-0.032	-0.096	-0.106		-0.065	-0.171	-0.145
		(0.110)	(0.128)	(0.123)		(0.116)	(0.115)	(0.122)
Constant	2.792**	3.391***	9.580***	-5.751*	-9.923***	-9.797***	-2.090*	-21.570***
	(0.958)	(0.841)	(0.499)	(2.198)	(1.416)	(1.384)	(0.827)	(2.091)
Observations	262	246	166	80	248	246	166	80
Within R^2	0.590	0.538	0.382	0.701	0.591	0.589	0.475	0.775
Num. of countries	19	19	13	6	19	19	13	6
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: natural log of employment in manufacturing of food products, beverages and tobacco based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4): ISIC 10-12. Specifications (1) - (4) consider total employment while specifications (5) - (8) display results with respect to full time equivalent employment. EU includes all EU15 countries except Luxembourg and Spain, EU15+ includes Czech Republic, Estonia, Hungary, Poland, Slovak Republic, Slovenia.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.14: Employment in textiles, wearing apparel, leather and related products

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Textiles_l1	-0.048*	-0.048*	-0.072***	0.063	-0.055*	-0.055*	-0.077***	0.057
	(0.023)	(0.022)	(0.017)	(0.086)	(0.023)	(0.022)	(0.018)	(0.088)
lnempl	0.168	-0.090	-1.107	2.986*	0.035	-0.275	-1.437*	3.279*
	(0.422)	(0.385)	(0.643)	(1.189)	(0.458)	(0.403)	(0.613)	(1.204)
gdpgrowth_l1	0.035***	0.032***	0.024**	0.027*	0.038***	0.035***	0.026**	0.029*
	(0.008)	(0.008)	(0.008)	(0.010)	(0.008)	(0.009)	(0.008)	(0.011)
ln_gdp/cap	-2.366***	-2.259***	-1.728***	-3.127***	-2.397***	-2.272***	-1.670**	-3.241***
	(0.167)	(0.178)	(0.427)	(0.443)	(0.163)	(0.178)	(0.465)	(0.441)
ln_trade	0.018	0.007	-0.275	0.358*	-0.003	-0.014	-0.302	0.361*
	(0.152)	(0.143)	(0.202)	(0.141)	(0.170)	(0.159)	(0.227)	(0.149)
labcostgrowth	-0.572***				-0.729***			
	(0.146)				(0.147)			
wage_growth		-0.037	-0.190	0.014		-0.142	-0.292*	-0.179
		(0.191)	(0.108)	(0.464)		(0.196)	(0.133)	(0.516)
Constant	18.579***	20.396***	27.407***	-2.343	19.656***	21.859***	29.901***	-4.335
	(3.988)	(3.671)	(5.269)	(7.576)	(4.339)	(3.897)	(5.077)	(7.630)
Observations	233	232	165	67	233	232	165	67
Within R^2	0.663	0.652	0.584	0.817	0.661	0.646	0.584	0.821
Num. of countries	18	18	13	5	18	18	13	5
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: employment in textiles, wearing apparel, leather and related products based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4): ISIC 13-15. Specifications (1) - (4) consider total employment while specifications (5) - (8) display results with respect to full time equivalent employment. EU includes all EU15 countries except Luxembourg and Spain, EU15+ includes Czech Republic, Estonia, Poland, Slovak Republic and Slovenia.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.15: Employment in computer, electronic and optical products

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Comp_electronics_L1	0.214**	0.184*	0.287**	0.111*	0.198**	0.189**	0.301**	0.108*
	(0.073)	(0.065)	(0.091)	(0.049)	(0.069)	(0.065)	(0.090)	(0.046)
lnempl	-0.099	0.168	-0.301	1.392	-0.032	-0.087	-0.803*	1.466
	(0.228)	(0.206)	(0.359)	(0.877)	(0.211)	(0.225)	(0.381)	(0.878)
gdpgrowth_l1	0.016**	0.013*	0.014	0.010*	0.016**	0.015*	0.016*	0.012*
	(0.004)	(0.005)	(0.007)	(0.004)	(0.004)	(0.006)	(0.007)	(0.004)
ln_gdp/cap	-1.040**	-1.311***	-1.067*	-1.563***	-1.246***	-1.279***	-0.834*	-1.636***
	(0.277)	(0.258)	(0.383)	(0.399)	(0.223)	(0.243)	(0.382)	(0.405)
ln_trade	0.297***	0.317***	0.318***	0.353***	0.287***	0.307***	0.323***	0.351***
	(0.039)	(0.039)	(0.054)	(0.032)	(0.043)	(0.047)	(0.062)	(0.039)
labcostgrowth	-0.375*				-0.344*			
	(0.140)				(0.139)			
wage_growth		-0.108	0.201	-0.273*		-0.159	0.148	-0.315**
		(0.080)	(0.138)	(0.096)		(0.098)	(0.139)	(0.110)
Constant	11.614***	10.854***	12.154**	3.226	11.779***	12.597***	15.295**	2.758
	(2.626)	(2.457)	(3.805)	(6.377)	(2.562)	(2.692)	(4.021)	(6.298)
Observations	259	241	163	78	245	241	163	78
Within R^2	0.509	0.530	0.590	0.560	0.520	0.524	0.594	0.574
Num. of countries	19	19	13	6	19	19	13	6
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: employment in Computer, electronic and optical products based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), ISIC 26. Specifications (1) - (4) consider total employment while specifications (5) - (8) display results with respect to full time equivalent employment. EU includes all EU15 countries except Luxembourg and Spain, EU15+ includes Czech Republic, Estonia, Poland, Hungary, Slovak Republic, Slovenia.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.16: Employment in Motor vehicles, trailers and semi-trailers

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Motor_vehicles_L1	0.036*	0.056**	0.009	0.048***	0.073**	0.084**	0.159*	0.047**
	(0.015)	(0.015)	(0.026)	(0.012)	(0.021)	(0.023)	(0.066)	(0.012)
lnempl	-1.791***	-1.527***	-0.171	-1.931**	-2.227***	-2.189***	-2.046**	-1.231*
	(0.234)	(0.247)	(0.331)	(0.520)	(0.396)	(0.353)	(0.690)	(0.448)
gdpgrowth_l1	0.012***	0.012***	0.019***	0.010**	0.017***	0.020***	0.024**	0.008*
	(0.003)	(0.003)	(0.004)	(0.003)	(0.004)	(0.004)	(0.007)	(0.004)
ln_gdp/cap	0.746***	0.592***	-0.423	0.852***	0.804***	0.694**	0.599	0.563***
	(0.184)	(0.129)	(0.382)	(0.116)	(0.168)	(0.193)	(0.316)	(0.122)
ln_trade	0.197**	0.191***	0.070	0.234***	0.176***	0.180**	0.040	0.262***
	(0.058)	(0.038)	(0.078)	(0.041)	(0.045)	(0.054)	(0.071)	(0.035)
labcostgrowth	-0.014		-0.181	-0.119	-0.129		-0.204	-0.024
	(0.099)		(0.112)	(0.220)	(0.173)		(0.196)	(0.263)
wage_growth		-0.346**				-0.483**		
		(0.097)				(0.139)		
Constant	23.508***	20.535***	13.818***	23.437***	25.019***	24.902***	22.355***	18.456***
	(1.603)	(1.832)	(2.425)	(3.827)	(2.771)	(2.399)	(4.058)	(3.283)
Observations	258	180	164	94	182	180	102	80
Within R^2	0.449	0.604	0.198	0.820	0.453	0.543	0.344	0.750
Num. of countries	19	15	13	6	15	15	9	6
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: employment in Motor vehicles, trailers and semi-trailers based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), ISIC 29. Specifications (1) - (4) consider total employment while specifications (5) - (8) display results with respect to full time equivalent employment. EU in specification (3) includes all EU15 countries except Luxembourg and Spain. EU15+ includes Czech Republic, Estonia, Poland, Hungary, Slovak Republic, Slovenia. EU in specification (7) excludes additionally Belgium, Germany, France, UK.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.17: Low-tech manufacturing sectors

	(1) Food_bev_tobac	(2) Textiles	(3) Wood_paper	(4) Coke_refined_petr	(5) Metal
RD_L1	0.053**	-0.048*	-0.034*	0.035	-0.034***
	(0.014)	(0.023)	(0.012)	(0.026)	(0.007)
lnempl	1.227***	0.168	-0.000	0.738	0.365*
	(0.097)	(0.422)	(0.315)	(0.824)	(0.172)
gdpgrowth_l1	0.010***	0.035***	0.015**	0.008	0.001
	(0.001)	(0.008)	(0.005)	(0.005)	(0.002)
ln_gdp/cap	-0.830***	-2.366***	-0.545***	-1.405**	0.400***
	(0.099)	(0.167)	(0.122)	(0.458)	(0.083)
ln_trade	-0.057	0.018	0.095	-0.076	-0.018
	(0.030)	(0.152)	(0.111)	(0.054)	(0.039)
labcostgrowth	-0.124	-0.572***	-0.197	-0.230	0.132
	(0.069)	(0.146)	(0.139)	(0.196)	(0.082)
Constant	2.792**	18.579***	14.248***	5.966	7.560***
	(0.958)	(3.988)	(2.517)	(7.228)	(1.488)
Observations	262	233	249	157	255
Within R^2	0.590	0.663	0.326	0.330	0.352
Num. of countries	19	18	18	14	19
Country FE	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all
Full time empl.					
RD_L1	0.061***	-0.055*	-0.039*	0.028	-0.028**
	(0.013)	(0.023)	(0.014)	(0.026)	(0.007)
lnempl	1.000***	0.035	-0.130	0.472	0.428*
	(0.183)	(0.458)	(0.333)	(0.891)	(0.199)
gdpgrowth_l1	0.010***	0.038***	0.016**	0.009	0.001
	(0.001)	(0.008)	(0.005)	(0.005)	(0.002)
ln_gdp/cap	-0.734***	-2.397***	-0.670***	-1.381*	0.464***
	(0.141)	(0.163)	(0.130)	(0.499)	(0.084)
ln_trade	-0.115***	-0.003	0.100	-0.096	-0.043
	(0.024)	(0.170)	(0.129)	(0.057)	(0.048)
labcostgrowth	-0.162	-0.729***	-0.189	-0.250	0.068
	(0.090)	(0.147)	(0.148)	(0.211)	(0.099)
Constant	-9.907***	19.647***	15.710***	8.143	6.293***
	(1.414)	(4.338)	(2.599)	(7.791)	(1.497)
Observations	248	233	235	157	179
Within R^2	0.591	0.661	0.335	0.352	0.441
Num. of countries	19	18	18	14	15
Country FE	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all

Employment in (1) Food products, beverages and tobacco, ISIC 10-12, (2) Textiles, wearing apparel, leather and related products, ISIC 13-15, (3) Wood and paper products, and printing, ISIC 16-18, (4) Coke and refined petroleum products, ISIC 19, (5) Fabricated metal products, except machinery and equipment, ISIC 25. (3) excludes Spain, Lithuania, Luxembourg, Latvia and Slovak Republic. (4) excludes Denmark, Spain, Estonia, Hungary, Ireland, Lithuania, Luxembourg, Latvia and Sweden. (5) excludes Spain, Lithuania, Luxembourg and Latvia. The full-time equivalent employment additionally excludes Belgium, Germany, France and UK. *Note:* Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.18: Medium-tech manufacturing sectors

	(1) Rubber_plastic	(2) Mineral	(3) Basic_metals	(4) Other_manu
RD_L1	-0.008	-0.042*	0.036***	-0.017*
	(0.019)	(0.015)	(0.009)	(0.006)
lnempl	-0.900***	0.409	0.632**	0.588*
	(0.213)	(0.293)	(0.216)	(0.224)
gdpgrowth_l1	0.001	0.011**	0.015***	0.005*
	(0.002)	(0.004)	(0.002)	(0.002)
ln_gdp/cap	0.932***	-0.624***	-0.644***	-0.071
	(0.070)	(0.113)	(0.128)	(0.066)
ln_trade	-0.035	-0.014	-0.016	-0.051*
	(0.035)	(0.121)	(0.045)	(0.023)
labcostgrowth	0.172	-0.061	-0.164*	-0.042
	(0.107)	(0.103)	(0.078)	(0.076)
Constant	15.272***	9.880**	6.412*	6.739**
	(1.901)	(2.862)	(2.257)	(2.174)
Observations	229	237	246	245
Within R^2	0.471	0.343	0.319	0.150
Num. of countries	19	19	18	19
Country FE	yes	yes	yes	yes
EU accession	all	all	all	all
Full time empl.				
RD_L1	-0.026	-0.077***	0.030	-0.033**
	(0.031)	(0.015)	(0.028)	(0.009)
lnempl	-1.254**	0.688	0.486	0.509*
	(0.382)	(0.484)	(0.448)	(0.199)
gdpgrowth_l1	0.002	0.013**	0.014***	0.006*
	(0.002)	(0.004)	(0.002)	(0.002)
ln_gdp/cap	1.086***	-0.673***	-0.642***	-0.119
	(0.088)	(0.119)	(0.129)	(0.131)
ln_trade	-0.002	0.042	-0.015	-0.065*
	(0.032)	(0.145)	(0.042)	(0.030)
labcostgrowth	0.070	-0.135	-0.280	-0.101
	(0.132)	(0.133)	(0.147)	(0.093)
Constant	17.362***	8.306	7.484*	7.655**
	(2.916)	(4.004)	(3.415)	(2.021)
Observations	163	171	170	231
Within R^2	0.453	0.334	0.306	0.175
Num. of countries	15	15	14	19
Country FE	yes	yes	yes	yes
EU accession	all	all	all	all

Employment in (1) Rubber and plastic products, ISIC 22, (2) Other non-metallic mineral products, ISIC 23, (3) Basic metals, ISIC 24, (4) Furniture; other manufacturing; repair and installation of machinery and equipment, ISIC 31-33. (1) and (2) excludes Spain, Lithuania, Luxembourg and Latvia. The full-time equivalent employment additionally excludes Belgium, Germany, France and UK. (3) excludes Spain, Estonia, Lithuania, Luxembourg and Latvia. The full-time equivalent employment additionally excludes Belgium, Germany, France and UK. (4) excludes Spain, Lithuania, Luxembourg and Latvia. *Note:* Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.19: High-tech manufacturing sectors

	(1) Chemicals	(2) Pharma	(3) Comp	(4) El_equip	(5) Machinery	(6) Vehicles	(7) Transp
RD_L1	0.090**	0.163**	0.214**	0.036	0.024	0.036*	-0.053*
	(0.026)	(0.044)	(0.073)	(0.024)	(0.021)	(0.015)	(0.025)
lnempl	0.511*	1.312***	-0.099	0.574*	0.750**	-1.791***	0.880
	(0.238)	(0.139)	(0.228)	(0.257)	(0.198)	(0.234)	(0.428)
gdpgrowth_l1	0.009***	-0.002	0.016**	0.010*	0.004*	0.012***	0.004
	(0.001)	(0.004)	(0.004)	(0.004)	(0.001)	(0.003)	(0.008)
ln_gdp/cap	-0.586***	0.028	-1.040**	-0.107	-0.221**	0.746***	-0.750***
	(0.131)	(0.316)	(0.277)	(0.094)	(0.072)	(0.184)	(0.169)
ln_trade	-0.106**	-0.087**	0.297***	0.014	0.064	0.197**	0.043
	(0.034)	(0.026)	(0.039)	(0.067)	(0.041)	(0.058)	(0.046)
labcostgrowth	-0.042	0.283	-0.375*	0.060	0.014	-0.014	-0.095
	(0.088)	(0.164)	(0.140)	(0.114)	(0.072)	(0.099)	(0.219)
Constant	5.917**	-5.375**	11.614***	5.423*	5.198**	23.508***	5.634
	(2.048)	(1.534)	(2.626)	(2.564)	(1.497)	(1.603)	(3.192)
Observations	211	216	259	259	259	258	243
Within R^2	0.490	0.245	0.509	0.147	0.160	0.449	0.145
Num. of countries	16	18	19	19	19	19	19
Country FE	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all
Full time empl.							
RD_L1	0.076*	0.093**	0.198**	0.015	-0.007	0.073**	-0.114**
	(0.033)	(0.031)	(0.069)	(0.024)	(0.021)	(0.021)	(0.039)
lnempl	0.223	-0.088	-0.032	0.139	0.552**	-2.227***	0.335
	(0.230)	(0.211)	(0.211)	(0.271)	(0.177)	(0.396)	(0.509)
gdpgrowth_l1	0.008***	-0.007	0.016**	0.011*	0.005**	0.017***	-0.006
	(0.002)	(0.004)	(0.004)	(0.004)	(0.002)	(0.004)	(0.008)
ln_gdp/cap	-0.419**	0.859***	-1.246***	0.015	-0.048	0.804***	-0.482*
	(0.141)	(0.201)	(0.223)	(0.120)	(0.073)	(0.168)	(0.203)
ln_trade	-0.151***	-0.065*	0.287***	-0.005	0.040	0.176***	0.052
	(0.038)	(0.024)	(0.043)	(0.070)	(0.053)	(0.045)	(0.080)
labcostgrowth	-0.171	0.319*	-0.344*	0.013	-0.095	-0.129	0.136
	(0.126)	(0.141)	(0.139)	(0.137)	(0.048)	(0.173)	(0.202)
Constant	7.878***	5.349*	11.779***	8.852**	6.628***	25.019***	10.183*
	(1.957)	(2.301)	(2.562)	(2.496)	(1.374)	(2.771)	(3.886)
Observations	197	199	245	245	245	182	173
Within R^2	0.417	0.462	0.520	0.102	0.127	0.453	0.170
Num. of countries	16	18	19	19	19	15	15
Country FE	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all

Employment in (1) Chemicals and chemical products, ISIC 20, (2) Basic pharmaceutical products and pharmaceutical preparations, ISIC 21, (3) Computer, electronic and optical products, ISIC 26, (4) Electrical equipment, ISIC 27, (5) Machinery and equipment n.e.c., ISIC 28, (6) Motor vehicles, trailers and semi-trailers, ISIC 28, (7) Other transport equipment, ISIC 30. (4) and (5) excludes Spain, Lithuania, Luxembourg and Latvia. (2) additionally excludes Estonia and (1) additionally excludes Denmark and Sweden. (7) excludes Spain, Lithuania, Luxembourg and Latvia. he full-time equivalent employment additionally excludes Belgium, Germany, France and UK. *Note:* Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.20: Employment in Scientific research and development

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Scientific_research_L1	0.194***	0.195***	0.204***	0.199***	0.207***	0.205***	0.180***	0.212***
	(0.028)	(0.027)	(0.029)	(0.029)	(0.023)	(0.023)	(0.025)	(0.027)
lnempl	2.600***	2.484***	2.431***	2.967***	2.366***	2.281***	1.891***	2.919***
	(0.305)	(0.314)	(0.516)	(0.583)	(0.271)	(0.277)	(0.454)	(0.510)
gdpgrowth_l1	-0.005	-0.006	-0.003	-0.011*	-0.006	-0.006*	-0.006	-0.012**
	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.004)
ln_gdp/cap	-0.713***	-0.662***	-0.673*	-0.771***	-0.734***	-0.710***	-0.260	-0.905***
	(0.056)	(0.055)	(0.257)	(0.121)	(0.060)	(0.059)	(0.209)	(0.110)
labcostgrowth	-0.360**				-0.326*			
	(0.125)				(0.142)			
wage_growth		-0.206***	-0.187**	-0.346***		-0.328***	-0.140*	-0.504***
		(0.051)	(0.065)	(0.080)		(0.048)	(0.067)	(0.069)
Constant	-13.853***	-13.025***	-13.318**	-15.307***	-12.208***	-11.508***	-9.663*	-14.917***
	(2.647)	(2.739)	(4.159)	(4.051)	(2.288)	(2.331)	(3.661)	(3.507)
Observations	283	276	182	94	279	276	182	94
Within R^2	0.540	0.542	0.580	0.543	0.552	0.575	0.618	0.612
Num. of countries	21	21	14	7	21	21	14	7
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: employment in Scientific research and development based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), ISIC 72. Specifications (1) - (4) consider total employment while specifications (5) - (8) display results with respect to full time equivalent employment. EU includes all EU15 countries except Luxembourg. EU15+ includes Czech Republic, Estonia, Poland, Hungary, Lithuania, Slovak Republic, Slovenia.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.21: Employment in Telecommunications

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_Telecom_L1	-0.021*	-0.021	-0.039***	-0.003	-0.030**	-0.030**	-0.048***	-0.001
	(0.009)	(0.011)	(0.006)	(0.035)	(0.009)	(0.011)	(0.008)	(0.035)
lnempl	-1.582***	-1.530***	-1.184**	-1.684	-1.806***	-1.748***	-1.617**	-0.370
	(0.172)	(0.234)	(0.404)	(1.755)	(0.221)	(0.279)	(0.426)	(1.785)
gdpgrowth_l1	-0.003	-0.001	-0.003	0.004	-0.003	-0.000	-0.004	0.005
	(0.002)	(0.002)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.005)
ln_gdp/cap	0.665***	0.471**	-0.011	0.845	0.784***	0.576**	0.331	0.374
	(0.164)	(0.144)	(0.283)	(0.437)	(0.102)	(0.160)	(0.300)	(0.444)
labcostgrowth	0.016				0.002			
	(0.308)				(0.282)			
wage_growth		-0.418**	-0.346**	-0.429*		-0.453**	-0.374**	-0.534*
		(0.124)	(0.097)	(0.153)		(0.153)	(0.124)	(0.170)
Constant	22.192***	22.395***	22.143***	18.940	23.726***	23.926***	24.828***	10.484
	(1.530)	(1.951)	(2.838)	(12.564)	(1.964)	(2.280)	(3.018)	(12.753)
Observations	172	171	135	36	172	171	135	36
Within R^2	0.191	0.316	0.396	0.362	0.224	0.347	0.446	0.352
Num. of countries	19	19	13	6	19	19	13	6
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	EU15	EU15+	all	all	EU15	EU15+

Dependent variable: employment in Telecommunications based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4), ISIC 61. In specifications (1)-(4) the dependent variable is natural logarithm of total employment while in specifications (5) - (8) natural log of employment is in full time equivalents. EU includes all EU15 countries except Luxembourg and Sweden. EU15+ includes Czech Republic, Estonia, Poland, Hungary, Lithuania, and Slovenia.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.22: Employment in high- and medium-tech service sectors

	High-tech services				Medium-tech services			
	Total empl.		Full time		Total empl.		Full time	
	Scientific	IT	Scientific	IT	Telecom	Profess	Telecom	Profess
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RD_L1	0.195***	0.123***	0.205***	0.120***	-0.021	0.022**	-0.030**	0.016*
	(0.027)	(0.027)	(0.023)	(0.026)	(0.011)	(0.006)	(0.011)	(0.005)
lnempl	2.484***	0.358	2.281***	0.293	-1.530***	0.567	-1.748***	0.554
	(0.314)	(0.707)	(0.277)	(0.658)	(0.234)	(0.369)	(0.279)	(0.297)
gdpgrowth_l1	-0.006	-0.010	-0.006*	-0.008	-0.001	-0.003	-0.000	-0.002
	(0.003)	(0.005)	(0.003)	(0.004)	(0.002)	(0.002)	(0.003)	(0.001)
ln_gdp/cap	-0.662***	1.506***	-0.710***	1.400***	0.471**	0.873***	0.576**	0.834***
	(0.055)	(0.211)	(0.059)	(0.215)	(0.144)	(0.167)	(0.160)	(0.163)
wage_growth	-0.206***	-0.381***	-0.328***	-0.393***	-0.418**	-0.278***	-0.453**	-0.336***
	(0.051)	(0.084)	(0.048)	(0.071)	(0.124)	(0.047)	(0.153)	(0.057)
Constant	-13.025***	0.500	-11.508***	1.336	22.395***	4.192	23.926***	4.396
	(2.739)	(5.792)	(2.331)	(5.350)	(1.951)	(2.668)	(2.280)	(2.068)
Observations	276	184	276	184	171	167	171	167
Within R^2	0.542	0.867	0.575	0.861	0.316	0.612	0.347	0.638
Num. of countries	21	20	21	20	19	21	19	21
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all	all

Dependent variable in (1) and (3): employment in Scientific research and development, ISIC 72. Dependent variable in (2) and (4): employment in IT and other information services, ISIC 62-63. Dependent variable in (5) and (7): employment in Telecommunications, ISIC 61. Dependent variable in (6) and (8): employment in Professional, scientific and technical activities, except scientific research and development, ISIC 69-75X, based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4). (1) and (3) exclude Luxembourg and Latvia. (2) and (4) exclude Luxembourg, Latvia and Sweden. (5) and (7) exclude Luxembourg, Latvia, Slovak Republic and Sweden. (6) and (8) exclude Luxembourg and Latvia. *Note:* Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.23: Employment in low-tech service sectors

	(1) Financial	(2) Audiovis	(3) Retail	(4) Admin	(5) Transport	(6) Accomm	(7) Real_estate
RD_L1	-0.002	-0.008	0.007	0.005	0.003	0.015**	-0.005
	(0.003)	(0.008)	(0.004)	(0.004)	(0.002)	(0.005)	(0.003)
lnempl	0.058	1.521***	0.707***	1.011*	0.390***	1.030*	0.711***
	(0.166)	(0.199)	(0.099)	(0.372)	(0.090)	(0.416)	(0.139)
gdpgrowth_l1	-0.003*	0.001	-0.000	-0.002	0.002*	-0.003	-0.000
	(0.001)	(0.001)	(0.000)	(0.002)	(0.001)	(0.003)	(0.002)
ln_gdp/cap	0.069	-0.419**	-0.012	0.523*	0.034	0.353	0.135
	(0.090)	(0.126)	(0.029)	(0.221)	(0.054)	(0.267)	(0.191)
wage_growth	-0.338***	-0.191	-0.117**	0.013	0.049	0.095	-0.118
	(0.054)	(0.154)	(0.041)	(0.155)	(0.071)	(0.082)	(0.090)
Constant	11.292***	-1.679	7.451***	1.919	9.135***	2.101	4.603*
	(1.229)	(1.433)	(0.815)	(2.640)	(0.786)	(3.240)	(1.541)
Observations	214	72	251	153	191	123	109
Within R^2	0.178	0.345	0.710	0.368	0.329	0.370	0.199
Num. of countries	20	13	21	21	20	16	17
Country FE	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all
Full time empl.							
RD_L1	-0.005	-0.008	-0.009	0.001	0.003	0.010	-0.006
	(0.004)	(0.010)	(0.005)	(0.003)	(0.002)	(0.005)	(0.004)
lnempl	0.011	1.464***	0.412*	1.036*	0.205	0.925**	0.301
	(0.180)	(0.195)	(0.164)	(0.377)	(0.118)	(0.320)	(0.177)
gdpgrowth_l1	-0.002	0.002	0.001	-0.002	0.002	0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)	(0.003)
ln_gdp/cap	-0.033	-0.494**	-0.036	0.565*	0.003	0.155	0.346
	(0.080)	(0.119)	(0.041)	(0.253)	(0.076)	(0.214)	(0.265)
wage_growth	-0.419***	-0.159	-0.212***	-0.052	0.046	-0.039	-0.177
	(0.051)	(0.205)	(0.033)	(0.155)	(0.094)	(0.078)	(0.092)
Constant	11.903***	-1.095	10.189***	1.353	10.714***	3.589	7.315***
	(1.409)	(1.333)	(1.322)	(2.511)	(1.011)	(2.449)	(1.436)
Observations	214	72	251	153	191	123	109
Within R^2	0.203	0.340	0.220	0.380	0.118	0.344	0.147
Num. of countries	20	13	21	21	20	16	17
Country FE	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all

Dependent variable in (1): employment in Financial and insurance activities, ICIC 64-66, (2): employment in Audiovisual and broadcasting activities, ICIC 59-60, (3): employment in Wholesale and retail trade, repair of motor vehicles and motorcycles, ICIC 45-47, (4): employment in Administrative and support service activities, ICIC 77-82, (5): employment in Transportation and storage, ICIC 49-53, (6): employment in Accommodation and food service activities, ICIC 55-56, (7): employment in Real estate activities, ICIC 68. (1) excludes Hungary, Luxembourg and Latvia. (2) excludes Belgium, Germany, Estonia, France, UK, Lithuania, Luxembourg, Latvia, Slovak Republic and Sweden. (3) and (4) exclude Luxembourg and Latvia. (5) excludes Luxembourg, Latvia and Slovak Republic. (6) excludes Austria, Estonia, Hungary, Luxembourg, Latvia, Poland and Slovak Republic. (7) excludes Ireland, Luxembourg, Latvia, Portugal, Slovak Republic and Sweden. *Note:* Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. ** $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

Table 1.24: Employment in other

	Total employment				Full time equivalent			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Agri	Mining	Electr	Constr	Agri_	Mining_	Electr_	Constr_
RD_L1	-0.026*	0.011	0.025***	-0.030*	-0.042**	0.003	0.025***	-0.042**
	(0.011)	(0.016)	(0.004)	(0.014)	(0.011)	(0.017)	(0.005)	(0.014)
lnempl	0.838**	2.067***	0.986***	2.190***	0.737***	2.210***	0.917***	2.306***
	(0.230)	(0.258)	(0.191)	(0.451)	(0.169)	(0.239)	(0.195)	(0.427)
gdpgrowth_l1	0.013***	0.013*	0.002	0.004	0.016***	0.014*	0.002*	0.007
	(0.003)	(0.006)	(0.001)	(0.004)	(0.003)	(0.006)	(0.001)	(0.004)
ln_gdp/cap	-1.275***	-1.980***	-0.451***	-0.082	-1.483***	-2.071***	-0.459***	-0.254*
	(0.108)	(0.156)	(0.104)	(0.128)	(0.113)	(0.178)	(0.115)	(0.117)
wage_growth	-0.139	-0.188	-0.238***	0.029	-0.179	-0.240**	-0.208**	0.152
	(0.068)	(0.091)	(0.053)	(0.185)	(0.093)	(0.084)	(0.068)	(0.223)
Constant	9.972***	-1.781	3.770*	-5.428	11.790***	-2.772	4.221*	-5.782
	(1.871)	(2.515)	(1.488)	(3.700)	(1.337)	(2.415)	(1.491)	(3.587)
Observations	260	235	247	263	260	235	247	263
Within R^2	0.701	0.455	0.278	0.347	0.708	0.465	0.233	0.377
Num. of countries	21	19	20	21	21	19	20	21
Country FE	yes	yes	yes	yes	yes	yes	yes	yes
EU accession	all	all	all	all	all	all	all	all

Dependent variable: (1) and (5): Employment in Agriculture, forestry and fishing, ISIC 01-03; (2) and (6): Mining and quarrying, ISIC 05-09; (3) and (7): Electricity, gas and water supply; sewerage, waste management and remediation activities, ISIC 35-39; and (4) and (8): Construction, ISIC 41-43, based on the International Standard Industrial Classification of all economic activities, Revision 4 (ISIC Rev. 4). (1), (5), (4) and (8) exclude Luxembourg and Latvia. (2), (6), (3) and (7) exclude Luxembourg, Latvia and Slovak Republic.

Note: Fixed-effects (within) regression with Driscoll and Kraay standard errors. Standard errors in parenthesis. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Chapter 2

Optimal Promotions of Competing Firms in a Frictional Labour Market with Organizational Hierarchies[1]

2.1 Introduction

Empirical evidence suggests that workers progress in their careers by means of internal promotions within firms, job-to-job transitions between firms and experience accumulation[2]. However, existing research analyses promotions and job-to-job mobility within different strands of literatures. Whereas search and matching studies developed strong techniques for the analytical treatment of on-the-job search and between-firm mobility of workers, research on internal promotions within firms is conducted in the literature on internal labour markets and principle agent models[3]. In this study we develop a unified search and matching framework with hierarchical firms, experience accumulation, job-to-job mobility and internal promotions. A combination of these areas leads to new insights on how the composition of the applicant pool, competition between (heterogeneous) firms and search frictions influence the optimal timing of promotions. Our model is compatible with the empirical evidence that high skill workers are promoted faster than low skill workers and are overrepresented in higher hierarchical levels of firms. Moreover, in a setting with pyramidal firms we show that stronger competition for workers on lower hierarchical levels forces firms to require more experience which delays internal promotions.

In particular, we develop a search and matching model with three hierarchical levels in the career ladder. The first level consists of non-managerial jobs available to all workers without frictions. In addition, there are firms in the market consisting of two professional positions: one junior position and one senior position. This structure implies that there are three hierarchical job levels and two submarkets in our model: the primary market for young

[1]This Chapter is co-authored with Prof. Dr. Herbert Dawid and J.-Prof. Dr. Anna Zaharieva.

[2]Baker et al. (1994), Lluis (2005), Bidwell and Mollick (2015), Cassidy et al. (2016).

[3]Excellent surveys on both research directions are Rogerson et al. (2005) and Waldman (2009) respectively.

inexperienced individuals applying for their first junior manager position and a secondary market for experienced workers applying for senior manager positions. Firms with open positions post vacancies in each of the two submarkets respectively. As in Gibbons and Waldman (1999) the productivity of junior managers is growing over time due to experience accumulation and there is complementarity between experience and the hierarchical layer the worker is assigned to.

The main choice variable of the firm is the promotion time. Specifically, firms choose the minimum experience cutoff which is necessary for the junior worker to be internally promoted to the senior level. This experience cutoff is announced by the firm in the beginning of the employment relationship. Note that the actual promotion can only take place if the junior worker accumulated the minimum experience level set by the firm and there is an open senior position in this firm. This is different from the model of Gibbons and Waldman (1999), where every worker can always be promoted in every firm and promotions do not depend on the availability of open positions at higher hierarchical levels. The tradeoff for firms can be characterized in the following way: if the inexperienced worker is promoted too early in his/her career, this worker will have a relatively low productivity after the promotion because this worker's experience is too low for the senior level. In this situation it is a better strategy for the firm to wait and search for a more experienced worker in the secondary submarket for senior managers. This submarket exists because some workers have already reached sufficient experience to be promoted, but there are no open positions in their firms. Thus these workers start searching for senior managerial jobs with alternative employers (on-the-job search). This is different from the model of Burdett and Mortensen (1998), where all employees are always searching for better paid jobs, and shows that promotions and on-the-job search are closely linked to each other, moreover, this link is missing in the previous studies.

Based on this model we find that the optimal promotion time of a given firm is increasing in the average promotion time of the market, so there is strategic complementarity between the promotion times of the different firms. This is because the optimal individual promotion time of the firm depends on the distribution of experience of managerial applicants in the secondary submarket, which again is determined by the promotion decisions of the other firms in the market. We account for this competition effect by characterizing Nash equilibrium assuming steady states of the labour flows. We find that there are two symmetric Nash equilibria but only one of them is stable. In addition, we analyse the steady state adjustment of worker stocks and transition probabilities in response to the optimal promotion time set by the firms. We find that this general equilibrium effect is mitigating the individual intentions of firms. In particular, if one firm has incentives to delay promotions of its' junior workers and hire more senior managers in the market it will choose a higher experience requirement. Positive optimal response implies that other firms also delay promotions of their junior workers and require higher experience. Because of this workers stay longer in junior positions and there are fewer applicants in the senior submarket, so job-to-job transitions between firms are substantially reduced and internal promotions become a more important source of upward mobility for workers. This shows how the general equilibrium effect counteracts the initial decision of firms.

We consider three extensions of our benchmark model. First, we assume that additional output is generated if two workers (junior and senior) are working together as a team. We find that such team synergy is associated with earlier promotions. The reason is that search frictions in the senior submarket are more severe, so hiring junior workers is easier for firms in our model than hiring experienced managers. So, in order to fill both positions, firms promote their own junior employees earlier compared to the benchmark case and try to hire another junior worker afterwards. This strategy leads to the highest gain from the team synergy for firms.

In the second extension we consider skill heterogeneity of workers, assuming that high skill workers are more productive than low skill workers only in senior managerial jobs. This model extension can explain the empirical evidence that high skill workers are promoted earlier than low skill workers (Baker et al. (1994), McCue (1996) and Lluis (2005)). In addition, there is substitution between the two skill groups. If there are exogenous reasons forcing firms to promote one skill group earlier, they will delay promotions of the other skill group and let them accumulate more experience. We show that increasing the fraction of high skill workers in the population induces slower promotions of all workers, whereas in a setting with homogeneous workers an increase of the skill level leads to faster promotions. The key difference between these scenarios is that under worker heterogeneity an increase of the fraction of high skill workers increases the expected skill of a worker hired from the market *relative* to the skill of the junior worker under consideration for internal promotion, regardless of the actual type of the junior worker. This induces a delay in internal promotions. With homogeneous workers by definition the skill of an outside hire is always identical to that of an internally promoted worker.

In the third extension a fraction of professional firms has a pyramidal structure with one senior position and two junior positions. Here we follow the empirical evidence, e.g. Caliendo et al. (2015) who reports that a vast majority of firms in their sample have a hierarchical pyramidal structure with several layers, such that workers situated at higher layers earn higher wages. We find that in the presence of pyramidal firms promotions occur later than if only vertical firms are in the market. The reason is that a larger number of junior positions in the market leads to the oversupply of experienced workers, thus hiring experienced managers becomes easier for firms. At the same time there is stronger competition between firms for inexperienced workers starting their career since there is a larger number of vacancies in this submarket. Thus a longer experience requirement allows firms to keep their junior workers longer in the firm and reduces the cost of labour turnover. Pyramidal firms promote later than their vertical competitors because the fraction of time in which they have vacant senior positions is smaller which makes it more attractive to keep junior workers longer in their current position. One empirical implication of this finding is that workers in large pyramidal firms have more experience and earn higher wages compared to the small vertical firms, which is supported by the existing empirical research (Lallemand et al., 2007; Oi and Idson, 1999). Moreover, we find that the firm size wage premium is increasing with the hierarchical level of the position, which is in line with a recent empirical finding in Fox (2009).

Apart from these new economic insights about optimal promotion strategies of firms this paper also makes a methodological contribution to the literature by combining an analytical approach with a simulation analysis in order to characterize general equilibrium behaviour of firms also in the extensions of the model with heterogeneous firms and workers in which a full analytical treatment is no longer feasible. For the benchmark model with homogeneous firms and workers we are able to provide a full analytical characterization of the firms' best response functions and also of the labour flows under the stationary distribution. Based on this we can numerically determine the general equilibrium of the model under different parameter settings.

For the extension with heterogeneous workers we are still able to provide an analytical characterization of firms' best response, but we can no longer determine in closed form the transition rates resulting from a given set of promotion cutoffs followed by all firms on the market. Hence, we use an agent-based simulation framework to determine the long-run transition rates. Finally, for the extension with heterogeneous firms also the characterization of the firms' best responses by analytical means is no longer feasible. Hence, in this case we also employ a simulation approach to numerically determine the best response functions of the firms of different type and use this to determine the general equilibrium of the model. In order to validate the simulation approach we first implement it for the benchmark case for which analytical results are available and show that the simulation approach replicates the analytical results with a high degree of precision and reliability. Our methodological approach allows to analyse models, which otherwise would be intractable, in a rigorous way based on standard equilibrium concepts. The validation of our simulation approach using theoretical findings for the benchmark serves as disciplining device for the setup and implementation of the simulation study. We believe that this combination of methodologies can be fruitfully applied for many issues in labour market research and beyond.

Our study is closely related to the literature on organizational hierarchies and internal labour markets. Organizational hierarchies are intensively studied since the seminal contribution by Garicano (2000). This paper considers an endogenous formation of firm hierarchies based on the time constraint for acquiring knowledge by workers. Some (ex-ante homogeneous) agents acquire special knowledge and are specializing in problem-solving; these agents are the managers and are situated on the top level of the firm hierarchy, while other agents are specialized on the actual production. Thus the equilibrium organization structure is pyramidal, with each layer of a smaller size than the previous one. This benchmark model is extended in different directions by Garicano and Rossi-Hansberg (2015). The literature on knowledge-based hierarchies is successful in explaining empirical facts and it is an appealing feature of this theory that hierarchies arise endogenously when matching problems to those who know how to solve them. On the other hand, this research direction is lacking dynamics in individual careers, as workers assigned to different levels are never promoted within or across firms, thus there is no link between organizational hierarchies and career paths of individuals.

The second research stream is dealing with internal labour markets, so the main focus here is on individual career paths and promotions but the firm hierarchy is taken exogenously and fixed in this literature. One large research direction here includes tournament models in the spirit of Lazear and Rosen (1981). In their setting promotion decisions are modelled as a tournament in which workers exert costly effort to perform better than their co-workers and to be considered for promotion. Later tournament models include the fact that promotions can be used as a signal of higher ability, see for example, Zabojnik and Bernhardt (2001). Recent studies, such as DeVaro (2006) confirm empirically that firms are choosing wage spreads strategically to elicit more effort from their employees. In addition, DeVaro and Waldman (2012) find that promotions are sometimes used as a signal of worker's ability. While the role of competition in providing working incentives to employees must be acknowledged, we focus on human capital accumulation as a reason for promotion and analyse between-firm competition for experienced employees.

The literature on human capital accumulation and job assignments is more closely related to our research. The seminal contribution here is by Gibbons and Waldman (1999). In their study worker's productivity depends on the individual's skill level, accumulated experience and the hierarchical layer the worker is assigned to. As workers accumulate experience and knowledge they are optimally promoted by firms to higher positions due to the assumed complementarity between worker's productivity (skills and accumulated experience) and hierarchical layers within the firm. We use the same setup as a starting point in our model. Overall, the literature on career paths and promotions is successful in explaining wage dynamics of individuals within firms, whether due to experience accumulation or exerted effort. However, most of this literature is based on the principal agent modelling approach in isolation from the labour market and doesn't allow for the study of interaction between organizational structures and the economy. Most of these studies make restrictive assumptions on the model structure ensuring that there are no job changes between firms in the equilibrium.

Next our study is conducted in the search and matching framework (Diamond (1982), Mortensen (1982), and Pissarides (1985)). We model job-to-job transitions following the approach of Burdett and Mortensen (1998). To the best of our knowledge the first study analysing tenure in a search and matching framework with job-to-job transitions is Pissarides (1994). There are good and bad jobs in his setting, thus unemployed workers accept bad jobs but continue searching for good jobs. An important feature of the model is that workers accumulate job-specific experience and their wage grows over time. In the equilibrium very experienced workers with high wages stop searching at all since the gain from moving to a good job becomes smaller than the cost of searching. The main difference of this study from current work is that we treat experience as transferable across firms while it is completely lost upon the quit in Pissarides (1994). Recent work in this field includes prominent extensions by Burdett and Coles (2003), Burdett et al. (2011) and Bagger et al. (2014). These studies analyse tenure accumulation with on-the-job search, but they do not consider internal promotions. From the perspective of matching we use an urn-ball matching mechanism. Pissarides and Petrongolo (2001) and Albrecht et al. (2003) show that this matching function is increasing in both unemployment and vacancies and has constant returns to scale for large values of both arguments. The reason for using the urn-ball matching mechanism rather than a more traditional Cobb-Douglas approach, is that the urn-ball matching function is micro-founded and can be directly implemented in the simulation whereas the Cobb-Douglas approach is a "black box" from the perspective of practial implementation. Thus using the urn-ball matching technology allows us to closely replicate the analytical model in the simulation setting and avoid discrepancies in the approximation of the matching technology.

Finally, our study is related to work in the area of agent-based simulations of the labour market. The usefulness of this approach for the analysis of dynamic labour market issues has been clearly demonstrated in the literature, which is reviewed for example in Neugart and Richiardi (2018). Moreover, it has also been shown that agent-based models are very successful in reproducing large sets of empirical stylized facts on different levels of aggregation in several economic areas, including labour markets (see e.g. Axtell (2018), Ballot (2002), Dawid and Delli Gatti (2018), Dawid et al. (2018), Dosi et al. (2017)). The high potential of agent-based approaches for the analysis of labour market issues, in particular such that consider effects of institutional differences, has been stressed among others by Richard Freeman in Freeman (1998, 2007).

The rest of the paper is structured as follows. In section 2.2 we introduce the economic framework and analyse the dynamics of workers and firms across states. Section 2.3 presents the value functions of firms and their choice of the optimal promotion time as well as the emerging partial and general equilibrium in the benchmark setting. In section 2.4 we extend the model to two skill groups. Section 2.5 considers the extension of the benchmark model with pyramidal firms and section 2.6 shows the robustness of our findings with respect to changes in the firms' production function. Section 2.7 concludes the paper. The Appendices contain additional details of our analysis, including an extensive description and validation of the simulation approach used in parts of our study.

2.2 The Model

2.2.1 The economic framework

Time is continuous with an infinite horizon. There is a continuum of both firms and workers with a total measure of workers normalised to 1. The inflow of new workers into the labour market is denoted by d. In the benchmark model all entering workers are homogeneous with identical skills, however, in the extension we also analyse consequences of skill heterogeneity. Job ladders have three hierarchical levels. All young workers entering the market immediately take simple jobs on the low level. These are subsistence jobs that don't yield any professional experience. All entering firms are identical and every firm is a dyad consisting of two positions: one junior position and one senior (managerial) position. The inflow of new firms is denoted by n. Both positions are empty when the firm enters the market and can be posted simultaneously. Posting an open position (junior or senior) is associated with a flow cost s for the firm. For the purpose of tractability we assume that there are no dismissals, thus the pool of applicants for junior positions consists of young workers employed in low level jobs. Only workers with substantial professional experience are eligible to apply for senior positions. Let u denote the stock of workers in low level jobs, e_1 – are workers employed in junior positions and e_2 denotes managers in senior positions, so that $u + e_1 + e_2 = 1$ due to the normalisation.

Once accepted in the junior position young workers start accumulating professional experience $x \geq 0$ with $\dot{x} = 1$. This experience is observable by the current employer but not by other firms in the market. It is general human capital and can be fully transferred to other firms. In the beginning of the employment relationship with some inexperienced worker every firm i chooses an experience cutoff $\bar{x}_i$, which makes the worker eligible for promotion to the senior position in this firm. Even though $\bar{x}_i$ is an endogenous choice variable of the firm, we assume that it is written down in the labour contract and verifiable by court. Once the worker reached experience $\bar{x}_i$, the firm is obliged to provide an experience evaluation to the worker and promote this worker to the senior position if this position is free. In the opposite case when the senior position is filled, the worker starts applying to senior positions in other firms. This is the process of on-the-job search. The documented experience evaluation is a sufficient proof of experience for other employers. We assume that experience accumulation is costly to workers, thus workers stop learning upon receiving an experience evaluation and start searching on-the-job. Intuitively, we model situations when firms encourage junior workers to attend training courses taking a part of the working time up to the level of human capital $\bar{x}_i$ (e.g. language and computer courses, MBA or CFA, dual studies). Beyond this level of human capital workers are expected to focus on their job tasks and firms do not permit any training activities at work.

This model structure leads to the existence of two separate submarkets, one where firms are posting junior positions and anticipate a worker with $x = 0$ and another one where firms are posting their senior positions and anticipate workers searching on-the-job and possessing a proof of sufficient experience. Workers employed in junior positions produce output $d_1 + c_1 e^{\gamma x}$, whereas workers employed in senior positions (managers) produce output $d_2 + c_2 e^{\gamma x}$, where $d_1 > d_2$ and $c_1 < c_2$ as in Gibbons and Waldman (1999). Intuitively, this means that the fixed component of output d_j, $j = 1, 2$ is falling with a higher hierarchical level, while experience becomes more important, that is c_j, $j = 1, 2$ is increasing with j. In a symmetric equilibrium all firms choose an identical promotion cutoff $\bar{x}$, thus firms correctly anticipate that applicants to senior positions achieved an experience level $\bar{x}$ and their output in senior positions is $d_2 + c_2 e^{\gamma \bar{x}}$. As argued above, there is no human capital accumulation in senior positions and output is constant. Workers employed in senior managerial positions retire at an exogenous rate ρ. If the manager retires and the junior position is not filled, the firm is empty and exits the labour market. In our analysis we only consider the steady state, moreover the entry and exit parameters d and ρ are chosen to keep the population size constant.

Since the focus of the paper is on the optimal promotion decisions of firms and feedback effects of these decisions on the resulting structure of the labour market, we assume that workers don't act strategically in the model and take their behaviour as given. Specifically, young workers without experience are always searching for their first job, accumulate experience till the level specified in their labour contract and start applying to managerial jobs if there is no open position in their firm. It is a simplifying assumption of the model that there is no labour market exit among searching workers and those employed in junior positions.

Let $1 - \beta$ denote the fraction of output accruing to firms, thus the flow profit is equal to $(1 - \beta)(d_j + c_j e^{\gamma x})$ depending on the hierarchical level of the position $j = 1, 2$ and worker's experience x. Workers receive a wage $w_j(x) = \beta c_j e^{\gamma x}$, thus $\ln w_j(x) = \ln \beta + \ln c_j + \gamma x$.[4] This means that γ can be interpreted as a return to tenure in the model. This shows that wages in our model can grow due to the accumulation of tenure, internal promotions and between firm transitions. Further, we assume that there is a profit synergy Δ if the firm is employing both

[4]The remaining part of the output βd_j can be interpreted as the cost of capital that firms pay. This is a simplifying assumption which does not influence our results.

workers simultaneously, that is, one junior worker accumulating experience and one senior manager.[5] So the total profit of this firm is given by $(1-\beta)(d_1 + c_1 e^{\gamma x} + d_2 + c_2 e^{\gamma \bar{x}}) + \Delta$. Intuitively, this is a synergy from team work because younger inexperienced workers gain from the advice of senior managers, whereas senior managers may gain from the innovative new ideas of younger workers.

Variable d_{00} denotes the stock of empty new firms in the market, whereas d_{01} is the stock of firms with a senior manager but no junior worker. Since all these firms have an open junior position the total stock of open junior positions available for matching is equal to $d_{00} + d_{01}$. These positions are randomly matched with zu searching inexperienced workers, where z denotes the search effort of workers. More precisely, z is the fraction of searching workers who prepare and send an application at every instant of time. To determine the number of matches in the submarket for junior positions we use an urn-ball matching mechanism. Suppose some worker sends an application to one randomly chosen firm, then the probability that a given firm doesn't receive this application is $1 - \frac{1}{d_{00}+d_{01}}$. Since workers send their applications independently without coordination, the probability that this firm doesn't get any of the zu applications is given by $(1 - \frac{1}{d_{00}+d_{01}})^{zu}$. Let q_1 be the job-filling rate resulting from this application process and λ_1 be the job-finding rate for inexperienced workers. They are given by:

$$q_1 = 1 - \Big(1 - \frac{1}{d_{00} + d_{01}}\Big)^{zu} \qquad \lambda_1 = z\frac{q_1(d_{00} + d_{01})}{zu} = q_1\frac{(d_{00} + d_{01})}{u} \tag{2.1}$$

The term $q_1(d_{00} + d_{01})$ is a total number of matches in the junior market, thus $\frac{q_1(d_{00}+d_{01})}{zu}$ is a probability of matching for workers conditional on sending an application in a given matching round. Multiplying this conditional matching probability with z we obtain the job-finding rate for junior workers. Further, let d_{10} denote firms with a junior worker but no senior manager. This means that the total number of open managerial positions is given by $d_{00} + d_{10}$. Finally, let d_{11}^N denote the stock of full firms with both employees, where the worker in the junior position is not yet eligible for promotion ($x < \bar{x}$). In a similar way, d_{11}^S – is the stock of full firms, where the junior worker is already eligible for senior positions and searching on-the-job. This means that the stock of applicants in the managerial market is given by zd_{11}^S. So the job-filling rate in the managerial market q_2 and the workers' job-finding rate in this market λ_2 are given by:

$$q_2 = 1 - \Big(1 - \frac{1}{d_{00} + d_{10}}\Big)^{zd_{11}^S} \qquad \lambda_2 = z\frac{q_2(d_{00} + d_{10})}{zd_{11}^S} = q_2\frac{(d_{00} + d_{10})}{d_{11}^S} \tag{2.2}$$

Note that we assume the same search intensity parameter z in both markets. This setting can be generalized to different search intensities for experienced and inexperienced workers, however, it is not important for our main results. So we keep the model simple and consider only one search intensity parameter z.

The total number of firms in the market is given by $d_{00} + d_{01} + d_{10} + d_{11}^N + d_{11}^S$. This

[5] It should be noted that Δ accounts only for the additional profit gained by the firm. In principle also wages could increase due to synergy, however none of our following results would be affected by incorporating also this increase.

notation also allows us to calculate the number of workers, so normalising the population size to 1 yields:

$$u + d_{10} + d_{01} + 2d_{11}^N + 2d_{11}^S = 1$$

Here $e_1 = d_{10} + d_{11}^N + d_{11}^S$ is the total number of employees in junior positions, and $e_2 = d_{01} + d_{11}^N + d_{11}^S$ is the total number of employees in senior positions.

2.2.2 Firm Dynamics

Transitions of firms are illustrated in figure 3.1. Consider changes in the stock of new empty firms d_{00}. The inflow of new firms into the market is given by n. Since every new firm posts both the junior and the senior position in the respective submarkets it exits the state d_{00} whenever it finds the first employee. So the outflow of firms from d_{00} takes place at rate $q_1 + q_2$. In this paper we restrict our analysis to the steady states and consider a stationary distribution of workers and firms across states. This means that $\dot{d}_{00} = 0$ in the steady state:

$$0 = \dot{d}_{00} = n - (q_1 + q_2)d_{00} \qquad \Rightarrow \qquad d_{00} = \frac{n}{q_1 + q_2} \tag{2.3}$$

The entry of firms into the market is given by n, whereas the exit is ρd_{01}. These are the firms that lose their only employee due to retirement, which happens at rate ρ. Thus we get $d_{01} = n/\rho$ to guarantee a constant number of firms in the market. This is equivalent to the standard assumption of a constant population of workers.

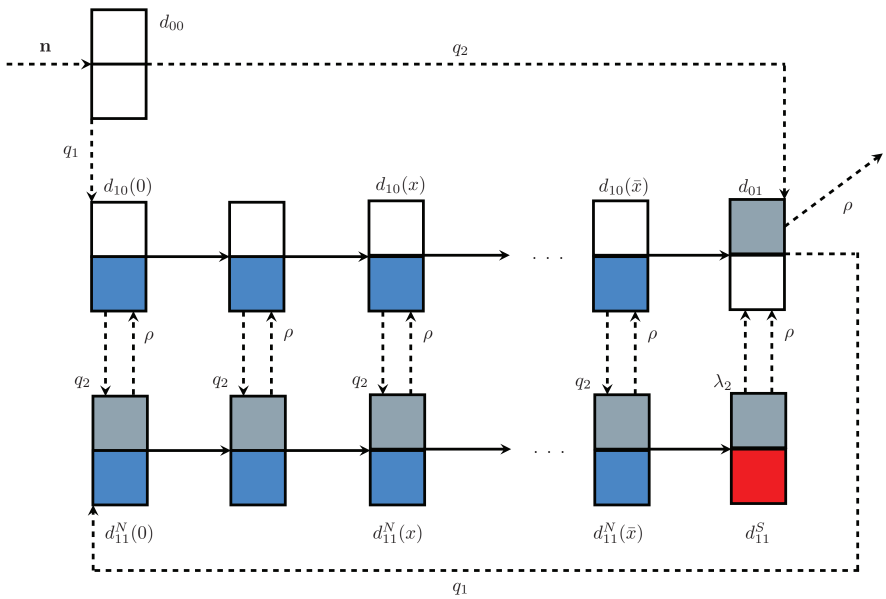


Figure 2.1: Types of firms and their transitions

Further, consider changes in the stocks of firms $d_{10}(x)$ and $d_{11}^N(x)$. Note that workers with experience $0 \leq x \leq \bar{x}$ are not yet searching on-the-job since their experience is not sufficient for managerial positions and there are no gains from changing to another junior job. Variable $\bar{x}$ here denotes the equilibrium promotion cutoff and will be determined in section 2.3. This means that the inflow of firms into state $d_{10}(x)$ is equal to $\rho d_{11}^N(x)$. These are the firms where the manager retires at rate ρ and they are left with only one junior worker. At the same time $\rho d_{11}^N(x)$ is the outflow of firms from the state $d_{11}^N(x)$. If the manager retires firms post the open position in the second submarket for experienced workers and find a manager at rate q_2. This means that the outflow of workers from the state $d_{10}(x)$ is equal to $q_2 d_{10}(x)$. This is also the inflow of firms into the state $d_{11}^N(x)$. So we get the following system of two first order linear differential equations[6]:

$$\begin{cases} \partial d_{10}(x)/\partial x &= -q_2 d_{10}(x) + \rho d_{11}^N(x) \\ \partial d_{11}^N(x)/\partial x &= q_2 d_{10}(x) - \rho d_{11}^N(x) \end{cases}$$

The coefficient matrix of this homogeneous system has eigenvalues 0 and $-(\rho + q_2)$, so the general solution is given by:

$$\begin{cases} d_{10}(x) &= k_1\rho + k_2 e^{-(\rho+q_2)x} \\ d_{11}^N(x) &= k_1 q_2 - k_2 e^{-(\rho+q_2)x} \end{cases}$$

In order to find the constant terms k_1 and k_2 we use the following initial conditions: $q_1 d_{00} = d_{10}(0)$ and $q_1 d_{01} = d_{11}^N(0)$. The first condition implies that the stock of firms $d_{10}(0)$ always consists of new firms finding their first junior worker $q_1 d_{00}$. The second condition implies that the stock of firms $d_{11}^N(0)$ consists of firms d_{01} who find a junior worker, that is $q_1 d_{01}$. Using these initial conditions we find that:

$$k_1 = \frac{q_1 n(\rho + q_1 + q_2)}{\rho(\rho + q_2)(q_1 + q_2)} > 0 \qquad k_2 = -\frac{(q_1)^2 n}{(\rho + q_2)(q_1 + q_2)} < 0$$

One can see that $k_2 < 0$, this means that $d_{10}(x)$ is increasing while $d_{11}^N(x)$ is decreasing in x. Intuitively this means that the flow $\rho d_{11}^N(x)$ due to retirement of senior managers always dominates the flow $q_2 d_{10}(x)$ implying that finding senior managers is a difficult task for firms in the considered setting. Note that the sum of two variables is a constant, that is $d_{10}(x) + d_{11}^N(x) = k_1(\rho + q_2)\ \forall x \in [0..\bar{x}]$.

By integrating variables $d_{10}(x)$ and $d_{11}^N(x)$ over the interval $[0..\bar{x}]$ we find the total stocks of firms d_{10} and d_{11}^N:

$$d_{10} = \int_0^{\bar{x}} d_{10}(x)dx = k_1\rho\bar{x} + \frac{k_2}{\rho + q_2}(1 - e^{-(\rho+q2)\bar{x}}) \tag{2.4}$$

$$d_{11}^N = \int_0^{\bar{x}} d_{11}^N(x)dx = k_1 q_2\bar{x} - \frac{k_2}{\rho + q_2}(1 - e^{-(\rho+q2)\bar{x}}) \tag{2.5}$$

The remaining unknown stock of firms is d_{11}^S. These are the firms with two employees, where the junior one is already searching for jobs with alternative employers. All firms of type $d_{11}^N(\bar{x})$ automatically enter the state d_{11}^S since the junior worker starts searching on-the-job

[6]In general the stock variable $d_{10}(x, t)$ may depend on time t, so the total derivative is given by:

$$\frac{\partial d_{10}(x,t)}{\partial x}\frac{\partial x}{\partial t} + \frac{\partial d_{10}(x,t)}{\partial t} = -q_2 d_{10}(x) + \rho d_{11}^N(x)$$

Since the distribution of firms $d_{10}(x, t)$ is stationary in the steady state we set the time derivative $\dot{d}_{10} = \frac{\partial d_{10}(x,t)}{\partial t}$ equal to zero. Moreover, experience x is accumulating one to one with the time because $\dot{x} = \partial x/\partial t = 1$).

upon attaining experience $\bar{x}$. This is the inflow of workers into the state d_{11}^S. At rate ρ the senior manager retires and the firm promotes the junior worker to the managerial job. In addition, it can also happen that the junior worker finds a new employer at rate λ_2. As one can see from figure 3.1, in both cases the firm leaves the state d_{11}^S and enters the stock of firms d_{01}. Hence we get:

$$0 = \dot{d}_{11}^S = d_{11}^N(\bar{x}) - (\rho + \lambda_2)d_{11}^S \quad \Rightarrow \quad d_{11}^S = \frac{d_{11}^N(\bar{x})}{\rho + \lambda_2} = \frac{k_1 q_2 - k_2 e^{-(\rho+q_2)\bar{x}}}{\rho + \lambda_2} \tag{2.6}$$

Finally, recall that u are the young individuals searching for their first job, so that $\dot{u} = d - \lambda_1 u$. In the steady state it should be that the inflow into this state d should be equal to the outflow $\lambda_1 u$, where the outflow are young inexperienced workers finding their first employer. So we get $u = d/\lambda_1$. Variable d is the endogenous entry of young individuals, which we can find from normalising the total population of workers to 1:

$$\frac{d}{\lambda_1} = 1 - (d_{10} + d_{01} + 2d_{11}^N + 2d_{11}^S) \tag{2.7}$$

Solving jointly the system of equations (2.2)-(2.7), $d_{01} = n/\rho$, $u = d/\lambda_1$ we can find the equilibrium distribution of firms $\{d_{00}, d_{10}, d_{11}^N, d_{11}^S, d_{01}\}$, as well as variables d and u and the equilibrium transition rates λ_j, and q_j, $j = 1, 2$. Note that variable $\bar{x}$ (promotion cutoff) is taken as given at this stage and will be endogenously derived in section 2.3.

2.2.3 Transition rates

We proceed by illustrating the mechanism of our model with a help of a numerical example which resembles realistic career paths of workers in developed economies. In this section we focus on the transitions of workers and firms for a given promotion cutoff $\bar{x}$. One period of time is set to be one quarter. Consider young workers entering the market at the age of 18 years. Variable z is the search intensity parameter which is the driving force behind the job-finding rate λ_1. We set $z = 0.0146$, this corresponds to $\lambda_1 = 0.0145$ and implies that workers stay in level 0 jobs for approximately $1/\lambda_1 = 69$ quarters or 17.25 years. Intuitively, this means that workers find their first managerial job on level e_1 at the age of 35.25 years on average. In state e_1 workers start accumulating professional managerial experience x. We assume that $\bar{x} = 45$, this means it takes 45 quarters or 11.25 years for workers to be eligible for the position of a senior manager. Thus workers reach the pre-specified necessary level of experience at the age of 46.5 years on average.

Recall that $d_{10}(\bar{x})$ is a stock of workers who are directly promoted to senior positions within their firm at every point in time. At the same time $d_{11}^N(\bar{x})$ is a stock of workers eligible for promotions, however, they can not be promoted directly within their firm since the senior position is occupied. These workers start searching on the job and enter the accumulated pool of workers searching and applying to senior positions d_{11}^S. So the total stock of workers eligible for promotion in a given period of time is $d_{10}(\bar{x}) + d_{11}^N(\bar{x}) + d_{11}^S = k_1(\rho + q_2) + d_{11}^S$. Out of these workers $d_{10}(\bar{x}) + (\rho + \lambda_2)d_{11}^S$ are actually promoted, where $d_{10}(\bar{x}) + \rho d_{11}^S$ are promoted directly within their firms and $\lambda_2 d_{11}^S$ make a transition to a senior position in another firm. So the average duration of time from the moment of becoming eligible $\bar{x}$ till the actual promotion within or between firms is given by:

$$\frac{k_1(\rho + q_2) + d_{11}^S}{k_1\rho + k_2 e^{-(\rho+q_2)\bar{x}} + (\rho + q_2)d_{11}^S}$$

In our model this duration is equal to 14 quarters or 3.5 years, so that workers become senior managers at the age of 50 years on average. This duration is achieved by setting the number of entering firms n equal to 0.0026. This also implies that the average stock of firms active in the market is equal to 0.6. So there are on average 600 active firms or 1200 positions per 1000 workers. However, not all of these positions are filled due to the search frictions and experience requirements. Further, we set $\rho = 0.015$, so the average time workers spend in senior positions till retirement is $1/\rho = 66.6$ quarters or 16.6 years. So workers retire on average at the age of 66.6 years. Finally, the total population is normalized to 1. Given that the exit rate of workers is $\rho = 0.015$, constant size of the population can be achieved by setting $d = 0.0052$. This means that 5.2 workers on average enter the market with a population of 1000 workers. Our choice of parameters at this stage is summarized in table 2.1. Note that variable $\bar{x}$ is endogenous in the overall model, even though we keep it fixed at the current stage of analysis. Endogenous values of the quarterly transition rates in the steady-state are summarized on the right side of table 2.1.

Parameter	Value	Interpretation	Variable	Value	Interpretation
z	0.0146	Search intensity of workers	q_1	0.0171	Job-filling rate, level 1
ρ	0.0150	Exit/retirement rate	q_2	0.0036	Job-filling rate, level 2
n	0.0026	Entry of empty firms	λ_1	0.0145	Job-finding rate, level 1
d	0.0052	Entry of young workers	λ_2	0.0146	Job-finding rate, level 2

Table 2.1: Values of exogenous parameters and quarterly transition rates

Table 2.2 shows the distributions of workers and firms in the steady-state. We can see that 35.7% of all workers remain on average in simple jobs e_0. Further, 29.7% are employed in junior positions e_1, where 6.3% of workers are searching on-the-job and applying to senior positions (d_{11}^S). 34.5% of workers occupy senior management positions e_2. These numbers imply that $p_1 = 0.297/(0.297 + 0.345) = 0.462$, that is 46.2% of workers in professional jobs are employed in junior positions, with the remaining 53.7% being employed in senior positions. Considering transitions of workers, we can see that 1.2% of e_1 workers reach senior positions by changing employers. Another 5.7% of junior workers are internally promoted within their firms per year. Even though internal mobility of workers is not intensive, these numbers are close to the empirical findings. For example, Lluis (2005) finds that in Germany the annual probability of internal promotions is 5.7% for relatively young workers with less than 10 years of market experience and it falls afterwards with an average for all workers groups equal to 2.7%. The same study reports that internal mobility is more intensive in the US, with 6.7% for men and 6.2% for women with less than 10 years of experience and 5.0% on average for all men (4.6% for all women). A more recent study by Cassidy et al. (2016) reports an average probability of internal promotions equal to 4.6% in Finland.

The left panel of figure 2.2 shows the stocks of firms $d_{10}(x)$ and $d_{11}^N(x)$ for different experience levels x of the junior worker. As expected $d_{10}(x)$ is increasing, while $d_{11}^N(x)$ is

Variable	Value	Variable	Equation	Value
d_{00}	0.1273	Workers in simple jobs e_0	$= 1 - e_1 - e_2$	0.3577
d_{01}	0.1760	Workers in junior jobs e_1	$= d_{10} + d_{11}^N + d_{11}^S$	0.2966
d_{10}	0.1270	Workers in managerial jobs e_2	$= d_{01} + d_{11}^S + d_{11}^N$	0.3456
d_{11}^S	0.0633	Internally promoted (per year)	$= (d_{10}(\bar{x}) + \rho d_{11}^S)/e_1$	0.0576
d_{11}^N	0.1063	Job-to-job movers (per year)	$= \lambda_2 d_{11}^S/e_1$	0.0124

Table 2.2: Stationary distributions of workers and firms for parameters from Table 2.1 and $\bar{x} = 45$

decreasing with x. Note that the starting ratio of these two stocks is $d_{10}(0)/d_{11}^N(0) = \rho/(q_1 + q_2)$ but the long-run ratio for larger values of x is: $\lim_{x\to\infty} d_{10}(x)/\lim_{x\to\infty} d_{11}^N(x) = \rho/q_2$. So the ratio is clearly increasing with higher experience levels. At the same time we know that the sum of these two stocks is fixed and equal to $k_1(\rho+q_2)$ and each of them is a monotonous function of x. This confirms again that $d_{10}(x)$ should be increasing. So as workers accumulate more and more experience they are more likely to find themselves in a situation with an open senior position. The reason is that senior managers retire over time, but the probability of substituting them with an external candidate is relatively low.

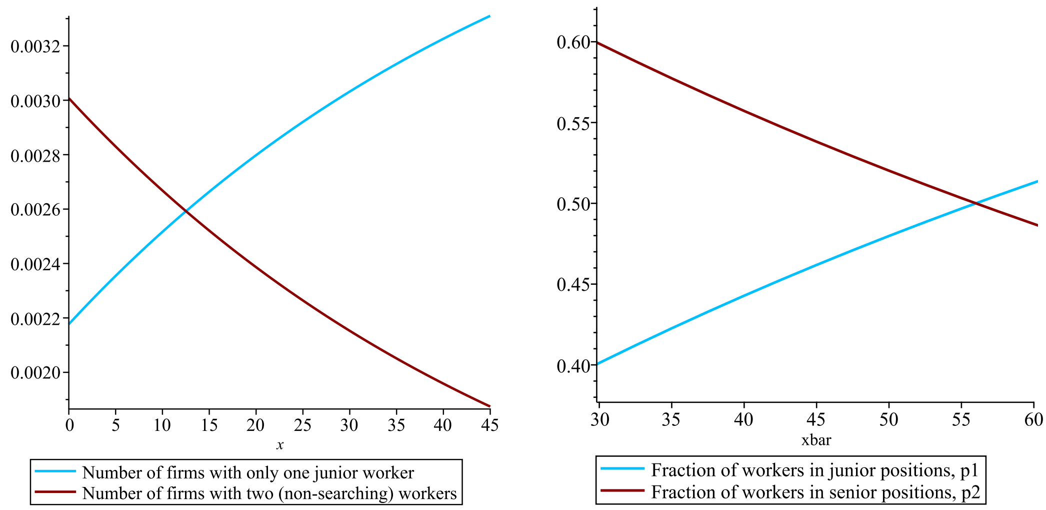


Figure 2.2: Left panel: Numbers of firms with only one worker in the junior position $d_{10}(x)$ and with two (non-searching) workers $d_{11}^N(x)$ as a function of worker's experience x ($\bar{x} = 45$). Right panel: Fractions of workers employed in the junior level $p_1 = e_1/(e_1 + e_2)$ and in the senior level $p_2 = 1 - p_1$ depending on the promotion cutoff $\bar{x}$

The right panel of figure 2.2 shows comparative statics results with respect to the promotion cutoff $\bar{x}$. We vary this variable in the range [30..60] quarters or [7.5..15] years, with the benchmark value $\bar{x} = 45$, that is 11.25 years. We can see that earlier promotions reduce the fraction of workers in junior positions p_1 and increase the fraction of workers in senior positions $p_2 = 1 - p_1$. If we consider the implications of earlier promotions for the pool of applicants to senior positions then there are two counteracting effect. If there are many open senior vacancies in the economy then a smaller $\bar{x}$ will lead to many internal promotions, so the pool of external applicants to senior positions will diminish. But on the other hand, if the number of senior positions is limited and internal promotions are rare, a smaller $\bar{x}$ will increase the pool of external applicants to senior positions. We find that the second effect is dominating in our setting. This is a general equilibrium effect, which is not anticipated by individual firms when they choose their optimal promotion cutoff.

The left panel of figure 2.3 shows changes in the mobility of workers between levels 1 and 2 with respect to the promotion cutoff $\bar{x}$. Later promotions reduce the intensity of transitions from junior to senior positions. Both internal promotions and job-to-job transitions are less frequent with a higher promotion cutoff. This is because workers have to wait for the experience evaluation by firms certifying their skills to other employers. The same figure (right axis) also illustrates the relative fraction of internally promoted workers, we obtain it by dividing the number of promoted workers $d_{10}(\bar{x}) + \rho d_{11}^S$ with a total number of workers making it to the senior position $\lambda_2 d_{11}^S + d_{10}(\bar{x}) + \rho d_{11}^S$. We can see that this relative fraction is increasing from 77% when $\bar{x} = 25$ to 86% when $\bar{x} = 65$. This reveals an unusual general equilibrium effect in our model. If some firm i decides to delay internal promotions and wants to hire more senior managers on the external market it sets a higher cutoff value $\bar{x}_i$. However, if all firms follow the same strategy and set a higher cutoff $\bar{x}$ then the relative fraction of senior managers reaching senior positions via internal promotions is increasing. Thus internal promotions become a more important source of upward mobility for workers even though the individual intention of every firm is different[7]. The reason is that with a higher experience requirement $\bar{x}$, there are less applicants in the external market, so the job-to-job mobility rate declines stronger then the internal promotion rate.

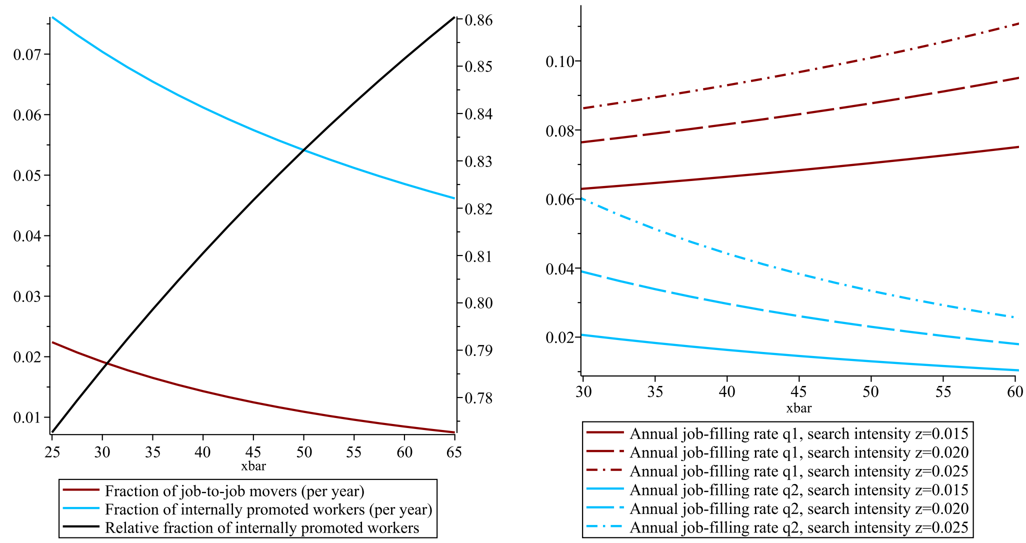


Figure 2.3: Selected variables for different values of the promotion cutoff $\bar{x}$ and search intensity z. Left panel: Fractions of internally promoted workers $(d_{10}(\bar{x}) + \rho d_{11}^S)/e_1$ and job-to-job movers $\lambda_2 d_{11}^S/e_1$ per year. Right panel: Annual job-filling rates q_1 and q_2.

The right panel of figure 2.3 shows changes in the job-filling rates q_1 and q_2. More intensive job search by workers makes it easier for firms to fill their open positions, so q_1 and q_2 are both increasing in z. But there are adverse effects of the promotion cutoff $\bar{x}$. Later promotions

[7]This is illustrated in figure 2.15 in Appendix B. We simulate the relative fraction of internally promoted workers of a single firm i for varying $\bar{x}_i$ while keeping the promotion cutoff of all other firms constant. By delaying internal promotions firm i is able to hire more senior workers from the market if other firms don't change their strategy.

reduce the pool of competing vacancies on level 1. Reduced competition of firms in this submarket improves their hiring chances, so the job-filling rate q_1 is increasing with $\bar{x}$. There is an opposite effect in the second submarket for experienced workers. Delayed promotions reduce the pool of applicants for senior positions which leads to the lower job-filling rate q_2.

2.3 Optimal promotion by firms

In this section we analyse the optimal promotion strategy of firms in several steps. First, in Subsection 2.3.1 we determine the best response of an individual firm to a given promotion threshold used by all other firms. Second, in Subsection 2.3.2 we do a partial equilibrium analysis and show that for our calibration of the model there is a unique stable fixed point of the best response map for fixed values of the job-filling and job-finding rate. We then show that the transition rates generated under the (partial) equilibrium value of the promotion threshold actually coincide with the values underlying our partial equilibrium analysis. Hence, the obtained promotion threshold also constitutes a symmetric general equilibrium of our model. In Subsection 2.3.3 we then explore the implications of changes in key parameters on the optimal firm promotion threshold disentangling partial and general equilibrium effects.

2.3.1 Firm's best response

As a first step we characterize in this subsection the optimal promotion time chosen by an individual firm for a given promotion threshold of all competitors and for given job filling rates for junior and senior positions. Denoting by $J_{00}(\bar{x}_i, \bar{x})$ the present value of a firm starting to search for a worker, i.e. a firm with neither a junior nor a senior level worker, which uses a promotion threshold $\bar{x}_i$, whereas all other firms on the market promote at $\bar{x}$. When a new firm opens it has to choose its promotion strategy and the optimal choice is given by

$$\bar{x}_i^*(\bar{x}) = \arg\max_{\bar{x}_i \geq 0} J_{00}(\bar{x}_i, \bar{x}). \tag{2.8}$$

In order to analyse this optimization problem the value function J_{00} has to be determined. When entering the market the firm has two open positions – one junior and one senior – so the firm is searching for workers in both markets simultaneously and has a double cost $2s$. Therefore,

$$rJ_{00}(\bar{x}_i, \bar{x}) = -2s + q_1(J_{10}(0|\bar{x}_i, \bar{x}) - J_{00}) + q_2(J_{01}(\bar{x}|\bar{x}_i, \bar{x}) - J_{00}),$$

where $J_{10}(x|\bar{x}_i, \bar{x})$ is the present value for a firm with only one junior worker, whose experience is x, and no senior level worker and $J_{01}(y|\bar{x}_i, \bar{x})$ is the present value for a firm with only one senior level worker, whose experience is y, and no junior worker. If the firm first finds an inexperienced worker, which happens at rate q_1 it moves to the state $J_{10}(0)$, since we know that $x = 0$. In contrast, if the firm first finds a senior manager which happens at rate q_2 it moves to the state $J_{01}(\bar{x})$ since we know that all managers in the senior market have experience $\bar{x}$.

To determine $J_{10}(x|\bar{x}_i, \bar{x})$ let $J_{11}^N(x, y|\bar{x}_i, \bar{x})$ be the present value of profits for a firm with a worker, whose experience is x, and a manager with experience y. Note that both value functions indirectly depend on the promotion cutoff $\bar{x}_i$ chosen by firm i and on the market experience level $\bar{x}$ chosen by competing firms. Let $\pi_1(x) = (d_1 + c_1 e^{\gamma x})(1-\beta)$ and $\pi_2(y) = (d_2 + c_2 e^{\gamma y})(1-\beta)$ denote the flow profits obtained by the firm from a filled junior and senior position respectively. The present value $J_{10}(x|\bar{x}_i, \bar{x})$ is given by the following equation:

$$rJ_{10}(x|\bar{x}_i,\bar{x}) \;=\; \pi_1(x) - s + q_2(J_{11}^N(x,\bar{x}|\bar{x}_i,\bar{x}) - J_{10}(x|\bar{x}_i,\bar{x})) + \frac{\partial J_{10}(x|\bar{x}_i,\bar{x})}{\partial x} \qquad (2.9)$$

The firm receives a flow profit $\pi_1(x)$ by employing its worker in the junior position and the worker is accumulating experience x. In addition, the firm pays a flow cost s for posting a vacancy in the market for experienced workers. At rate q_2 the firm is successful in this market and moves to the state $J_{11}^N(x,\bar{x}|\bar{x}_i,\bar{x})$, where $\bar{x}$ is the market level of experience set by other firms and guaranteeing workers' eligibility for senior positions. For the ease of exposition in the following we use $J_{10}(x)$ for $J_{10}(x|\bar{x}_i,\bar{x})$ and $J_{11}^N(x,y)$ for $J_{11}^N(x,y|\bar{x}_i,\bar{x})$ and omit the indirect dependence on $\{\bar{x}_i,\bar{x}\}$ in other value functions. We come back to the explicit notation when we determine the optimal promotion time $\bar{x}_i^*$ of firm i and the equilibrium value of $\bar{x}$ in the end of this section.

Next consider the present value $J_{11}^N(x,y)$, where x is the current experience of the worker in the junior position and y is the constant experience level of the manager. Note that $y = \bar{x}$ if the manager was hired in the market but it can be different from $\bar{x}$ if the manager was promoted within the firm:

$$rJ_{11}^N(x,y) \;=\; \pi_1(x) + \Delta + \pi_2(y) - \rho(J_{11}^N(x,y) - J_{10}(x)) + \frac{\partial J_{11}^N(x,y)}{\partial x}$$

Here the firm receives additional profit Δ from teamwork, but may lose the manager due to retirement which happens at rate ρ. Let $\Delta J(x,\bar{x}) = J_{11}^N(x,\bar{x}) - J_{10}(x)$ be the capital gain of the firm from filling a senior position in the market which guarantees experience $y = \bar{x}$, so that

$$(r+\rho+q_2)\Delta J(x,\bar{x}) = \pi_2(\bar{x}) + \Delta + s + \frac{\partial \Delta J(x,\bar{x})}{\partial x}$$

The general solution of this first order linear differential equation is given by:

$$\Delta J(x,\bar{x}) = \frac{\pi_2(\bar{x}) + \Delta + s}{r+\rho+q_2} + Ke^{(r+\rho+q_2)x}$$

where K is the integration constant. This equation shows that the capital gain from hiring a manager in the market has three components: (1) the firm receives the flow profit $\pi_2(\bar{x})$ and (2) the additional profit Δ from team work and (3) the firm saves the cost of posting a vacancy s. Next insert $\Delta J(x,\bar{x})$ into equation (3.9), this yields:

$$rJ_{10}(x) = \pi_1(x) - s + q_2\frac{(\pi_2(\bar{x}) + \Delta + s)}{r+\rho+q_2} + q_2 K e^{(r+\rho+q_2)x} + \frac{\partial J_{10}(x)}{\partial x} \qquad (2.10)$$

This allows us to find the general solution for the present value of profits $J_{10}(x)$ (with A denoting the integration constant, see Appendix A for the derivation) and $J_{11}^N(x,\bar{x})$. Recall that $J_{11}^N(x,\bar{x}) = \Delta J(x,\bar{x}) + J_{10}(x)$, so we get:

$$J_{10}(x) = \frac{d_1(1-\beta) - s}{r} + q_2 \frac{(\pi_2(\bar{x}) + \Delta + s)}{r(r+\rho+q_2)} + Ae^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{q_2 K e^{(r+\rho+q_2)x}}{\rho+q_2}$$
$$J_{11}^N(x,\bar{x}) = \frac{(\pi_2(\bar{x}) + \Delta + s)(r+q_2)}{r(r+\rho+q_2)} + \frac{\rho K e^{(r+\rho+q_2)x}}{\rho+q_2} + \frac{d_1(1-\beta) - s}{r} + Ae^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma}$$

Next consider $J_{01}(y)$, which is the present value of profits for a firm with only one manager, whose experience level is y:

$$rJ_{01}(y) = \pi_2(y) - \rho J_{01}(y) - s + q_1(J_{11}^N(0,y) - J_{01}(y))$$

The firm receives the flow profit $\pi_2(y) = (d_2 + c_2 e^{\gamma y})(1-\beta)$ generated by the manager and is continuously posting a vacancy in the market for junior workers, which is associated with a flow cost s. At rate q_1 the firm is successful in this market and moves to the state $J_{11}^N(0,y)$. This is because applicants to junior positions are young and inexperienced with $x = 0$. Finally, at rate ρ the firm may lose the senior manager and remains empty. All empty firms exit the market. Rewrite $J_{01}(y)$ in the following way:

$$J_{01}(y) = \frac{\pi_2(y) - s + q_1 J_{11}^N(0,y)}{r+\rho+q_1}$$

The last state for the firm is when the junior worker has already accumulated experience necessary for promotion. Recall that $\bar{x}_i$ denotes promotion cutoff of some arbitrary firm i. This means that the junior worker obtains experience evaluation and becomes eligible for senior positions having accumulated experience $\bar{x}_i$. This promotion cutoff is chosen by the firm upon signing the employment contract. If the senior position is open in firm i, the worker with $x = \bar{x}_i$ is promoted immediately . However, it is also possible that the senior position is occupied, so the worker starts searching for alternative employment. Let $J_{11}^s(\bar{x}_i, y)$ be the present value of profits for a firm with a searching worker whose experience is $(\bar{x}_i)$ and a manager (y):

$$rJ_{11}^s(\bar{x}_i,y) = \pi_1(\bar{x}_i) + \Delta + \pi_2(y) - \rho(J_{11}^s(\bar{x}_i,y) - J_{01}(\bar{x}_i)) - \lambda_2(J_{11}^s(\bar{x}_i,y) - J_{01}(y))$$

This equation shows the following. The firm obtains the flow profit generated by both workers $\pi_1(\bar{x}_i) + \pi_2(y)$ and additional profit Δ from teamwork. At rate ρ the manager may retire, so the searching worker is promoted to the senior position and the firm moves to the state $J_{01}(\bar{x}_i)$. Alternatively, it may happen that the worker finds alternative employment and quits at rate λ_2. In this case the firm is left with only one manager and the present value of profits is $J_{01}(y)$. Next we know that other firms promote their workers at $\bar{x}$, so all managers hired in the market have experience $y = \bar{x}$. Then $J_{11}^S(\bar{x}_i, \bar{x})$ is given by:

$$J_{11}^S(\bar{x}_i,\bar{x}) = \frac{\pi_1(\bar{x}_i) + \Delta + \pi_2(\bar{x}) + \rho J_{01}(\bar{x}_i) + \lambda_2 J_{01}(\bar{x})}{r+\rho+\lambda_2}$$

In order to find the two integration constants A and K we use the following two boundary conditions: $J_{10}(\bar{x}_i) = J_{01}(\bar{x}_i)$ and $J_{11}^N(\bar{x}_i,\bar{x}) = J_{11}^S(\bar{x}_i,\bar{x})$. The first condition says that firms are committed to promote the worker upon experience $\bar{x}_i$ if the senior position is open, so the present value of the firm changes from $J_{10}(\bar{x}_i)$ to $J_{01}(\bar{x}_i)$. The second condition says that workers with experience $\bar{x}_i$ stop accumulating experience and start searching for alternative jobs at $\bar{x}_i$ if the senior position is filled, so the present value of the firm is changing from $J_{11}^N(\bar{x}_i, \bar{x})$ to $J_{11}^S(\bar{x}_i, \bar{x})$.

The first boundary condition $J_{10}(\bar{x}_i) = J_{01}(\bar{x}_i)$ can be written as:

$$\begin{aligned}
J_{10}(\bar{x}_i) &= \frac{d_1(1-\beta)-s}{r} + q_2\frac{\pi_2(\bar{x})+\Delta+s}{r(r+\rho+q_2)} + Ae^{r\bar{x}_i} + \frac{c_1(1-\beta)e^{\gamma\bar{x}_i}}{r-\gamma} - \frac{q_2Ke^{(r+\rho+q_2)\bar{x}_i}}{\rho+q_2} \\
&= \frac{\pi_2(\bar{x}_i)-s+q_1J_{11}^N(0,\bar{x}_i)}{r+\rho+q_1} = J_{01}(\bar{x}_i)
\end{aligned}$$

The second boundary condition $J_{11}^N(\bar{x}_i, \bar{x}) = J_{11}^S(\bar{x}_i, \bar{x})$ becomes:

$$\begin{aligned}
J_{11}^N(\bar{x}_i, \bar{x}) &= \frac{(\pi_2(\bar{x})+\Delta+s)(r+q_2)}{r(r+\rho+q_2)} + \frac{\rho Ke^{(r+\rho+q_2)\bar{x}_i}}{\rho+q_2} + \frac{d_1(1-\beta)-s}{r} + Ae^{r\bar{x}_i} \\
&+ \frac{c_1(1-\beta)e^{\gamma\bar{x}_i}}{r-\gamma} = \frac{\pi_1(\bar{x}_i)+\Delta+\pi_2(\bar{x})}{r+\rho+\lambda_2} + \frac{\rho(\pi_2(\bar{x}_i)-s+q_1J_{11}^N(0,\bar{x}_i))}{(r+\rho+\lambda_2)(r+\rho+q_1)} \\
&+ \frac{\lambda_2(\pi_2(\bar{x})-s+q_1J_{11}^N(0,\bar{x}))}{(r+\rho+\lambda_2)(r+\rho+q_1)} = J_{11}^S(\bar{x}_i, \bar{x})
\end{aligned}$$

Note that one term which is still unknown in both boundary conditions is $J_{11}^N(0, \bar{x}_i)$. We derive this term in Appendix A. Solving these two boundary conditions for A and K we can see that both variables depend on the individual decision of firm i and on the behaviour of other firms $\bar{x}$, that is $A(\bar{x}_i, \bar{x})$ and $K(\bar{x}_i, \bar{x})$.

Based on this analysis we can now write the firm's optimization problem (2.8) as

$$\bar{x}_i^*(\bar{x}) = \arg\max_{\bar{x}_i \geq 0}[q_1J_{10}(0|\{\bar{x}, A(\bar{x}_i, \bar{x}), K(\bar{x}_i, \bar{x})\}) + q_2J_{01}(\bar{x}|\{\bar{x}, A(\bar{x}_i, \bar{x}), K(\bar{x}_i, \bar{x})\})],$$

where we show explicitly the arguments of functions $J_{10}(0)$ and $J_{01}(\bar{x})$. The solution of this maximization problem gives the optimal response function $\bar{x}_i(\bar{x})$ of firm i. Since firms are homogeneous with respect to their profit functions, they all have identical optimal response functions. In light of this in what follows we restrict our attention to symmetric Nash equilibria and impose the equilibrium condition $\bar{x}_i^*(\bar{x}) = \bar{x}$ to find the equilibrium promotion time $\bar{x}$.

2.3.2 Partial and general equilibrium

The complexity of the expressions derived for J_{10} and J_{01} makes an analytical characterization of the best response function and the resulting equilibrium infeasible, even if we consider a partial equilibrium with fixed transition rates. Therefore, we illustrate the main properties of the best response function and the equilibrium by extending the calibration of our model developed in Section 2.2.3 (Table 2.1) and carrying out a numerical analysis. First, we consider a partial equilibrium framework with fixed transition rates $\{q_1, q_2, \lambda_1, \lambda_2\}$, with the corresponding values from table 2.1. We choose the annual discount rate equal to 4%, so that $r = 0.01$. We also take a standard value of the bargaining power $\beta = 0.5$ following

Pissarides and Petrongolo (2001) and Pissarides (2009). The flow cost of an open vacancy is set low ($s = 0.1$), as it is not in the focus of our analysis. Further, parameters $d_2 < d_1$ and $c_2 > c_1$ are calibrated so that $\bar{x} = 45$, corresponding to a promotion time of 11.25 years, is an equilibrium outcome of the overall model. Even though it is an endogenous variable in the complete model, we keep it fixed in this section and analyse the optimal response of a single firm i. We start with a benchmark value $\Delta = 0$ and postpone the analysis of production complementarities to the next section.

We set the rate of return to tenure at 1.2% per year, which yields $\gamma = 0.003$ on the quarterly basis. According to Farber (1999) the usual OLS estimate of the return to tenure in the United States is 2% per year with the same employer. Empirical methods generally separate this number into two parts: 1. human capital accumulation within the firm and 2. selection component due to the fact that high ability workers stay longer in their jobs and earn more. Farber (1999) finds that 1.5% of the return to tenure is due to the accumulation of human capital and only 0.5% due to selection. In a more recent study Bingley and Westergaard-Nielsen (2003) report the same 2% return to tenure in Denmark, but the human capital component is estimated only at 0.5% per year. These numbers reveal that our parameter choice—1.2% per year due to human capital accumulation within the firm—is in the middle range of the existing empirical estimates. Moreover, it coincides with the return to tenure estimated by Iftikhar and Zaharieva (2018) for Germany. The second set of parameters is summarized in table 3.1 below:

	Value	Interpretation		Value	Interpretation
r	0.010	Quarterly discount rate	γ	0.003	Quarterly return to tenure
β	0.500	Bargaining power	s	0.100	Flow cost of an open vacancy
c_1	0.500	Slope parameter, level 1	c_2	2.000	Slope parameter, level 2
d_1	0.200	Intercept parameter, level 1	d_2	0.100	Intercept parameter, level 2

Table 2.3: Values of exogenous parameters

Figure 2.4 shows the objective function of firm i – $J_{00}(\bar{x}_i)$ – for a fixed market promotion time $\bar{x} = 45$ and for fixed transition rates $\{q_1, q_2, \lambda_1, \lambda_2\}$ (left panel). We can see that promoting junior workers too early is not optimal for the firm. This is despite the fact that $d_1 + c_1 < d_2 + c_2$, which means that the flow profit of the firm is higher in the senior position even if the worker doesn't possess any managerial experience and $x = 0$. The reason is that firms are forward-looking and anticipate a larger gain from promotion once the worker accumulated some managerial experience. At the same time waiting too long is also suboptimal for the firm because the foregone profit is increasing. This is the indirect cost of delayed promotions. In addition, there is the direct flow cost of an open vacancy in the senior position s. As can be clearly seen for our considered parameter values the optimal promotion time is $\bar{x}_i^*(45) = 45$.

The right panel of figure 2.4 shows the optimal response function $\bar{x}_i^*(\bar{x})$ for different values of the market promotion time $\bar{x}$ and fixed transition rates (black solid curve). We can see that firm i has strong incentives to delay promotions if other firms in the market promote their junior workers later. Higher $\bar{x}$ implies that managers applying externally are more experienced, so the quality of the candidate pool in the managerial market is better. In this

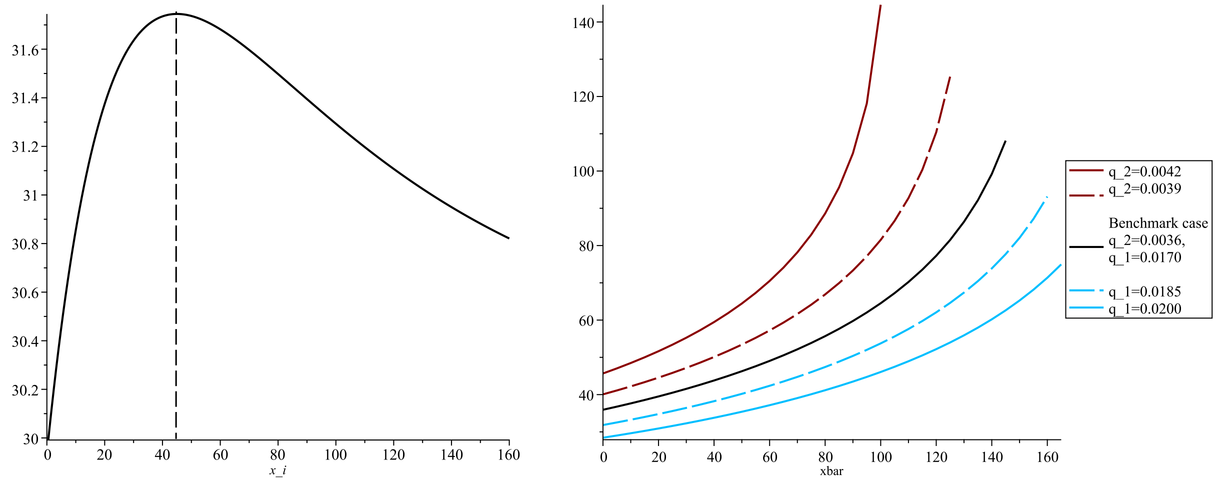


Figure 2.4: Left panel: Objective function of firm i and the optimal choice $\bar{x}_i^*(\bar{x})$ for a fixed market promotion cutoff $\bar{x} = 45$ and fixed transition rates. Right panel: Optimal response function $\bar{x}_i^*(\bar{x})$ for different values of $\bar{x}$, comparative statics with respect to the job-filling rates q_1 and q_2

situation it is optimal for firm i to wait longer because the marginal gain from waiting is increasing with $\bar{x}$ due to the better quality of external candidates. Hence, we obtain that there is strategic complementarity between the promotion times of the different firms in the market.

Further, we consider the effect of increasing the job-filling rate q_1 keeping fixed all other transition rates. So it becomes easier for firms to fill their junior positions. The right panel of figure 2.4 shows that the optimal response curve $\bar{x}_i^*(\bar{x})$ is shifting downwards for all $\bar{x}$. Note that s/q_1 is the average cost of an open junior position because s is the cost per unit time and $1/q_1$ is the average duration of the vacancy. Higher q_1 lowers the cost of open junior positions, so it is optimal for the firm to promote its junior worker earlier. The opposite is true when we increase q_2, so the optimal response curve $\bar{x}_i^*(\bar{x})$ is shifting upwards for all $\bar{x}$. In this case open senior positions become cheaper because s/q_2 is decreasing, so firm i finds it optimal to delay promotions. This shows that the two positions are substitutes from the perspective of the firm.

We already know that $\bar{x}_i^* = \bar{x}^{pe} = 45$ for all firms i is a symmetric partial equilibrium of the model for the given transition rates (values from table 2.1). But is it a unique partial equilibrium? Figure 2.5 shows that in addition to the low equilibrium $\bar{x}_l^{pe} = 45$ there also exists a second partial equilibrium with $\bar{x}_h^{pe} = 157.6$ for these transition rates. Both equilibria are illustrated on the right panel of figure 2.5. In light of the strategic complementarity between the optimal promotion times of the firms it is not surprising that multiple equilibria exist in our model. However, as can be clearly seen in right panel of figure 2.5 only the low equilibrium is strategically stable. Any best response dynamics initialized with a market promotion level $\bar{x} \in [0, \bar{x}_h^{pe}]$ converges to the lower equilibrium $\bar{x}_l^{pe} = 45$.

In Section 2.2.3 we have shown that if all firms use a promotion threshold of $\bar{x} = 45$, then the transition rates under the stationary distribution are given by $\{q_1 = 0.0171, q_2 = 0.0036, \lambda_1 = 0.0145, \lambda_2 = 0.0146\}$ (see Table 2.1). Since these are exactly the transition rates

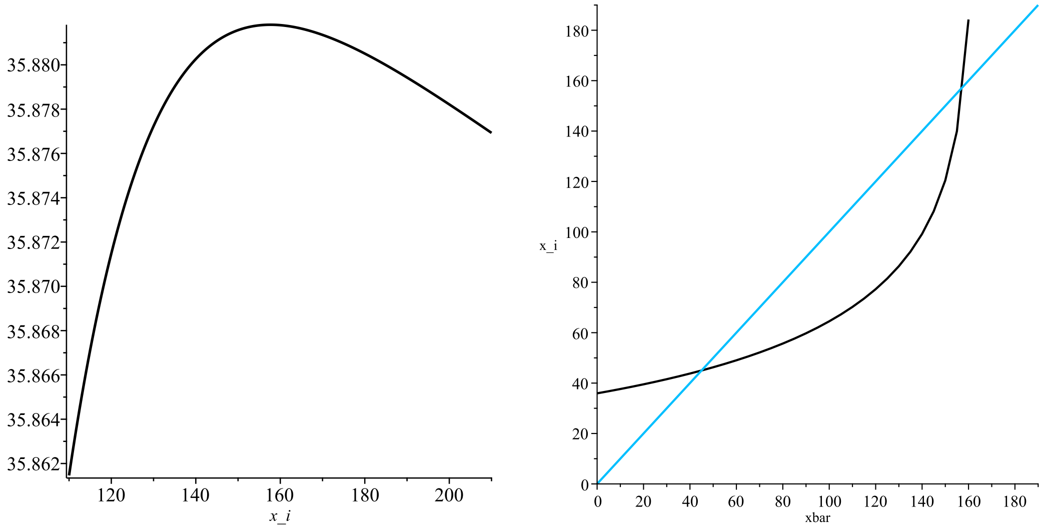


Figure 2.5: Left panel: Objective function of firm i for $\bar{x} = 157.6$. Right panel: Optimal response curve $\bar{x}_i^*(\bar{x})$ exhibiting the two partial equilibria $\bar{x}_l^{pe} = 45$ and $\bar{x}_h^{pe} = 157.6$ for fixed transition rates from table 2.1

under which we have carried out the partial equilibrium analysis above, it follows directly that $\bar{x}_i^* = \bar{x}_l^{pe} = 45, i \in [0, 1]$ is also a general equilibrium of the model. Similarly to the partial equilibrium setting, also with endogenous transition rates a second equilibrium with a very high promotion threshold exists, which however is unstable. Hence in what follows we focus on the lower equilibrium and in the following section examine how the equilibrium promotion threshold changes in response to a variation of key parameters in the model.

2.3.3 Comparative statics: partial and general equilibrium effects

Based on the benchmark numerical example developed in the previous section we now address two key questions of our study: (1) how promotion chances of junior workers are affected if there exist production complementarities and synergies from the team work and (2) what is the link between the optimal promotion time and the skill level of the worker?

In order to address the first question we gradually increase the synergy parameter Δ, which was fixed at 0 in the benchmark case. This is illustrated on the left panel of figure 2.6. If the synergy parameter is increasing from 0 to 0.6 the promotion cutoff $\bar{x}^{ge}$ in the general equilibrium is decreasing from 45 down to 43.7. Stronger complementarities in the production process create stronger incentives for firms to employ a full team of two employees rather than having open vacancies. In our setting the job-filling rate in the junior market $q_1 = 0.0171$ is substantially higher than the job-filling rate in the senior market $q_2 = 0.0036$ which means that hiring junior workers is easier than senior managers. In this situation firms prefer earlier promotions of junior employees in the hope that the junior position will be filled faster than the senior position and the firm can gain additional profits from the team production process. Note that this gain comes at the expense of accepting less experienced senior managers.

Further, we decompose this effect into three parts. We write the individually optimal promotion threshold $\bar{x}_i^*(\bar{x}, \zeta, \Delta)$ as a function of the market promotion level $\bar{x}$ as well as the vector of transition rates ζ and the synergy parameter Δ. Furthermore, $\bar{x}^{pe}(\zeta, \Delta)$ denotes the

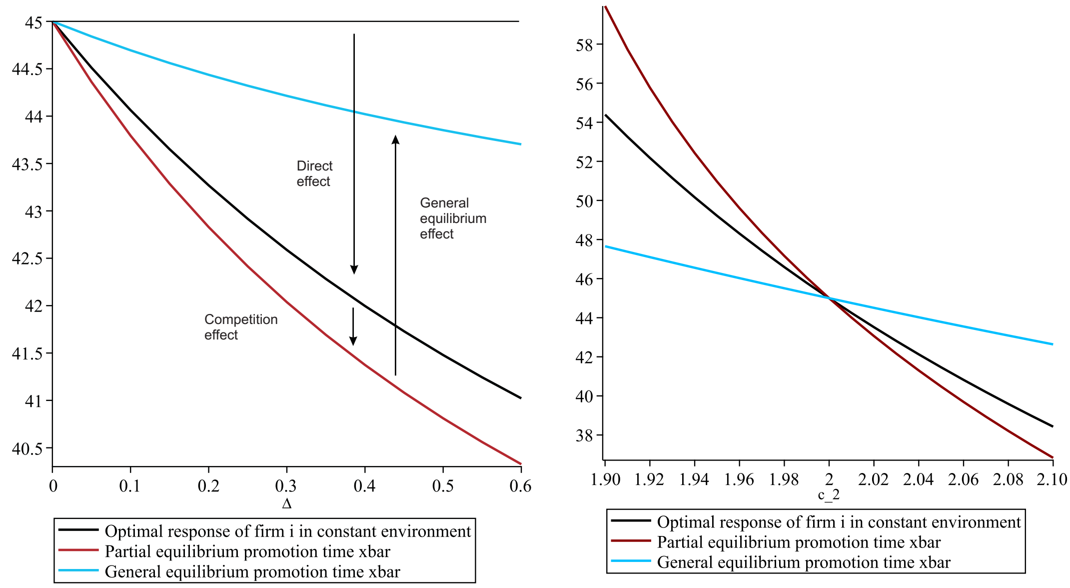


Figure 2.6: Left panel: Equilibrium promotion time $\bar{x}_i(.)$ as a function of the synergy parameter Δ. Right panel: Equilibrium promotion time $\bar{x}_i(.)$ as a function of the skill parameter c_2.

(partial) equilibrium market cutoff under transitions rates ζ and ζ^{Δ} the general equilibrium transition rates for the synergy parameter Δ. The general equilibrium cutoff under synergy Δ is then denoted as $\bar{x}^{ge}(\Delta) := \bar{x}^{pe}(\zeta^{\Delta}, \Delta)$. Hence $\bar{x}_i^*(\bar{x}^{pe}(\zeta^0, 0), \zeta^0, 0) = \bar{x}^{pe}(\zeta^0, 0) = \bar{x}^{ge}(0) = 45$. Using this notation we obtain the following decomposition of the effect of a change in Δ:

$$\begin{aligned}
\bar{x}^{ge}(0) - \bar{x}^{ge}(\Delta) &= \bar{x}^{pe}(\zeta^0, 0) - \bar{x}^{pe}(\zeta^{\Delta}, \Delta) = \bar{x}_i^*(\bar{x}^{pe}(\zeta^0, 0), \zeta, 0) - \bar{x}_i^*(\bar{x}^{pe}(\zeta^{\Delta}, \Delta), \zeta^{\Delta}, \Delta) \\
&= \underbrace{[\bar{x}_i^*(\bar{x}^{pe}(\zeta^0, 0), \zeta^0, 0) - \bar{x}_i^*(\bar{x}^{pe}(\zeta^0, 0), \zeta^0, \Delta)]}_{\text{Direct effect}} \\
&+ \underbrace{[\bar{x}_i^*(\bar{x}^{pe}(\zeta^0, 0), \zeta^0, \Delta) - \bar{x}_i^*(\bar{x}^{pe}(\zeta^0, \Delta), \zeta^0, \Delta)]}_{\text{Competition effect}} \\
&+ \underbrace{[\bar{x}_i^*(\bar{x}^{pe}(\zeta^0, \Delta), \zeta^0, \Delta) - \bar{x}_i^*(\bar{x}^{pe}(\zeta^{\Delta}, \Delta), \zeta^{\Delta}, \Delta)]}_{\text{General equilibrium effect}}
\end{aligned}$$

First, figure 2.6 (left panel) shows the *direct effect*, this is a change in the optimal promotion time of firm i as a function of Δ in a setting with constant environment. As we can see from the figure, the firm has very strong incentives to promote earlier. If the synergy parameter is increasing from 0 to 0.6 the optimal promotion cutoff of firm i is decreasing from 45 down to 41 (black curve). So the direct effect for $\Delta = 0.6$ is equal to $4 = 45 - 41$. Second, we allow for changes in the behaviour of competing firms $\bar{x}^{pe}(\zeta^0, \Delta)$ but keep the set of transition rates ζ^0 fixed. This is the *competition effect*. We already know from figure 2.4 that earlier promotions by the competitors lead to earlier promotions of firm i. This is illustrated by the red curve on figure 2.6. If the synergy parameter is increasing from 0 to 0.6 and the firm takes earlier promotions of competitors into account the optimal promotion cutoff is decreasing even stronger from 41 down to 40.3, so the competition effect is equal to $0.7 = 41 - 40.3$. It makes promotions more sensitive to the production complementarity Δ. The sum of these two effects would be observed in a partial equilibrium setting, in which the transition rates are kept constant. Third, we analyse the *general equilibrium effect* and allow for the endogenous changes in the transition rates. From figure 2.3 we already know that if all firms set earlier promotion times then q_1 is decreasing and q_2 is increasing. Intuitively, this means that earlier promotions make it easier for firms to hire senior managers but hiring junior workers becomes more difficult. This general equilibrium effect mitigates the incentives of firm i to promote earlier and makes promotions less sensitive to the production complementarity Δ. The general equilibrium effect is illustrated by the blue curve and is equal to $-3.4 = 40.3 - 43.7$. Based on this decomposition we can conclude that the direct effect and the general equilibrium effect are quantitatively larger than the competition effect in our setting.

Next we turn to the effect of education. We proxy this effect by changes in the parameter c_2. The intuition behind this proxy is that more educated workers with higher skills will be more productive in senior positions than low skill workers even if they have similar practical experience. This is due to the methodological competence, broader knowledge and problem-solving skills associated with higher education. Following this logic we assume that higher c_2 corresponds to the labour market with more educated workers but there are no productivity differences in junior jobs (c_1). The right panel of figure 2.6 shows changes in the promotion times where $c_2 = 2$ is the benchmark case in the middle of the figure. We can see that higher education generally leads to earlier promotions. The effects are reversed when the labour force is less qualified: if c_2 is decreasing from 2 to 1.95, firm i responds by setting the equilibrium promotion time equal to 49.2 in a constant environment. If all competitors follow the same strategy and set longer promotion times the partial equilibrium is achieved at $\bar{x}_i^*(\bar{x}^{pe}) = \bar{x}^{pe} = 51$. The decomposition reveals again that the general equilibrium effect dampens the direct effect of the parameter change on the optimal promotion time and makes it less sensitive to the education parameter. We obtain for $c_2 = 1.95$ a general equilibrium cutoff of $\bar{x}^{ge} = 46.3$. Even though this result provides first evidence of the positive link between education and the speed of promotions in our model, it is only a comparative statics result and it is not clear if it will be confirmed in a setting where two skill types are mixed in the same labour market. We continue this analysis in the next section.

2.4 Two skill levels

2.4.1 Optimal promotion with two skill levels

In this section we extend the model to the setting with two skill groups and analyse the spillover effects that the presence of one skill group imposes on the other group. To keep the model tractable we refrain from the synergy effect and set $\Delta = 0$ throughout this extension. Let c_2^L be the education parameter of low skill workers. Once employed in the senior job they generate the flow profit $\pi_2^L(x) = (d_2 + c_2^L e^{\gamma x})(1-\beta)$ for the firm. Further, $c_2^H > c_2^L$ denotes the education parameter of high skill workers, so they generate the flow profit $\pi_2^H(x) = (d_2 + c_2^H e^{\gamma x})(1-\beta)$. We assume that the difference between c_2^L and c_2^H is sufficiently small so that firms do not reject low skill applicants. Moreover, c_1 remains the same for both worker groups indicating that high and low skill workers are equally productive when performing junior level jobs. It is the difference in managerial abilities that we want to capture in this extension. Let a denote the fraction of low skill workers in the population. Variables $\bar{x}_i^L$ and $\bar{x}_i^H$ denote the promotion times set by firm i for each skill group respectively. As before this decision is made upon the entry and there is full commitment on the side of the firm.

Further, let α_1 denote the fraction of low skill applicants in the junior market and α_2 be the fraction of low skill applicants in the senior market. The entering firm solves the optimization problem

$$\begin{aligned}\{\bar{x}_i^{L*}, \bar{x}_i^{H*}\} &= \arg\max_{\bar{x}_i^L, \bar{x}_i^H} q_1[\alpha_1 J_{L0}(0|\{\bar{x}_i^L, \bar{x}_i^H, \bar{x}_L, \bar{x}_H\}) + (1-\alpha_1) J_{H0}(0|\{\bar{x}_i^L, \bar{x}_i^H, \bar{x}_L, \bar{x}_H\})] \\ &+ q_2[\alpha_2 J_{0L}(\bar{x}_L|\{\bar{x}_i^L, \bar{x}_i^H, \bar{x}_L, \bar{x}_H\}) + (1-\alpha_2) J_{0H}(\bar{x}_H|\{\bar{x}_i^L, \bar{x}_i^H, \bar{x}_L, \bar{x}_H\})] \quad (2.11)\end{aligned}$$

where $\{\bar{x}_i^{L*}, \bar{x}_i^{H*}\}$ denote the optimal choices, $\bar{x}_j$ is the market experience level of applicants in the managerial market with a skill level $j = L, H$, J_{j0} is a firm with an inexperienced worker of skill $j = L, H$ and an open senior vacancy while J_{0f} is a firm with a senior worker of skill $f = L, H$ and a junior vacancy. The corresponding Bellman equations and the solution procedure for the two skill level case are shown in Appendix A. As before we consider symmetric equilibria, so that $\bar{x}_i^{L*}(\bar{x}_L, \bar{x}_H) = \bar{x}_L$ and $\bar{x}_i^{H*}(\bar{x}_L, \bar{x}_H) = \bar{x}_H$ which guarantee that firms do not have incentives to deviate.

2.4.2 Partial equilibrium

To illustrate the implications of skill heterogeneity for our results we first consider again a partial equilibrium framework with fixed transition rates from table 2.1. We set $c_2^L = 1.95$ and $c_2^H = 2.05$, so that high skill workers are more productive than low skill workers in senior jobs. From our analysis in section 2.3.3 we know that for these parameters and the transition rates emerging from our default setting (see Table 2.1), in the absence of high-skill workers (i.e. $\alpha_1 = \alpha_2 = 1$), the partial equilibrium promotion threshold for low skill workers is $\bar{x}_L^{pe} = 51$. We start with a situation when $\alpha_1 = \alpha_2 = 0.7$, which implies that 70% of workers in the market are low skilled. For comparison, Albrecht and Vroman (2002) use a close value of 67%, while in the model by Stupnytska and Zaharieva (2017) the fraction of low skill workers is taken at 60%. The left panel of figure 2.7 shows the objective function of the firm for the default transition rates. We find that the partial equilibrium is achieved for $\bar{x}_L^{pe} = 59.7$ and $\bar{x}_H^{pe} = 28.4$, which implies that high skill workers are promoted much earlier than low skill workers. Intuitively, a firm with a low skill worker in a junior position has a strong incentive to delay the promotion of this worker because this delay increases the chance for the firm to hire a high skill worker from the market for the senior position. Quite on the contrary, if the junior worker has high skills then it is profitable for the firm to exploit these skills in the senior position rather than hiring from the market which comes at the risk of putting a low skill worker into the senior position.

In the right panel of figure 2.7 we illustrate the nature of the partial equilibrium in the model with two worker groups. First, we find the optimal promotion cutoffs for high skill workers $\bar{x}_i^{H*}(\bar{x}_H, \bar{x}_i^L = \bar{x}_L) = \bar{x}_H$ for any given promotion cutoff of low skill workers $\bar{x}_i^L = \bar{x}_L$. If we exogenously decrease $\bar{x}_i^L = \bar{x}_L$ we can see that firms respond by later promotions of high skill workers (black dashed curve). Considering the left panel of figure 2.7 we can see that this

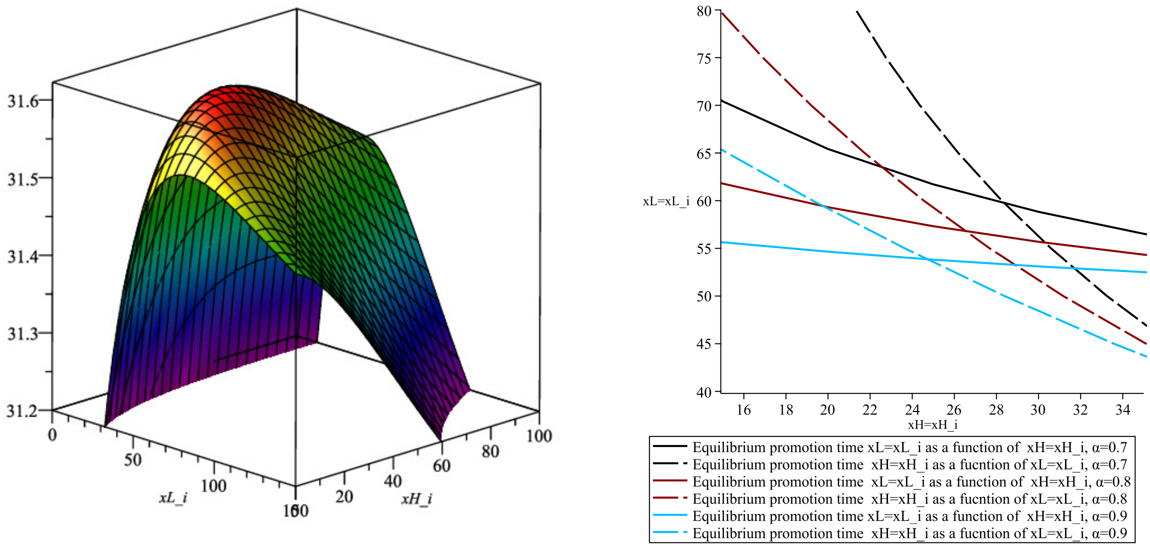


Figure 2.7: Left panel: Two-dimensional objective function of the firm in the space $\{\bar{x}_i^L, \bar{x}_i^H\}$ for $\alpha_1 = \alpha_2 = 0.7$ and market promotion cutoffs of $\bar{x}_L = 59.7, \bar{x}_H = 28.4$. Right panel: Sequence of partial equilibria for different values of $\alpha = \alpha_1 = \alpha_2$.

negative dependence of the optimal threshold for x_i^L respectively x_i^H from the value of the other threshold also arises if we keep the thresholds of all other firms constant. Intuitively, faster promotion of own low-skill workers makes it more likely that the firm's senior position is filled at any point in time. A firm never wants to provide experience evaluation to high-skill workers and make them eligible for promotion at a point in time when its senior position is filled, due to the higher risk of losing these workers. Hence the increase of the probability of a filled senior position induced by a decrease of $\bar{x}_L$ reduces the firm's incentive to set a low promotion cutoff for high-skill workers. Even though there are also other side effects, the numerical evidence shown in figure 2.7 suggests that the described mechanism dominates giving rise to strategic substitutability between the two promotion thresholds. A substitution effect also applies if we consider the impact of an exogenous decrease of $\bar{x}_i^H = \bar{x}_H$ on the optimal promotion threshold for low skilled, although the effect is much smaller in this case (black solid curve). The partial equilibrium obtains at the intersection of the two curves, since no firm has incentives to deviate.

If we increase $\alpha_1 = \alpha_2$ to 0.8 we find the equilibrium promotion cutoffs $\bar{x}_L^{pe} = 56.8, \bar{x}_H^{pe} = 26.5$, thus both types of workers are promoted earlier (red curves). This trend is continued further when we increase $\alpha_1 = \alpha_2$ to 0.9. Here the equilibrium promotion cutoffs are $\bar{x}_L^{pe} = 53.9$ and $\bar{x}_H^{pe} = 24.7$ (blue curves). In the limiting case when $\alpha_1 = \alpha_2 = 1$ we arrive at the economy with only low skill workers with productivity level $c_2^L = 1.95$ and the corresponding equilibrium threshold is $\bar{x}_L^{pe} = 51$ (see section 2.3.3). Hence, we can conclude that a lower average skill level in the labour force (due to the larger share of low skill workers) is associated with earlier promotions. In the next section we check if this result will persist after the general equilibrium adjustment in the transition rates.

2.4.3 General equilibrium

Finding a general equilibrium for the model with heterogeneous skills is substantially more complex compared to the benchmark case with homogeneous workers treated in Section 2.3.2. First, the number of states in which a single firm can be found is more than doubled in a setting with heterogeneous workers. Combined with the fact that the shares of high and low skill workers in the pool of applicants are endogenous, this would triple the number of steady-state equations describing firms' transitions in a heterogeneous setting. Second, the best response function, for which a fixed-point has to be found is two dimensional. Third, the determination of the best response $(\bar{x}_i^{L*}, \bar{x}_i^{H*})$ to a pair of market promotion values $(\bar{x}_L, \bar{x}_H)$ in a general equilibrium setting requires to first calculate the transition rates and the average fraction of each skill group in the pools of applicants (α_1 and α_2) under the stationary distribution implied by $(\bar{x}_L, \bar{x}_H)$ and then to determine the individually optimal promotion threshold based on the analysis presented in Section 2.4.1. All of these steps are computationally intensive, so due to the high complexity of the model we follow a different path for the analysis of the general equilibrium and rely on a simulation of the model which captures explicitly the (stochastic) transition of each worker between simple jobs, junior and senior positions. Another advantage of this approach is a possibility of performing several extensions, such as a case of pyramidal firms, which is a straightforward extension of the simulation but would require a completely different and hardly tractable analytical model.

Simulation analysis of the model

We implement a simulation model in which every firm and worker is a separate agent and the stochastic matching between firms and workers as well as the random retirement of workers by firms is explicitly modelled. For every profile of the firms' promotion thresholds the resulting long-run transition rates as well as the discounted expected present values of the different firms upon entering the market are determined based on a sufficiently large ensemble of simulation runs[8]. In the simulation of the model we consider a firm population N_F and a worker population N_W with $|N_F| = n_F, |N_W| = n_W$. The sizes of both populations stay constant over time since a new worker is added to the population only when a member of the population retires and a new firm is added only if an existing firm has become empty and leaves the market. Each worker $j \in N_W$ is characterized by her skill level (low/high) and each firm $i \in N_F$ by its promotion cutoff(s) $(\bar{x}_i^L, \bar{x}_i^H)$. Any worker or firm entering the population inherits this characteristic from the agent it replaces. The scenarios with a single skill group are treated as a special case of the general setup in which all workers have low skills. The simulation evolves in discrete time steps. Initially, at $t = 0$ all firms have no employees (type d_{00}) and all workers are in simple jobs. Afterwards, in every period $t = 1, ..T$ the following steps are executed

1. Every firm $i \in N_F$ with a vacant senior position and a junior worker with skill $s \in \{L, H\}$ and experience $x \geq \bar{x}_i^s$ promotes this worker to the senior position.
2. All firms $i \in N_F$ with open junior or senior positions post these vacancies.

[8] The simulation is done in RepastJ, a software for agent-based modelling.

$a = 1;\ \bar{x} = 45$							
	Simulation	SD	Numerical		Simulation	SD	Numerical
λ_1	0.0145	0.0002	0.0145	Internally promoted	0.0575	0.0007	0.0576
λ_2	0.0146	0.0006	0.0146	Job-to-job movers	0.0126	0.0004	0.0124
q_1	0.0171	0.0002	0.0171	d_{00}	0.1256	0.0021	0.1273
q_2	0.0036	0.0002	0.0036	d_{01}	0.1772	0.0021	0.1760
e_0	0.3545	0.0041	0.3577	d_{10}	0.1270	0.0021	0.1270
e_1	0.2985	0.0021	0.2966	d_{11}^S	0.0633	0.0018	0.0633
e_2	0.3487	0.0030	0.3456	d_{11}^N	0.1082	0.0014	0.1063

Table 2.4: Comparison between simulation and numerical results, SD: standard deviation. Simulation values are obtained by taking an average over the last 1000 iterations of each run, where one run consists of 1500 iterations. Averages over 100 simulation runs are shown.

3. Every worker in a simple job sends with probability z an application to a random junior vacancy.

4. Every searching junior worker (i.e. every junior worker whose experience is above its employer's promotion threshold) sends with probability z an application to a random senior vacancy.

5. Every firm $i \in N_F$ for each of its vacancies randomly (with equal probabilities) selects one of its applicants and hires this worker. If the firm has not received any applications then the vacancy is not filled in period t.

6. The experience of all junior workers is updated.

7. Every senior worker retires with probability ρ.

8. All statistics (employed, unemployed, filled/unfilled vacancies, job finding rates, job filling rates) for period t are recorded.

The job-finding rate at the first level (λ_1) is defined as the number of agents in simple jobs who found a junior position in the current period as a fraction of the total number of agents in simple jobs in the beginning of the period. Similarly, the job-finding rate at the second level (λ_2) is the fraction of junior workers who found a senior position in another firm in the current period relative to the total number of searching junior workers in the beginning of the period. On the other hand, the job-filling rate of junior positions (q_1) is the number of filled junior vacancies during the current period as a fraction of total number of junior vacancies in the beginning of the period. Analogously, the job-filling rate of senior positions (q_2) is the fraction of filled senior vacancies in the current period (excluding promotions) relative to the total number of senior vacancies in the beginning of the period. Further, the promotion rate is calculated as the fraction of promoted workers in the current period relative to the total number of employed junior workers in the beginning of the period. On the other hand, the job-to-job transition rate is defined as the newly hired managers (excluding promotions) as a fraction of the total number of junior workers. And finally, α_1 and α_2 are the fractions of low skill applicants in the junior and senior market, respectively.

In our simulation we consider populations of size $n_F = 600, n_W = 1000$ and for a given profile of promotion thresholds $\{(\bar{x}_i^L, \bar{x}_i^H)\}_{i \in N_F}$, 100 simulation runs are done where each run

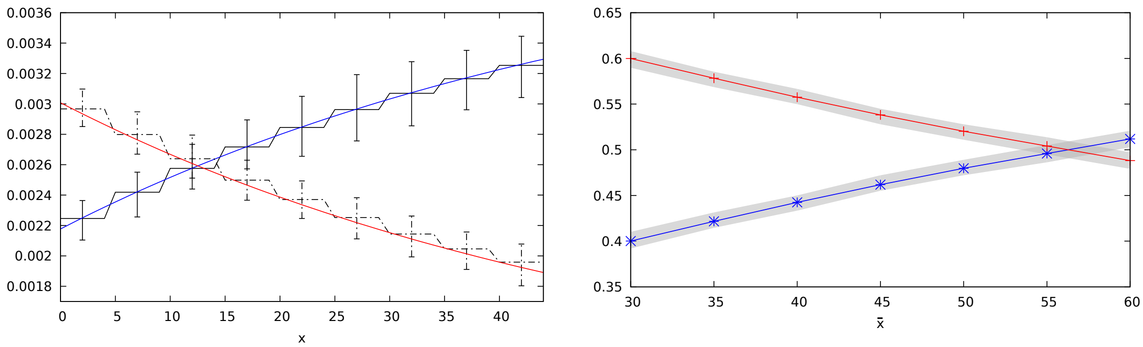


Figure 2.8: Left panel: Number of d_{10} firms as a function of the junior worker's experience (solid line). Number of d_{11}^N firms as a function of the junior worker's experience (dashed line). The vertical bars represent the minimum and maximum value recorded during the 100 simulation runs where each value is an average over the last 500 iterations of each run and one run consists of 1000 iterations. Right panel: Fraction of workers in junior positions (blue line) and senior positions (red line) for different market promotion cutoffs. The confidence bands display the minimal and maximal average recorded.

consists of 1500 iterations. We collect the average values of the job-finding rates (λ_1, λ_2), the vacancy-filling rates (q_1, q_2), the distribution of firms $(d_{00}, d_{10}, d_{01}, d_{11}^N, d_{11}^S)$ and workers (e_0, e_1, e_2), the fractions of low skill applicants in the two markets (α_1, α_2) and the number of exiting firms per period (n) over the last 1000 periods of each run. The first 500 periods are disregarded in order to allow the system to reach its stationary distribution.

In order to validate this approach and to show that it replicates very well the theoretical results for the cases, in which such findings are available, we first consider our benchmark case discussed in Section 2.3.2 with fixed promotion time $\bar{x} = 45$ and $a = 1$, i.e. workers are homogeneous with respect to skills. Table 2.4 displays the results of the simulation analysis and compares them to the numerical results presented in section 2.2.3. It can be seen that the results obtained through the simulations closely match the values obtained through the analytical approach. Additionally, figure 2.8 also demonstrates that the dependence of the rates $d_{10}(x), d_{11}^N(x)$ on the junior worker's experience x, as well as the dependence of the distribution of workers across hierarchical levels on the market threshold $\bar{x}$, as shown in figure 2.2, are exactly reproduced using the simulation approach. Figure 2.9 is a replication of figure 2.3 and shows the fraction of externally (job-to-job movers) and internally promoted workers for different values of $\bar{x}$ as well as well as the firms job filling rates for junior and senior positions for different search intensities of workers. Also in this respect the results obtained by simulation qualitatively and quantitatively are in close accordance with the analytical results.

Determining Firms' Optimal Promotion Cut-offs

If the simulations are used only to determine the transition rates for a given uniform strategy profile, we set $(x_i^L, x_i^H) = (\bar{x}^L, \bar{x}^H)$ for all $i \in N_F$ and collect only the data discussed in the previous subsection. However, in scenarios, in which no analytical characterization of the optimal promotion cutoff of a firm for a given strategy profile of the other firms is available, the simulations can also be used to determine the firm's optimal response.

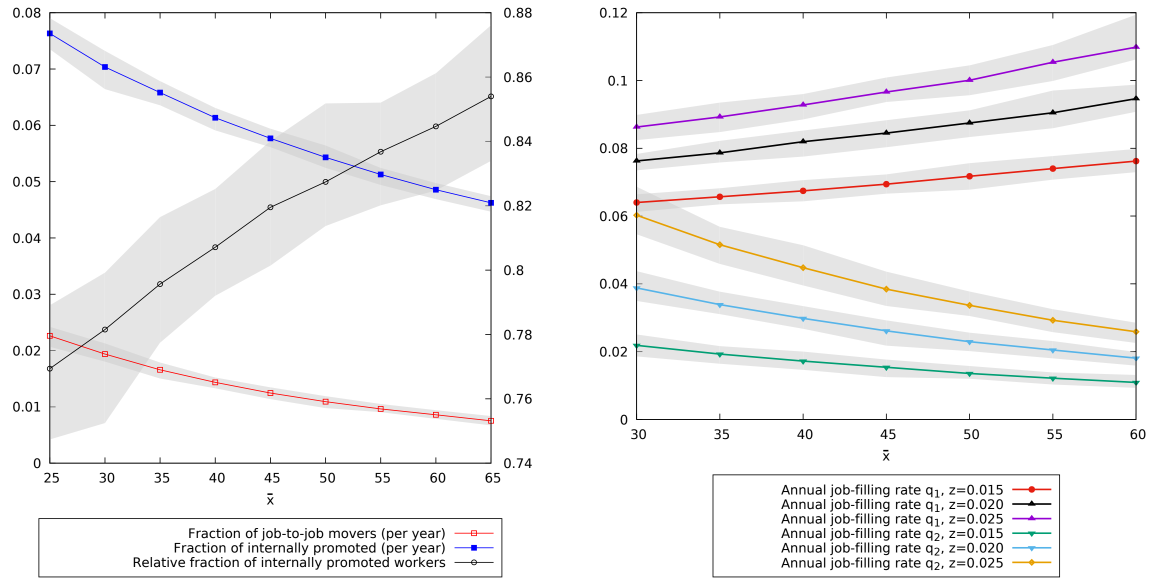


Figure 2.9: Left panel: fraction of externally (job-to-job movers) and internally promoted workers for different values of $\bar{x}$. Right panel: job filling rates for junior and senior positions for different search intensities of workers. The values show an average over 100 simulation runs and the confidence bands display the minimal and maximal average recorded.

In order to find such a best response to given threshold values $(\bar{x}^L, \bar{x}^H)$ of the competitors we first employ the simulation to determine the (long-run) transition rates if all firms employ these thresholds and then, using these rates, calculate the expected discounted sum of profits of a single firm i for all values of (x_i^L, x_i^H) from a finite grid covering the relevant range of x^L and x^H. Using this approach we implicitly assume that the change of the single firm's threshold does not affect the transition rates on the market, which is consistent with the assumption of a continuum of firms underlying the theoretical model. For clarity of exposition we assume in the following description that all workers have the same skill such that the firm strategy is described by a single threshold x_i^L. Details of the extension of our approach to the different model extensions is described in Appendix C.

For the calculation of the expected discounted payoff we assume that τ_1, τ_2, τ_3, τ_4 are random variables such that $\tau_1 \sim Exp(q_1)$, $\tau_2 \sim Exp(q_2)$, $\tau_3 \sim Exp(\lambda_2)$ and $\tau_4 \sim Exp(\rho)$, where q_1, q_2 and λ_2 are the transition rates generated by the simulation and ρ is the retirement rate. Hence, τ_1 represents the waiting time until finding a junior worker, τ_2 is the time until finding a senior worker from the market, τ_3 is the time until the junior worker who is searching for a senior position moves to another firm and τ_4 is the time until the senior worker retires.

We simulate a hypothetical firm from its entry to its exit from the market. Initially, the new d_{00} firm makes the random draws, τ_1 and τ_2. If $\min\{\tau_1, \tau_2\} = \tau_1$, the firm finds a junior worker first and becomes of d_{10} type. Conversely, if $\min\{\tau_1, \tau_2\} = \tau_2$ the firm finds the senior worker first and becomes of d_{01} type. Next, if the firm is in the d_{10} state, it makes a random draw for τ_2 which is compared to the time left until the worker achieves x_i^L, the promotion cutoff of the considered firm. Whichever comes first determines into which state the firm will transition next: d_{11}^N or d_{01}, respectively.

On the other hand, if the firm is of d_{01} type, it either finds a junior worker or the senior

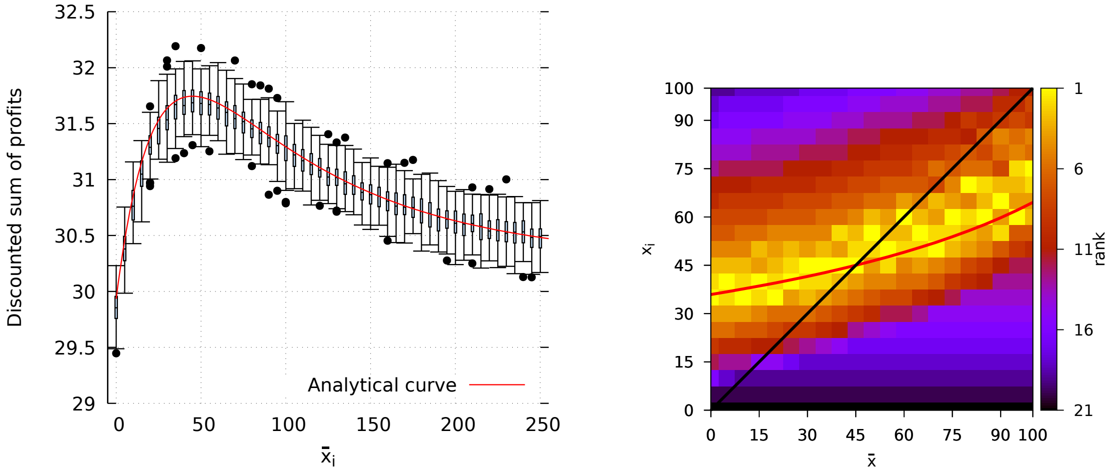


Figure 2.10: Replication of figure 2.4. Left panel: Estimated expected firm profits for $\bar{x} = 45$. Each box plot summarizes 100 profit estimations obtained by simulation for a given $\bar{x}_i$. The red curve is the exact value of the objective function depicted also in figure 2.4. Right panel: Approximated best response function. For each value of the market promotion cutoff $\bar{x}$ the mean of the estimated expected discounted profits for different values of $\bar{x}_i$ are ranked with 1 being the highest.

worker retires in which case the firm exits. To determine which of these two possibilities are realized, random draws for τ_1 and τ_4, are made. If $\min\{\tau_1, \tau_4\} = \tau_1$, the firm finds a junior worker and becomes of d_{11}^N type and if $\min\{\tau_1, \tau_4\} = \tau_4$, the firm exits the labour market. Furthermore, if the firm is in d_{11}^N state, a random draw τ_4 is made which is then compared with the time left until the junior worker achieves x_i^L. If the worker gains the $\bar{x}_i^L$ level of experience first, the firm transitions into d_{11}^S state. Otherwise, the senior worker retires and the firm becomes of d_{10} type. Finally, for a firm in the state d_{11}^S, the random draws τ_3 and τ_4 are compared. If $\min\{\tau_3, \tau_4\} = \tau_3$, the searching junior worker moves to a different firm, whereas if $\min\{\tau_3, \tau_4\} = \tau_4$, the senior worker retires and is immediately replaced by the junior one. In both cases the firm becomes of d_{01} type.

Once the sequence of the considered firm's states from its entry until its exit from the market and the time spent in each state have been determined, the discounted sum of the firm's profits is calculated based on this data. In order to obtain an estimation of the expected firm's profit, the average discounted profit over 40000 instances of this firm is calculated. For each considered value of the threshold x_i^L we calculate 100 estimations of the expected profit in this way. The best response of the firm to $(\bar{x}^L, \bar{x}^H)$ is then determined as the value x_i^L among all thresholds in the considered grid for which the mean of the 100 estimated expected discounted profit values is highest. In figure 2.10 we illustrate the approach by applying it to our benchmark scenario with uniform skills of workers. The left panel of the figures shows how well the expected discounted profit of the firm is approximated using our simulation approach and the right panel reproduces the best response function shown in figure 2.5. The lighter the colour, the higher discounted sum of profits the firm achieves on average by setting the corresponding $\bar{x}_i$ for a given $\bar{x}$. In particular, the right panel of the figure illustrates that the purely simulation-based procedure, which also relies on the simulation-based best response function would arrive at the correct general equilibrium value of $\bar{x} = 45$, since this is where the first diagonal coincides with the highest ranked value of $\bar{x}_i$. Our simulation approach can be used also in settings in which an analytical characterization of this best response is not feasible, which will become particularly relevant in several model extensions considered below.

Equilibrium promotion cutoffs

For the version of the model with two skill levels the analysis in section 2.4.1 allows us to (numerically) determine the symmetric partial equilibrium thresholds $(\bar{x}_L^{pe}(\zeta), \bar{x}_H^{pe}(\zeta))$ for a given vector ζ of transition rates and market thresholds. Therefore, in this section the simulation is used only to determine the long-run transition rates for a given strategy profile. We first set the promotion cutoffs equal to the partial equilibrium values under the given vector of transition rates and fractions of low skill applicants in the two markets, which we denote by ζ^0 (see section 2.4.2). Using the simulation we then determine the actual transition rates and fractions of low skill applicants in the two markets $\zeta^1 = \{\lambda_1, \lambda_2, q_1, q_2, \alpha_1, \alpha_2\}$ under these promotion cutoffs. Inserting ζ^1 into the firm's decision problem (2.11) we then calculate the symmetric partial equilibrium profile $(\bar{x}_L^{pe}(\zeta^1), \bar{x}_H^{pe}(\zeta^1))$ under these rates and adjust the conjecture for the values of $\{\bar{x}_L, \bar{x}_H\}$ in the direction of these new partial equilibrium values. This procedure is repeated till the partial equilibrium values (rounded to the nearest integer) determined under the adjusted transition rates coincide with the conjectured profile under which the rates have been calculated and therefore a general equilibrium profile $(\bar{x}_L^{ge}, \bar{x}_H^{ge})$ has been found[9].

In table 2.5 the general equilibrium thresholds and the corresponding transition rates are displayed for different fractions of low-skill workers in the population. In all scenarios the fraction of low-skill workers among the applicants for junior positions (α_1) are close to their average fraction in the workforce (a), whereas the fraction of low-skilled among the applicants for senior positions (α_2) is significantly smaller: ($\alpha_2 < a$). This effect is due to the slower promotion of low-skill workers compared to their high-skill peers, which makes them under-represented in the market for senior positions. For instance in the case $a = 0.7$, even though 70% of the agents are low skill, only 61.7% or of the applicants to senior positions are also low skill.

Comparing the general equilibrium thresholds with the partial equilibrium values discussed in section 2.4.2 we observe that the promotion thresholds for high-skill workers are hardly affected by general equilibrium effects, whereas the promotion threshold for low-skill worker are significantly lower in general equilibrium compared to the partial equilibrium. For the case of $a = 0.7$ we obtain $\bar{x}_L^{ge}(\zeta^{ge}) = 55$ in general equilibrium compared to a threshold of $\bar{x}_L^{pe}(\zeta^0) = 60$ obtained for the partial equilibrium under the benchmark transition rates and the assumption that both for the junior and the senior positions the fraction of low-skill workers is given by $\alpha_1 = \alpha_2 = a = 0.7$. Intuitively, the reason for this difference is that under the partial equilibrium values $(\bar{x}_L^{pe}, \bar{x}_H^{pe}) = (60/28)$ the firm's actual job filling rate for senior positions on the market q_2 (see Table 2.7 in Appendix B) is lower and that for junior

[9] In Table 2.7 in Appendix B we illustrate the algorithm by displaying all steps needed to find the equilibrium values of $\bar{x}_L$ and $\bar{x}_H$ for $a = 0.7$. Although we do not provide a general convergence proof for our algorithm, we were able to find general equilibrium values for all considered scenarios using this approach.

	$a = 0.9$	$a = 0.8$	$a = 0.7$
Equilibrium Promotion Cut-Offs	$\{\bar{x}_L^{ge}, \bar{x}_H^{ge}\} = \{49, 25\}$	$\{\bar{x}_L^{ge}, \bar{x}_H^{ge}\} = \{52, 27\}$	$\{\bar{x}_L^{ge}, \bar{x}_H^{ge}\} = \{55, 28\}$
Transition Rates: ζ^{ge}	$\alpha_1 = 0.8903; \alpha_2 = 0.8650$ (0.0033); (0.0088) $\lambda_1 = 0.0145; \lambda_2 = 0.0146$ (0.0002); (0.0005) $q_1 = 0.01720; q_2 = 0.00355$ (0.0002); (0.0002)	$\alpha_1 = 0.7813; \alpha_2 = 0.7385$ (0.0043); (0.0121) $\lambda_1 = 0.0145; \lambda_2 = 0.0146$ (0.0002); (0.0005) $q_1 = 0.01717; q_2 = 0.00355$ (0.0002); (0.0001)	$\alpha_1 = 0.6733; \alpha_2 = 0.6169$ (0.0048); (0.0130) $\lambda_1 = 0.0145; \lambda_2 = 0.0145$ (0.0002); (0.0005) $q_1 = 0.01716; q_2 = 0.00357$ (0.0002); (0.0001)
Distribution	$e_0^L = 0.3485; e_0^H = 0.3901$ (0.0045); (0.0130) $e_1^L = 0.3110; e_1^H = 0.2276$ (0.0025); (0.0074) $e_2^L = 0.3415; e_2^H = 0.3832$ (0.0034); (0.0121)	$e_0^L = 0.3443; e_0^H = 0.3873$ (0.0042); (0.0092) $e_1^L = 0.3200; e_1^H = 0.2347$ (0.0024); (0.0049) $e_2^L = 0.3367; e_2^H = 0.3790$ (0.0032); (0.0083)	$e_0^L = 0.3393; e_0^H = 0.3852$ (0.0048); (0.0066) $e_1^L = 0.3293; e_1^H = 0.2392$ (0.0027); (0.0040) $e_2^L = 0.3324; e_2^H = 0.3766$ (0.0040); (0.0062)

Table 2.5: Equilibrium promotion cutoffs with two skill groups. Transition rates and distribution values for each run are obtained by averaging over the last 1000 iterations, where one run consists of 1500 iterations. The displayed values are averages over 100 simulation runs with standard deviation across runs in parenthesis.

positions q_1 is higher compared to the value assumed in the partial equilibrium (see Table 2.4). As we know from figure 2.4, this induces the firm to promote earlier, especially the majority group of low-skill workers and as a result $\bar{x}_L$ is lower in general equilibrium than under partial equilibrium.

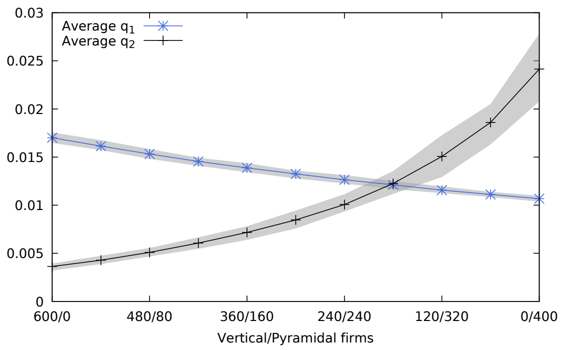
Analyzing the impact of a, we can see that qualitatively, the result that higher share of low skill workers is associated with earlier promotions remains unchanged after endogenizing the transition rates. Recall that in section 2.3.3 we have shown that lower quality of the homogeneous labour force is associated with later promotions. How can these two findings be reconciled? The key difference between these settings is that under worker heterogeneity an increase of the fraction of low skill workers reduces the expected skill of a worker hired from the market *relative* to the skill of the junior worker under consideration for internal promotion, regardless of the actual type of the junior worker. So the internal candidate becomes better in relative terms compared to the average external candidate. This induces earlier internal promotions. With homogeneous workers by definition the skill of an outside hire is always identical to that of an internal candidate. So when the skill level is falling firms want to compensate for the lower qualification of their internal candidates and let them accumulate more experience by delaying internal promotions. Thus changes in the quality of the labour force can have principally different implications for promotions in the two settings with homogeneous and heterogeneous workers. Taking into account that the firm's senior job filling rate decreases with the fraction of low skill workers we observe that the general equilibrium reinforces the partial equilibrium effect and leads to even earlier promotions of low skill workers. Overall, this discussion highlights that explicitly considering potential heterogeneities in the workforce is essential for understanding the relationship between the (average) skill level in the worker population and the firms' optimal promotion thresholds.

Table 2.5 also displays the distribution of high and low skill workers across hierarchical levels. In equilibrium a larger fraction of high skill workers are in managerial positions. For instance, considering the case in which 70% of the agents are low skill ($a = 0.7$), approximately 61.2% ($= e_2^H/(e_1^H+e_2^H)$) of high skill workers who are employed in professional jobs are on level 2 (61.8% in the case $a = 0.8$ and 62.8% when $a = 0.9$). This follows from the earlier promotion time firms set for high skill workers. As the fraction of low skill workers (a) decreases, the equilibrium promotion cutoffs: $\bar{x}^L$ and $\bar{x}^H$ increase which leads to fewer workers in senior positions (e_2^L and e_2^H) for both skill groups. This result corresponds to the findings from the benchmark model that later promotions increase the fraction of workers employed in junior jobs and decrease the fraction of senior workers.

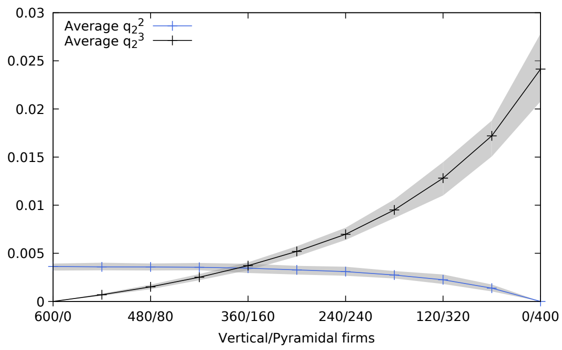
Before moving to the analysis of scenarios with multiple junior workers per firm we like to mention that our finding in this section that high skill workers are promoted faster than low skilled ones, have also been derived in existing models of internal labour markets. For instance, in a context of asymmetric learning, it has been shown that workers with higher ability (Bernhardt (1995)) or more schooling (DeVaro and Waldman (2012)) are promoted earlier. In both models promotions reveal information about workers ability and upon promotion firms offer higher wages as to prevent competitors from hiring the workers. In a context of symmetric learning, Gibbons and Waldman (2006) similarly derive the result that schooling is positively related to promotion probabilities since workers with more education accumulate human capital faster. However, in these frameworks there is no turnover in equilibrium. Integrating promotions and job-to-job transitions we are able to endogenize the rates at which firms meet workers of a specific type, either for their junior or senior vacancies. We show how firm's promotion strategies are then altered by general equilibrium effects. More specifically, the promotion requirement for the majority group of low skill workers responds strongly to endogenizing the market transition rates. Moreover, this allows us to explore how changes in the distribution of worker types affect promotion timing for all skill groups which is a novel testable empirical implication.

2.5 Pyramidal firm structure

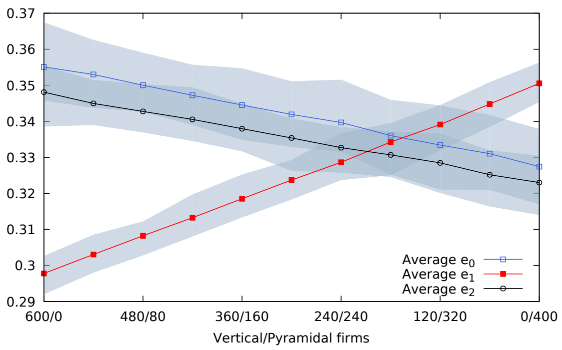
In this section we make a final extension to the model by introducing pyramidal firms with two junior positions and one senior. Here, we follow the empirical evidence that firms are organized as hierarchical pyramids in which the number of positions on each level decreases the higher the hierarchical level (Caliendo et al., 2015). Moreover, empirical studies find that firms of different sizes vary in many aspects concerning workers' careers. For instance, large firms pay higher wages than small firms (Brown and Medoff, 1989; Fox, 2009; Oi and Idson, 1999), employees in bigger firms tend to be older, have longer tenure and higher human capital (Oi and Idson, 1999). Following the documented size-related differences in firm behaviour, we introduce "large" firms into the simulation to explore how the firm size affects promotion timing. More specifically, we consider the case when some of the firms on the market have a pyramidal structure with three positions ("large" firms) while the rest have a vertical hierarchy with two positions ("small" firms) as in the benchmark model. In order to isolate the firm structure effect on optimal promotions, we abstract from the synergy effect and consider the case of homogeneous workers.



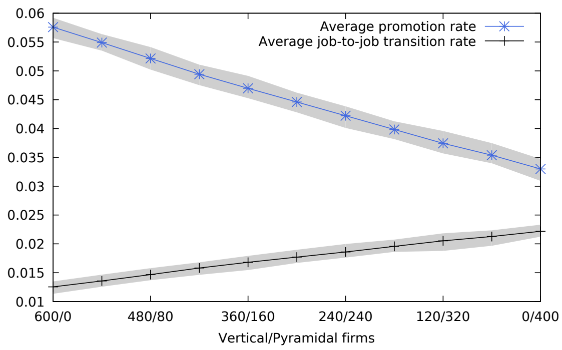
(a) Vacancy-filling rates



(b) q_2 decomposition



(c) Distribution of workers



(d) Promotions

Figure 2.11: Market adjustments: simulation values are obtained by taking and average over the last 1000 iterations of each run, where one run consists of 1500 iteration. The values show an average over 100 simulation runs and the bands display the minimal and maximal average recorded.

We define the additional possible states of pyramidal firms as follows: d_{20} are firms which have two junior workers and no senior worker, d_{21}^{NN} are the firms which have all three positions filled and none of the junior workers is searching for a senior position in another firm. Next, d_{21}^{NS} denotes the pyramidal firms which have two junior workers and one senior worker and one of the junior workers is already searching. And finally, d_{21}^{SS} denotes the firms in which both junior workers are searching[10].

2.5.1 Effects on labour flows

To demonstrate how the presence of pyramidal firms influences the labour flows and the allocation of workers to different types of jobs we incrementally increase the number of pyramidal firms on the market keeping the promotion cutoff at its benchmark equilibrium value $\bar{x} = 45$. Figure 2.11 presents the results from the simulation and shows the adjustment of transition rates when the market moves from having only vertical firms to having only pyramidal firms. Averages of the variables as well as 95% confidence intervals are displayed. The transition of firm types is shown on the x-axis, where at the origin we have 600 firms with two positions and 0 firms with three positions (600/0) or 1200 jobs in total. This is our benchmark model considered above. We gradually decrease the number of vertical firms and increase the number of pyramidal firms while keeping the total number of jobs constant. For example,

[10]Additionally, the upper script "3" denotes a pyramidal firm.

(360/160) means 360 firms with two positions and 160 firms with three positions and so on. The last point (0/400) shows the case with no two-position firms and 400 pyramidal firms.

Changing the market structure by introducing pyramidal firms increases the senior vacancy-filling rate q_2 approximately five-fold (figure 2.11a). The presence of more three-position firms increases the number of junior workers in the market (figure 2.11c). Since there are more junior workers and because the promotion cutoff is kept constant, the pool of applicants to senior positions becomes larger and the probability that a firm finds a senior worker from the market increases. For instance, in the case when there are only pyramidal firms in the market (0/400), the number of searching junior workers is on average 0.1332 ($= d_{11}^{S3} + d_{21}^{NS} + 2d_{21}^{SS}$) whereas in the benchmark case (600/0) it is 0.0633 ($= d_{11}^{S}$). On the other hand, there are on average 0.0775 ($= d_{00}^{3}+d_{10}^{3}+d_{20}$) senior vacancies in the market with three-position firms only and 0.2543 ($= d_{00}+d_{10}$) in the benchmark scenario. Hence, more e_1 workers compete for fewer senior vacancies and firms fill more often their e_2 positions from the market. Consequently, the number of internally promoted workers decreases while more e_1 workers reach senior position by changing firms (figure 2.11d). We further decompose the senior vacancy filling rate q_2 into senior vacancies filled by workers who were previously employed in two-position firms: q_2^2; and such filled by workers who were employed in three-position firms: q_2^3 (figure 2.11b)[11]. This distinction becomes relevant if the two types of firms set different promotion cutoffs. On the other hand, the job-finding rates λ_1 and λ_2 do not respond strongly to the changing market structure because they are primarily driven by workers' search intensity[12].

2.5.2 Optimal promotion

Next, we study the optimal promotion cutoff in the market with heterogeneous firms. In that respect two questions arise. First, how does the optimal promotion policy of a pyramidal firm compare to that of a vertical one, and, second, how does the presence of pyramidal firms influence the optimal promotion threshold of the vertical firms. In order to study these issues, we adjust the approach to simulate the discounted sum of profits of a single firm for the setting with heterogeneous firms. The procedure is described in Appendix C.

We consider a market with 540 vertical firms and 40 pyramidal firms. As a starting point we keep the market promotion threshold at $\bar{x} = 45$ and use the transition rates generated for this setting from the simulation: $\zeta^0 = \{\lambda_1, \lambda_2, q_1, q_2\} = \{0.01449, 0.01452, 0.01614, 0.00429\}$. We then compare the expected discounted profit of a single vertical respectively pyramidal firm across different values of its own promotion threshold $\bar{x_i}^j$, $j = 2, 3$. Figure 2.12 plots the results for a two- and three- position firm respectively. We observe that both types of firms should delay their promotion time in response to the firm heterogeneity. A vertical firm achieves highest expected profits if it sets the promotion time at $\bar{x}_i^2 = 75$, whereas a pyramidal firm maximizes expected profits at $\bar{x}_i^3 = 95$. This result is driven by the higher vacancy-filling rate of senior positions (q_2) and the lower vacancy-filling rate of junior positions (q_1), as already shown in figure 2.4. Firms would like to keep their junior worker longer, given that they have higher chance to hire a senior worker from the market and that finding a new junior worker becomes more difficult. Furthermore, for pyramidal firms it is optimal to

[11]Note that: $q_2 = q_2^2 + q_2^3$.
[12]See figure 2.16 in Appendix C.

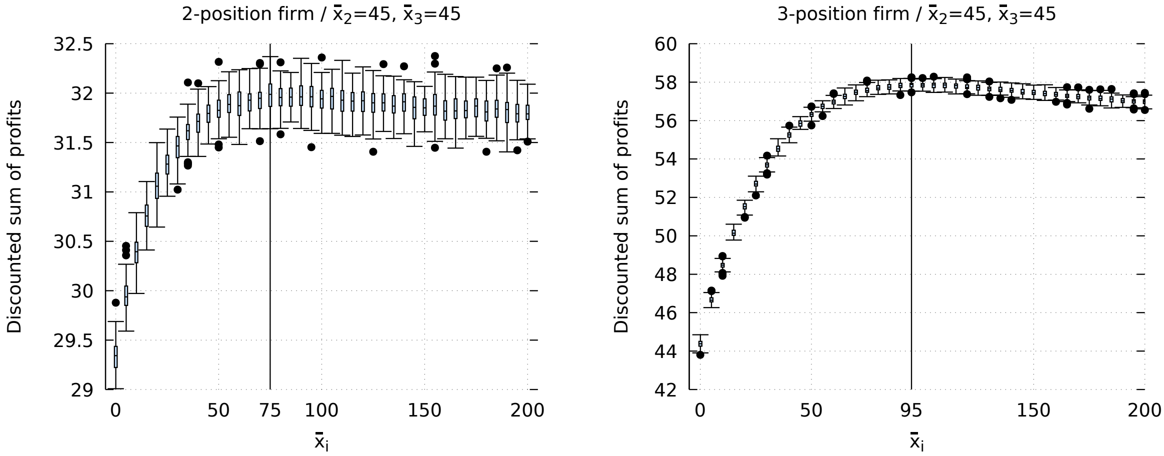


Figure 2.12: Optimal responses of deviating vertical (left panel) and pyramidal (right panel) firms with $\bar{x}^2 = \bar{x}^3 = 45$.

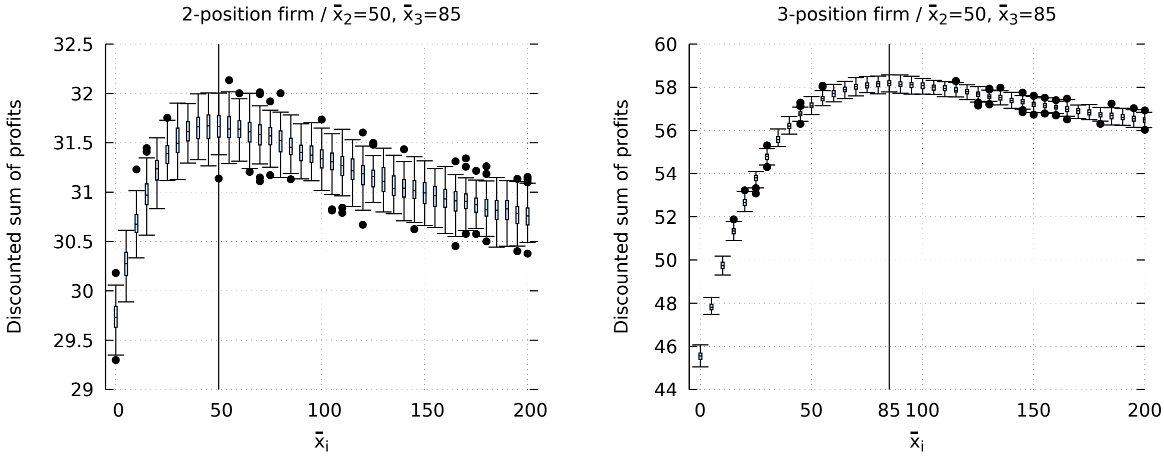


Figure 2.13: Profit function and best response of a two-position firm (left panel) and three-position firm (right panel) in a market with 540 vertical firms and 40 pyramidal firms.

promote later than their vertical competitors. Before discussing the intuition for this finding we verify whether our results qualitatively stay intact if we take into account the adjustment of the other firms on the market and of the transition rates in general equilibrium.

In order to obtain the general equilibrium promotion cutoffs in this market we again employ the procedure used already for the case of two skill groups and described in section 2.4.3. Since we now have two types of firms, in each step of the algorithm we determine for given transition rates and cutoff values of both types of firms in the market the best response for each type of firm. However, since in this setting with heterogeneous firms we do not have an analytical characterization of the firm's best response function, we use the results from the best response simulations to guide us in which direction to alter the conjectured promotion cutoffs of both types of firms before simulating the new transition rates. The algorithm stops if the optimal response of both types of firms coincides with the conjectured promotion cutoffs.

Applying this procedure we find that $\{\bar{x}^{2ge}, \bar{x}^{3ge}\} = \{50, 85\}$ is an equilibrium in the

$a = 1$; $\bar{x}^2 = 50$; $\bar{x}^3 = 85$								
	Sim	SD		Sim	SD		Sim	SD
λ_1	0.0145	0.0002	d_{00}	0.1074	0.0021	d_{11}^{S3}	0.0028	0.0003
λ_2	0.0146	0.0004	d_{00}^3	0.0036	0.0004	d_{20}	0.0056	0.0004
q_1	0.0168	0.0002	d_{01}	0.1528	0.0018	d_{21}^{NN}	0.0045	0.0004
q_2^2	0.0031	0.0001	d_{01}^3	0.0052	0.0004	d_{21}^{NS}	0.0038	0.0003
q_2^3	0.0005	0.00004	d_{10}	0.1254	0.0021	d_{21}^{SS}	0.0008	0.0002
e_0	0.3411	0.0040	d_{10}^3	0.0056	0.0004	Internally promoted	0.0503	0.0006
e_1	0.3266	0.0021	d_{11}^N	0.1028	0.0014	Promotion rate (vertical)	0.0538	0.0007
e_2	0.3334	0.0021	d_{11}^{N3}	0.0083	0.0004	Promotion rate (pyramidal)	0.0284	0.0010
n	2.3677	0.0356	d_{11}^S	0.0527	0.0017	Job-to-job movers	0.0110	0.0003

Table 2.6: Distribution of firms and workers; and equilibrium transition rates. SD: standard deviation. Simulation values are obtained by taking and average over the last 1000 iterations of each run, where one run consists of 1500 iteration. Averages over 100 simulation runs are shown.

market with 540 vertical and 40 pyramidal firms. Figure 2.13 displays the expected discounted profits of the two types of firms as a function of their promotion threshold in this setting. The distribution of workers and firms as well as the equilibrium transition rates are summarized in table 2.6. Hence, the insights that the presence of pyramidal firms induces delayed promotion of all firms, compared to the benchmark of a market of vertical firms, and that pyramidal firms should promote later than vertical ones, also apply in a full general equilibrium setting.

On average, 34.1% of agents are in simple jobs, 32.7% in junior positions and 33.4% in senior positions. Among those employed in professional jobs almost half are on level 1 and the other half occupies senior positions[13]. Further 6.1% of workers are searching on-the-job while on average 5% are internally promoted per year. Another 1.1% of junior workers move to a different firm to gain a promotion. In comparison with our benchmark case, having some firms with two level 1 jobs increases the equilibrium fraction of workers in junior positions. However, both the yearly promotion rate as well as the job transition rate decrease slightly compared to the benchmark model as result of the overall fewer senior jobs on the market and the larger promotion cutoffs firms choose in equilibrium. This is different from the partial equilibrium setting where the job-to-job transition rate increased as a result of firm heterogeneity (see figure 2.11d). We see that after endogenizing $\bar{x}^2$ and $\bar{x}^3$, the general equilibrium effect reverses the heterogeneous firm effect on the job-to-job transition rate and reduces the percentage of job-to-job movers from 1.4% in the partial equilibrium to 1.1% in the general equilibrium. Hence, in the equilibrium with heterogeneous firms, the job-to-job transition rate is slightly suppressed compared to the benchmark case where 1.2% of workers change firms to gain promotion. On the other hand, the negative impact of firm heterogeneity on the promotion rate (see figure 2.11d) is reinforced by the general equilibrium effect and the promotion rate is further reduced form 5.5% in the partial equilibrium to 5% in the general equilibrium. The rest of the transition rates are quantitatively very similar to the ones in the benchmark case with the exception of q_1 which is slightly lower. On average it takes longer for firms to fill their junior positions in the market with heterogeneous firms. There is a larger pool of competing vacancies for level 1 workers and, as shown above, in equilibrium

[13] $p_1 = 0.3266/(0.3266 + 0.3334) = 0.4949$ or approximately 49.5%.

firms choose longer promotion time to counteract this effect.

Furthermore, pyramidal firms set a higher promotion cutoff than vertical firms. Intuitively, this is due to the fact that for pyramidal firms the probability that the senior position is filled at a given point in time is larger than for a vertical firm and also there is the possibility that the other junior worker in the firm has already reached the promotion threshold and hence would be appointed to the senior position if the senior worker retires. Both these effects increase the firm's incentive to delay promotion in order not to risk loosing the junior worker. Hence, the pyramidal firm promotes later than the vertical one. Specifically, in equilibrium 63.2% of pyramidal firms have their senior position filled $(= (d_{01}^3 + d_{11}^{N3} + d_{11}^{3S} + d_{21}^{NN} + d_{21}^{NS} + d_{21}^{SS})/(d_{00}^3 + d_{10}^3 + d_{01}^3 + d_{11}^{N3} + d_{11}^{S3} + d_{20} + d_{21}^{NN} + d_{21}^{NS} + d_{21}^{SS}))$ compared to 57% of vertical firms $(= (d_{01} + d_{11}^N + d_{11}^S)/(d_{00} + d_{10} + d_{01} + d_{11}^N + d_{11}^S))$. Further, 5.4% of the junior workers employed in vertical firms are promoted per year compared to 2.8% of workers in pyramidal firms. Due to their promotion cutoff pyramidal firms do not only have slower turnover in their junior positions compared to vertical firms, but also have junior workers and senior workers with higher average experience than their smaller competitors with vertical structure. Average experience of junior workers in vertical firms is 29.3 vs. 49.6 for junior workers in pyramidal firms. Also, senior workers in vertical firms have on average experience of 50.8 compared to 80.7 for senior workers in pyramidal firms. This indicates a firm size wage gap of 6.3% in junior positions $(= \beta c_1(e^{\gamma 49.6} - e^{\gamma 29.3})/(\beta c_1 e^{\gamma 29.3}))$ and 9.4% in senior positions $(= \beta c_2(e^{\gamma 80.7} - e^{\gamma 50.8})/(\beta c_2 e^{\gamma 50.8}))$. Hence, our model shows that considering endogenous promotion choices can provide an explanation for the difference in workers' tenure and wages between small and large firms as reported in a survey by Oi and Idson (1999) and more recently by Lallemand et al. (2007) for five European countries. It can also capture a positive relationship between the firm size wage gap and the hierarchical levels as found by Fox (2009) for US and Swedish white-collar workers[14].

2.6 Robustness check: complementarity between worker experience

In the benchmark model used so far we have assumed production function of the firm that is fully separable between the output of the different workers. In particular, under this assumption the marginal increase of a firm's output due to higher experience of a junior or senior worker does not depend on whether the other position(s) in the firm are filled or which experience workers filling these other positions have. Although this separability assumption strongly increases the analytical tractability of the model, it might be considered as somehow restrictive from an economic perspective. Relying on our simulation approach

[14] Also Ke et al. (2018) find that promotion probabilities are smaller in larger firms and that there is a firm size wage premium. The underlying modelling framework and mechanism are, however, quite different to ours. The authors model firm's trade-off between obtaining productive efficiency and motivating workers by providing enough promotion opportunities. Since promotion prospects act as incentives for workers, one of the implications of their model is that workers in "top jobs" are always promoted and never hired from outside. In our model, firm competition in both junior and senior markets is an important determinant of optimal promotion strategies. This is in line with the empirical findings in Baker et al. (1994) that there is a substantial fraction of new hires at all hierarchical levels, rather than only at the lowest one, which implies that the conditions on the external market shape firm's decisions. Hence, our approach, contrary to Ke et al. (2018), allows us to study how firms optimally alter their promotion timing in the presence of larger competitors.

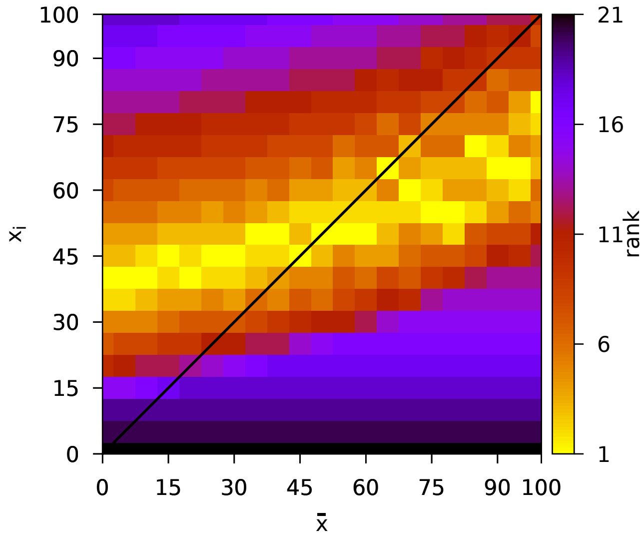


Figure 2.14: The optimal response of a single firm obtained by the simulation approach described in Appendix B. The average profit for each promotion cutoff of the deviating firm given $\bar{x}$ is recorded and the averages are ranked with 1 being the highest.

we can however check the robustness of our main findings if this assumption is dropped and a potential complementarity between the experience of junior and senior workers is taken into account. In particular, using again our benchmark setting with only vertical firms and homogeneous worker skills, we consider a CES production function of the form

$$f(\mathbb{1}_1, x, \mathbb{1}_2, y) = \left[\mathbb{1}_1(d_1 + c_1 e^{\gamma x})^{\frac{\sigma-1}{\sigma}} + \mathbb{1}_2(d_2 + c_2 e^{\gamma y})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{2.12}$$

where $f(\mathbb{1}_1, x, \mathbb{1}_2, y)$ is the output of a firm which has a junior worker with experience x and a senior worker with experience y. Here $\mathbb{1}_1$ and $\mathbb{1}_2$ are indicator functions which take a value of 1 if the respective position is filled and 0 otherwise. The parameter σ is the elasticity of substitution between the junior and the senior worker and in the limiting case of $\sigma \to \infty$, we have the linear production function used in the benchmark model. The profit of the firm is given by $\pi((\mathbb{1}_1, x, \mathbb{1}_2, y) = (1-\beta)f(\mathbb{1}_1, x, \mathbb{1}_2, y)$.

Empirical estimates suggest that there is imperfect substitutability between young and old or experienced and inexperienced workers. For example, using data for the U.S., UK and Canada, Card and Lemieux (2001) estimate the elasticity of substitution between men with similar educational attainment but different ages to be in the interval 4-6. D'Amuri et al. (2010) find based on German data that the elasticity of substitution between workers with the same educational level but different experience is 3.3. We choose an intermediate value of the existing estimates of $\sigma = 4$ and calculate for varying values of the market promotion cutoff the expected firm payoff under different values its own cutoff. Figure 2.14 clearly indicates that introducing a CES production technology preserves the result that the optimal promotion decision of a single firm increases in the market promotion cutoff. Actually, even the observation that choosing $\bar{x}_i = 45$ is optimal for a firm if all competitors use $\bar{x} = 45$ carries over to this case of a non-linear production function. Taking into account that transition rates are not directly influenced by the production function, but just by the choice of cutoffs this establishes that also in this setting $\bar{x}^{ge} = 45$ is a general equilibrium. Overall, apart from the key feature of strategic complementarity between promotion times also our other qualitative findings seem to stay intact as we move to a general CES production technology.

2.7 Conclusion

In this paper we develop and analyse a model which embeds the choice of optimal promotion times by hierarchical firms in a search and matching labour market with on the job search, which captures the option of a firm to fill senior positions through outside recruiting rather than internal promotion. A new methodological approach combining analytical results with agent-based simulations allows us to characterize the promotion strategies in a general equilibrium of this model, both in the presence of workers with heterogeneous skills and of firms with heterogeneous hierarchical structures. Our findings about the effect of the level and heterogeneity of worker skills and of the firm's hierarchical structure on optimal promotion times are innovative insight into the determinants of firm behaviour on the labour market and into the resulting implications for labour flows. They provide theory-based explanations for empirical observations about the difference in promotion times between high and low skill workers as well as about the relationship between firm size and human capital. Furthermore, our results also give rise to several innovative testable implication about the impact of different factors on promotion strategies, which can be used as the theoretical basis for future empirical work in this area. Our insight that the effects of parameter changes on promotion cutoffs are typically much smaller in a general equilibrium framework than under the assumption of fixed job-filling/job finding rates at the different hierarchical levels, highlights the importance of endogenizing the supply side of the labour market when analysing the design of promotion strategies.

From a methodological perspective this paper illustrates the potential of a careful combination of analytical and simulation approaches for the analysis of labour markets with frictions and different types of heterogeneities. The flexibility that this approach allows with respect to the structure of the analysed model opens the possibility for addressing a wide range of issues in labour economics and beyond.

The analysis presented in this paper can be extended in several promising directions. Apart from empirical work building on our results, endogenizing wages and considering a simultaneous setting of wages and promotion cutoffs by firms may provide further economic insights. Moreover, the impact of promotion strategies on wage inequality is a related promising area. Extending the framework developed in this paper allows to study the role of the promotion channel for transforming different types of skill heterogeneities into wage inequalities under different assumptions about the firms' hierarchical structure. In that respect also the role of professional networks for job transitions and emerging wage inequality might be considered. These networks might evolve endogenously through employment at the same company and influence the potential of workers for finding senior positions outside the own firm. Finally, the fact that individual firms do not internalize the general equilibrium effects in our model is likely to create a deadweight loss of welfare which opens space for the discussion of policy and regulation.

2.8 Appendix A: Additional calculations

Benchmark case

First, we solve equation (3.9), which is a first-order linear differential equation. This equation has the form $J'_{10}(x) = rJ_{10}(x) + g(x)$, where $g(x)$ is given by:

$$-g(x) = (d_1 + c_1 e^{\gamma x})(1-\beta) - s + q_2 \frac{(\pi_2(\bar{x}) + \Delta + s)}{r + \rho + q_2} + q_2 K e^{(r+\rho+q_2)x}$$

With A denoting the integration constant the general solution of this equation is given by $J_{10}(x) = Ae^{rx} + e^{rx}\int g(x)e^{-rx}$. The second part of this expression is given by:

$$\begin{aligned}
& e^{rx}\int g(x)e^{-rx} = -e^{rx}\Big[\int\Big(d_1(1-\beta) - s + q_2\frac{(\pi_2(\bar{x}) + \Delta + s)}{r+\rho+q_2}\Big)e^{-rx}dx \\
+ \quad & \int c_1(1-\beta)e^{(\gamma-r)x}dx + \int q_2 K e^{(\rho+q_2)x}dx\Big] \\
= \quad & \frac{d_1(1-\beta)-s}{r} + q_2\frac{(\pi_2(\bar{x}) + \Delta + s)}{r(r+\rho+q_2)} - \frac{e^{rx}c_1(1-\beta)e^{(\gamma-r)x}}{\gamma - r} - \frac{e^{rx}q_2 K e^{(\rho+q_2)x}}{\rho+q_2} \\
= \quad & \frac{d_1(1-\beta)-s}{r} + q_2\frac{(\pi_2(\bar{x}) + \Delta + s)}{r(r+\rho+q_2)} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{q_2 K e^{(r+\rho+q_2)x}}{\rho+q_2}
\end{aligned}$$

Further, we determine the function $J^N_{11}(0, x_i)$. To do so recall that $J^N_{11}(x, y)$ is given by:

$$rJ^N_{11}(x,y) \quad = \quad \pi_1(x) + \Delta + \pi_2(y) - \rho(J^N_{11}(x,y) - J_{10}(x)) + \frac{\partial J^N_{11}(x,y)}{\partial x}$$

Inserting $J_{10}(x)$ into this equation we get:

$$\begin{aligned}
& (r+\rho)J^N_{11}(x,y) = \pi_1(x) + \Delta + \pi_2(y) + \frac{\partial J^N_{11}(x,y)}{\partial x} \\
+ \quad & \rho\Big[\frac{d_1(1-\beta)-s}{r} + q_2\frac{\pi_2(\bar{x}) + \Delta + s}{r(r+\rho+q_2)} + Ae^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{q_2 K e^{(r+\rho+q_2)x}}{\rho+q_2}\Big]
\end{aligned}$$

The general solution of this linear first order differential equation is given by:

$$\begin{aligned}
J^N_{11}(x,y) \quad = \quad & \frac{s(r+q_2)}{r(r+\rho+q_2)} + \frac{\rho K e^{(r+\rho+q_2)x}}{\rho+q_2} + \frac{d_1(1-\beta)-s}{r} + Ae^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} \\
+ \quad & \frac{\pi_2(y)+\Delta}{r+\rho} + \frac{\rho q_2(\pi_2(\bar{x})+\Delta)}{r(r+\rho+q_2)(r+\rho)} + De^{(r+\rho)x}
\end{aligned}$$

with D being the integration constant. Evaluating this equation at $y = \bar{x}$, we should get $J^N_{11}(x, \bar{x})$, which implies that $D = 0$, because:

$$\frac{(\pi_2(\bar{x})+\Delta)}{r+\rho} + \frac{\rho q_2(\pi_2(\bar{x})+\Delta)}{r(r+\rho+q_2)(r+\rho)} = \frac{(\pi_2(\bar{x})+\Delta)(r+q_2)}{r(r+\rho+q_2)}$$

Inserting $x = 0$ and $y = x_i$, we get the function $J_{11}^N(0, x_i)$:

$$\begin{aligned} J_{11}^N(0, x_i) &= \frac{s(r+q_2)}{r(r+\rho+q_2)} + \frac{\rho K}{\rho+q_2} + \frac{d_1(1-\beta)-s}{r} + A + \frac{c_1(1-\beta)}{r-\gamma} \\ &+ \frac{(\pi_2(x_i)+\Delta)}{r+\rho} + \frac{\rho q_2(\pi_2(\bar{x})+\Delta)}{r(r+\rho+q_2)(r+\rho)} \end{aligned}$$

Two skill levels

Consider some firm with an inexperienced worker of skill $j = L, H$ employed in the junior position and an open vacancy on the senior level. The present value of discounted future profits of this firm is denoted by J_{j0} and given by:

$$rJ_{j0}(x) = \pi_1(x) - s + q_2[\alpha_2 J_{jL}^N(x, \bar{x}_L) + (1-\alpha_2)J_{jH}^N(x, \bar{x}_H) - J_{j0}(x)] + \frac{\partial J_{j0}(x)}{\partial x} \tag{2.13}$$

With probability α_2 the firm will hire another low skill worker for the senior position, which generates the present value of profits $J_{jL}^N(x, \bar{x}_L)$, while with the opposite probability $1 - \alpha_2$ the firm will hire a high skill worker which generates the present value of profits $J_{jH}^N(x, \bar{x}_H)$. Recall that $\bar{x}_j$ denotes the market experience level of applicants in the managerial market with a skill level $j = L, H$. Variables $J_{jf}^N(x, y)$, $j, f = L, H$ can be found as:

$$rJ_{jf}^N(x, y) = \pi_1(x) + \pi_2^f(y) - \rho(J_{jf}^N(x, y) - J_{j0}(x)) + \frac{\partial J_{jf}^N(x, y)}{\partial x} \tag{2.14}$$

Here $\pi_2^f(y)$ is the flow profit generated by the senior manager who may retire and exit the market at rate ρ. In this case the firm is left with the inexperienced junior worker and the corresponding present value $J_{j0}(x)$. Further, we define an auxilliary variable $\bar{J}_j(x) \equiv \alpha_2 J_{jL}^N(x, \bar{x}_L) + (1-\alpha_2)J_{jH}^N(x, \bar{x}_H)$ which is a weighted average between the two present values and is given by:

$$r\bar{J}_j(x) = \pi_1(x) + \alpha_2\pi_2^L(\bar{x}_L) + (1-\alpha_2)\pi_2^H(\bar{x}_H) - \rho(\bar{J}_j(x) - J_{j0}(x)) + \frac{\partial \bar{J}_j(x)}{\partial x} \tag{2.15}$$

Note that formally, $\bar{J}_j(x, \bar{x}_L, \bar{x}_H)$ depends on $\bar{x}_L$ and $\bar{x}_H$ but this dependence is suppressed for the ease of exposition. Equation (2.13) can then be written as:

$$rJ_{j0}(x) = \pi_1(x) - s + q_2[\bar{J}_j(x) - J_{j0}(x)] + \frac{\partial J_{j0}(x)}{\partial x} \tag{2.16}$$

In addition, define another auxilliary variable $\Delta J_j(x) \equiv \bar{J}_j(x) - J_{j0}(x)$, this is the average present value gain of finding a manager. Taking difference between equations (2.15) and (2.16) it becomes:

$$(r+\rho+q_2)\Delta J_j(x) = \alpha_2\pi_2^L(\bar{x}_L) + (1-\alpha_2)\pi_2^H(\bar{x}_H) + s + \frac{\partial \Delta J_j(x)}{\partial x}$$

The general solution of this first order linear differential equation is:

$$\Delta J_j(x) = \frac{\alpha_2\pi_2^L(\bar{x}_L) + (1-\alpha_2)\pi_2^H(\bar{x}_H) + s}{r+\rho+q_2} + K_j e^{(r+\rho+q_2)x} \tag{2.17}$$

where K_j is the integration constant. Let $\bar{\pi}_2(\bar{x}_L, \bar{x}_H) = \alpha_2\pi_2^L(\bar{x}_L) + (1-\alpha_2)\pi_2^H(\bar{x}_H)$ denote the average flow profit of the firm associated with hiring a manager in the market. With this notation we can rewrite equation (2.16) for $J_{j0}(x)$ by inserting $\Delta J_j(x)$ in the following way:

$$rJ_{j0}(x) = \pi_1(x) - s + q_2\Big[\frac{\bar{\pi}_2(\bar{x}_L, \bar{x}_H) + s}{r+\rho+q_2} + K_j e^{(r+\rho+q_2)x}\Big] + \frac{\partial J_{j0}(x)}{\partial x} \tag{2.18}$$

With A_j denoting the integration constant, the general solution of this differential equation can be written as:

$$J_{j0}(x) = \frac{d_1(1-\beta)-s}{r} + q_2\frac{\bar{\pi}_2(\bar{x}_L, \bar{x}_H)+s}{r(r+\rho+q_2)} + A_j e^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{q_2 K_j e^{(r+\rho+q_2)x}}{\rho+q_2} \tag{2.19}$$

Finally, inserting $J_{j0}(x)$ into equation (2.14) we get the last differential equation for $J_{jf}^N(x,y)$ which allows us to solve the main part of the model. The differential equation for $J_{jf}^N(x,y)$ is given by:

$$\begin{aligned}(r+\rho)J_{jf}^N(x,y) = \pi_1(x) + \pi_2^f(y) + \frac{\rho(d_1(1-\beta)-s)}{r} + \rho q_2\frac{\bar{\pi}_2(\bar{x}_L, \bar{x}_H)+s}{r(r+\rho+q_2)} \\ + \rho A_j e^{rx} + \frac{\rho c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{\rho q_2 K_j e^{(r+\rho+q_2)x}}{\rho+q_2} + \frac{\partial J_{jf}^N(x,y)}{\partial x}\end{aligned} \tag{2.20}$$

It can be rewritten as:

$$\begin{aligned}(r+\rho)J_{jf}^N(x,y) &= d_1(1-\beta) + \pi_2^f(y) + \frac{\rho(d_1(1-\beta)-s)}{r} + \rho q_2\frac{\bar{\pi}_2(\bar{x}_L, \bar{x}_H)+s}{r(r+\rho+q_2)} \\ &+ \rho A_j e^{rx} + \frac{(\rho+r-\gamma)c_1(1-\beta)e^{\gamma x}}{r-\gamma} - \frac{\rho q_2 K_j e^{(r+\rho+q_2)x}}{\rho+q_2} + \frac{\partial J_{jf}^N(x,y)}{\partial x}\end{aligned}$$

Let D_{jf} denote the integration constant, so the general solution of the above equation becomes:

$$\begin{aligned}J_{jf}^N(x,y) &= \frac{d_1(1-\beta)+\pi_2^f(y)}{r+\rho} + \frac{\rho(d_1(1-\beta)-s)}{r(r+\rho)} + \rho q_2\frac{\bar{\pi}_2(\bar{x}_L, \bar{x}_H)+s}{r(r+\rho+q_2)(r+\rho)} \\ &+ \frac{\rho A_j e^{rx}}{r+\rho-r} + \frac{(\rho+r-\gamma)c_1(1-\beta)e^{\gamma x}}{(r-\gamma)(r+\rho-\gamma)} - \frac{\rho q_2 K_j e^{(r+\rho+q_2)x}}{(\rho+q_2)(r+\rho-(r+\rho+q_2))} \\ &+ D_{jf}e^{(r+\rho)x} = \frac{d_1(1-\beta)}{r} + \frac{\pi_2^f(y)}{r+\rho} + \frac{\rho q_2\bar{\pi}_2(\bar{x}_L, \bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} + \Big[\frac{-s}{r} + \frac{rs}{r(r+\rho)} \\ &+ \frac{\rho q_2 s}{r(r+\rho+q_2)(r+\rho)}\Big] + A_j e^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{(r-\gamma)} + \frac{\rho K_j e^{(r+\rho+q_2)x}}{(\rho+q_2)} + D_{jf}e^{(r+\rho)x} \\ &= \frac{d_1(1-\beta)-s}{r} + \frac{\pi_2^f(y)}{r+\rho} + \frac{\rho q_2\bar{\pi}_2(\bar{x}_L, \bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} + \frac{s(r+q_2)}{r(r+\rho+q_2)} \\ &+ A_j e^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{(r-\gamma)} + \frac{\rho K_j e^{(r+\rho+q_2)x}}{(\rho+q_2)} + D_{jf}e^{(r+\rho)x}\end{aligned}$$

where D_{jf} is the corresponding integration constant. Next we combine equations (2.17) and (2.19) to find solution for the auxilliary variable $\bar{J}_j(x) = J_{j0}(x) + \Delta J_j(x)$:

$$\bar{J}_j(x) = \frac{d_1(1-\beta)-s}{r} + (r+q_2)\frac{\bar{\pi}_2(\bar{x}_L,\bar{x}_H)+s}{r(r+\rho+q_2)} + A_j e^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} + \frac{\rho K_j e^{(r+\rho+q_2)x}}{\rho+q_2} \tag{2.21}$$

Evaluating $J^N_{jL}(x,y)$ at $y = \bar{x}_L$ with the corresponding term D_{jL}, $J^N_{jH}(x,y)$ at $y = \bar{x}_H$ with the corresponding term D_{jH} and taking a weighted average between the two we get $(1-\alpha_2)J^N_{jH}(x,\bar{x}_H) = \bar{J}_j(x) - \alpha_2 J^N_{jL}(x,\bar{x}_L)$. The right-hand side of this equation is given by:

$$\begin{aligned}
\bar{J}_j(x) - \alpha_2 J^N_{jL}(x,\bar{x}_L) &= (r+q_2)\frac{\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r(r+\rho+q_2)} - \alpha_2\frac{\pi^L_2(\bar{x}_L)}{r+\rho} - \alpha_2\frac{\rho q_2\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} \\
&- \alpha_2 D_{jL}e^{(r+\rho)x} + (1-\alpha_2)\Big[\frac{d_1(1-\beta)-s}{r} + \frac{(r+q_2)s}{r(r+\rho+q_2)} \\
&+ A_j e^{rx} + \frac{c_1(1-\beta)e^{\gamma x}}{r-\gamma} + \frac{\rho K_j e^{(r+\rho+q_2)x}}{\rho+q_2}\Big]
\end{aligned}$$

Consider the first four terms of this equation:

$$\begin{aligned}
\frac{\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r+\rho} &+ \frac{\rho q_2\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} - \alpha_2\frac{\pi^L_2(\bar{x}_L)}{r+\rho} - \alpha_2\frac{\rho q_2\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} - \alpha_2 D_{jL}e^{(r+\rho)x} \\
&= (1-\alpha_2)\frac{\rho q_2\bar{\pi}_2(\bar{x}_L,\bar{x}_H)}{r(r+\rho+q_2)(r+\rho)} + (1-\alpha_2)\frac{\pi^H_2(\bar{x}_H)}{r+\rho} - \alpha_2 D_{jL}e^{(r+\rho)x}
\end{aligned}$$

because $\bar{\pi}_2(\bar{x}_L,\bar{x}_H) - \alpha_2\pi^L_2(\bar{x}_L) = (1-\alpha_2)\pi^H_2(\bar{x}_H)$. Comparing $\bar{J}_j(x) - \alpha_2 J^N_{jL}(x,\bar{x}_L)$ with $(1-\alpha_2)J^N_{jH}(x,\bar{x}_H)$ we can see that $(1-\alpha_2)D_{jH}e^{(r+\rho)x} = -\alpha_2 D_{jL}e^{(r+\rho)x}$, so that $(1-\alpha_2)D_{jH} + \alpha_2 D_{jL} = 0$.

In the next step we consider the last Bellman equations for firms with experienced junior workers and senior managers. Let $J_{0f}(y)$ denote the present value of future profits for a firm with only one senior manager whose experience is y:

$$rJ_{0f}(y) = \pi^f_2(y) - s - \rho J_{0f}(y) + q_1[\alpha_1 J^N_{Lf}(0,y) + (1-\alpha_1)J^N_{Hf}(0,y) - J_{0f}(y)]$$

With probability α_1 the firm fills its junior position with a low skill worker, while with probability $(1-\alpha_1)$ the open position is filled with a high skill worker. The last state that we have to take into account is $J^S_{jf}(x,y)$, where the junior worker accumulated sufficient experience and is already searching for senior positions in competing firms. It is given by:

$$rJ^S_{jf}(x,y) = \pi_1(x) + \pi^f_2(y) - \rho(J^s_{jf}(x,y) - J_{0j}(x)) - \lambda_2(J^s_{jf}(x,y) - J_{0f}(y))$$

If the senior manager retires, the remaining worker is promoted to the senior position, so the firm ends up with a present value of profits $J_{0j}(x)$. In contrast, if the junior worker quits the firm ends up with a present value of profits $J_{0f}(y)$.

As before we impose several boundary conditions:

$$J_{j0}(\bar{x}^j_i) = J_{0j}(\bar{x}^j_i) \qquad J^N_{jf}(\bar{x}^j_i,\bar{x}_f) = J^S_{jf}(\bar{x}^j_i,\bar{x}_f) \qquad j,f = L,H$$

These conditions imply that firms commit to promoting workers whenever they reach a pre-specified skill-specific experience level $\bar{x}_i^j$ depending on their skills $j = L, H$. However, if the senior position is filled the worker starts searching on-the-job. Combining this set of 6 equations with 2 equations $\alpha_2 D_{jL} + (1-\alpha_2)D_{jH} = 0$ we can find a vector of 8 integration constants $\{A_j, K_j, D_{jf}\}$ for the optimal skill-specific promotion times $\bar{x}_i^j$ of firm i and market experience cutoffs $\bar{x}_j$.

In the final step we consider the objective function of firm i. Given that the firm has to determine its strategy upon the entry, it aims at maximizing the present value of expected future profits J_{00} given by:

$$rJ_{00} = -2s + q_1[\alpha_1 J_{L0}(0) + (1-\alpha_1)J_{H0}(0) - J_{00}] + q_2[\alpha_2 J_{0L}(\bar{x}_L) + (1-\alpha_2)J_{0H}(\bar{x}_H) - J_{00}]$$

This equation shows that there are four sources of uncertainty for the firm at this stage: which position will be filled first – junior or senior – and which type of worker will be hired – high or low skilled. The choice variables of the firm are $\bar{x}_i^L$ and $\bar{x}_i^H$ which are the promotion cutoffs for each of the two skill groups.

2.9 Appendix B: Details of the simulation framework

Vertical firms

To illustrate that ability to simulate the market with heterogeneous firm profiles can allow for helpful additional insights even in scenarios for which a numerical determination of the equilibrium based on analytical results is possible, we show in figure 2.15 how the fraction of internally promoted workers at a firm depends on the firm's own promotion threshold if all other firms promote at the equilibrium value of $\bar{x} = 45$. The figure shows that the fraction of internally promoted workers decreases if $\bar{x}_i$ becomes larger, which is qualitatively different from an increase of the promotion level $\bar{x}$ of all firms, which induces an increase of the fraction of internally promoted.

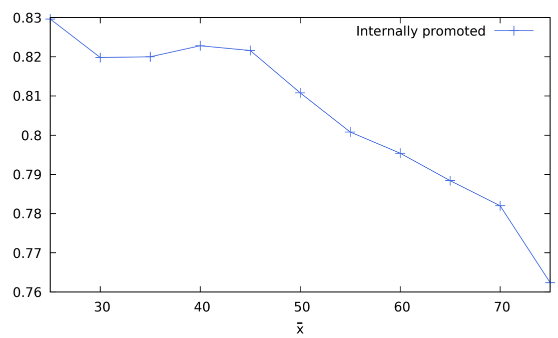


Figure 2.15: Fraction of internally promoted workers of a single firm i for $\bar{x}_i = [25..75]$, while $\bar{x} = 45$ is kept fixed. $\bar{x}_i$ is increased in steps of 5. For each $\bar{x}_i$ we let the firm i fill its senior position 5000 times and plot the fraction of internal promotions out of those 5000 hires.

Finding a General Equilibrium

In Table 2.7 the numerical procedure for finding general equilibrium promotion cutoffs with the use of simulations is illustrated for the case with a fraction of $a = 0.7$ low skill workers. In step (1) we use as an input for the simulation the partial equilibrium values found in section 2.4.2: $\bar{x}_L = 60$ and $\bar{x}_H = 28$ which are optimal under the fixed transition rates: $\zeta^0 = \{\lambda_1, \lambda_2, q_1, q_2, \alpha_1, \alpha_2\} = \{0.0145, 0.0146, 0.0171, 0.0036, 0.7, 0.7\}$. These are labelled as "Conjectured Cut-Offs". The transition rates reported below the conjectured cutoffs are the averages of the last 1000 iterations of 100 runs, where one run consists of 1500 iterations (standard deviation is given in parenthesis). The row "Opt. Cut-Offs" then displays the optimal promotions given these transition rates. The algorithm stops once the optimal cutoff values coincide with the conjectured cutoff values.

$a = 0.7$			
k	(1)	(2)	(3)
Conjectured Cut-Offs	$\{\bar{x}^L, \bar{x}^H\} = \{60, 28\}$	$\{\bar{x}^L, \bar{x}^H\} = \{58, 27\}$	$\{\bar{x}^L, \bar{x}^H\} = \{56, 28\}$
Rates ζ^k (through Simulation)	$\alpha_1 = 0.6680; \alpha_2 = 0.6045$ (0.0050); (0.0169) $\lambda_1 = 0.0145; \lambda_2 = 0.0147$ (0.0002); (0.0005) $q_1 = 0.01751; q_2 = 0.00337$ (0.0002); (0.0001)	$\alpha_1 = 0.6689; \alpha_2 = 0.6059$ (0.0043); (0.0143) $\lambda_1 = 0.0145; \lambda_2 = 0.0147$ (0.0002); (0.0005) $q_1 = 0.01731; q_2 = 0.00350$ (0.0002); (0.0002)	$\alpha_1 = 0.6752; \alpha_2 = 0.6149$ (0.0046); (0.0133) $\lambda_1 = 0.0145; \lambda_2 = 0.0145$ (0.0002); (0.0004) $q_1 = 0.01726; q_2 = 0.00354$ (0.0001); (0.0001)
Opt. Cut-Offs	$\{\bar{x}^L, \bar{x}^H\} = \{45, 27\}$	$\{\bar{x}^L, \bar{x}^H\} = \{51, 28\}$	$\{\bar{x}^L, \bar{x}^H\} = \{53, 28\}$
k	(4)	(5)	(6)
Conjectured Cut-Offs	$\{\bar{x}^L, \bar{x}^H\} = \{54, 28\}$	$\{\bar{x}^L, \bar{x}^H\} = \{55, 29\}$	$\{\bar{x}^L, \bar{x}^H\} = \{55, 28\}$
Rates ζ^k (through Simulation)	$\alpha_1 = 0.6739; \alpha_2 = 0.6202$ (0.0049); (0.0116) $\lambda_1 = 0.0145; \lambda_2 = 0.0146$ (0.0002); (0.0004) $q_1 = 0.01707; q_2 = 0.00365$ (0.0002); (0.0001)	$\alpha_1 = 0.6747; \alpha_2 = 0.6189$ (0.0042); (0.0134) $\lambda_1 = 0.0145; \lambda_2 = 0.0145$ (0.0002); (0.0004) $q_1 = 0.01720; q_2 = 0.00356$ (0.0002); (0.0001)	$\alpha_1 = 0.6733; \alpha_2 = 0.6169$ (0.0048); (0.0130) $\lambda_1 = 0.0145; \lambda_2 = 0.0145$ (0.0002); (0.0005) $q_1 = 0.01716; q_2 = 0.00357$ (0.0002); (0.0001)
Opt. Cut-Offs	$\{\bar{x}^L, \bar{x}^H\} = \{61, 29\}$	$\{\bar{x}^L, \bar{x}^H\} = \{54, 28\}$	$\{\bar{x}^L, \bar{x}^H\} = \{55, 28\}$

Table 2.7: Steps to finding the general equilibrium promotion cutoffs $\bar{x}_L^{ge}$ and $\bar{x}_H^{ge}$ for $a = 0.7$. The values show an average over 100 simulation runs with the standard deviation in parenthesis.

2.10 Appendix C: Details on pyramidal firms

Adjusting the calculation of a vertical firm's discounted payoff to the setting with heterogeneous firms requires introducing the following random variables: $\tau_1 \sim Exp(q_1)$, $\tau_2 \sim Exp(q_2^2)$, $\tau_3 \sim Exp(q_2^3)$, $\tau_4 \sim Exp(\lambda_2)$ and $\tau_5 \sim Exp(\rho)$, where q_1, q_2^2, q_2^3 and λ_2 are the transition rates generated by the agent-based simulation and ρ is the retirement rate. The difference to the benchmark setting is that we need to account separately for the waiting time until finding a senior worker from the market who has been previously employed in a vertical (τ_2) or a pyramidal (τ_3) firm. Then the algorithm is similar to the one described in section 2.4.3 with the exception that if the vertical firm has a senior vacancy it has to compare the outcomes

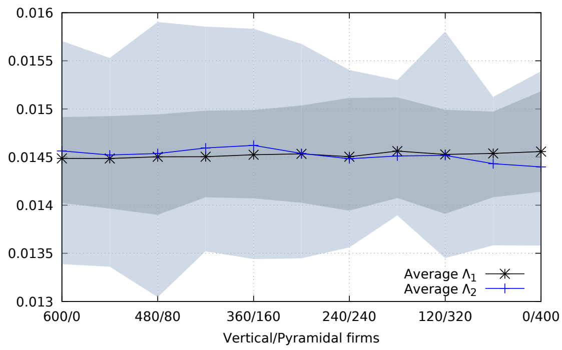


Figure 2.16: Job-fining rates for a varying fraction of pyramidal firms. The values show an average over 100 simulation runs and the confidence bands display the minimal and maximal average recorded.

of the random draws τ_2 and τ_3 with rest of the relevant possible events.

Simulating the discounted sum of profits of a deviating pyramidal firm follows a similar procedure to that of a vertical firm. We begin by defining $\tau_1^3 \sim Exp(q_1)$, $\tau_2^3 \sim Exp(2q_1)$, $\tau_3^3 \sim Exp(q_2^2)$, $\tau_4^3 \sim Exp(q_2^3)$, $\tau_5^3 \sim Exp(\lambda_2)$, $\tau_6^3 \sim Exp(2\lambda_2)$ and $\tau_7^3 \sim Exp(\rho)$. Here we need to introduce two new exponentially distributed random variables to account for the fact that a three-position firm could have two vacant junior positions simultaneously (τ_2^3 is the waiting time until such a firm finds a junior worker) and that if both junior positions are filled, the two junior workers might be searching (τ_6^3 is the waiting time until one of the two searching workers moves to another firm). All other random variables are interpreted as before where the superscript denotes that we are considering a deviating three-position firm. Hence, an entering three-position firm makes three random draws τ_2^3, τ_3^3 and τ_4^3. The smallest value determines whether the firm finds a junior or a senior worker first and becomes of d_{10}^3 or d_{01}^3 type. A d_{10}^3 firm could find a second junior worker, a senior worker or could promote its incumbent junior worker. To determine which of those occurs, the random draws τ_1^3, τ_3^3 and τ_4^3 are compared with the time left until the junior workers achieves $\bar{x}_i^3$ level of experience, the promotion cutoff of the deviating three-position firm. If τ_1^3 has the smallest value, the firm fills the second junior position and transitions into d_{20} state. Alternatively, if τ_3^3 or τ_4^3 are smaller, the firm finds a senior worker who comes from a two- or three-position firm, respectively, and becomes of d_{11}^{N3} type. Lastly, if the junior worker reaches $\bar{x}_i^3$ level of experience first, s/he is promoted and the firm transitions into d_{01}^3 state. On the other hand, a d_{01}^3 firm compares two random draws: τ_2^3 and τ_7^3. If $\min\{\tau_2^3, \tau_7^3\} = \tau_2^3$ the firm finds a junior worker and becomes of d_{11}^{N3} type, otherwise if $\min\{\tau_1^3, \tau_7^3\} = \tau_7^3$, the senior worker retires and the firm exits the market.

Next, a d_{11}^{N3} firm compares τ_7^3 and τ_1^3 with the time left until the junior worker starts searching. If τ_7^3 has the smallest value, the firm loses the senior worker and moves into d_{10} state. If, however, τ_1^3 is the smallest, the firm fills its second junior position and becomes of d_{21}^{NN} type. Alternatively, the incumbent junior worker starts searching before any of the other two events occur and the firm becomes of d_{11}^{S3} type. A d_{11}^{S3} firm, on the other hand, compares three random draws: τ_1^3, τ_5^3 and τ_7^3. If $\min\{\tau_1^3, \tau_5^3, \tau_7^3\} = \tau_1^3$, the firm fills the second junior position first and becomes of d_{21}^{NS} type. Further, if $\min\{\tau_1^3, \tau_5^3, \tau_7^3\} = \tau_5^3$, the searching worker moves to a different firm and alternatively, if $\min\{\tau_1^3, \tau_5^3, \tau_7^3\} = \tau_7^3$, the senior worker retires and the junior worker is promoted immediately. In both cases the firm becomes of d_{01}^3 type. Further, for a d_{20} firm the random draws τ_3^3 and τ_4^3 are compared with the remaining periods until each of the junior workers achieves $\bar{x}_i^3$ experience level. If τ_3^3 or τ_4^3 has the smallest value, the firm finds a senior worker from a two- or three-position firm, respectively and becomes of type d_{21}^{NN}. If, however, one of the junior workers accumulates $\bar{x}_i^3$ experience first, s/he is promoted and the firm transitions into d_{11}^{N3} state.

Finally, for the firms with all three positions filled, if the deviating firm is currently in d_{21}^{NN} state, the random draw τ_7^3 is compared with the two values which correspond to the time remaining until the two workers achieve $\bar{x}_i^3$ level of experience. If one of the workers reaches the promotion cutoff experience before any of the other events, s/he begins to search and the firm transitions into d_{21}^{NS} state. Else, if the random draw has the smallest value, the firm loses its senior worker and becomes of d_{20} type. Next, if the deviating firm is currently in d_{21}^{NS} state, the random draws τ_5^3 and τ_7^3 are compared with the time left until the second junior worker begins searching. If τ_5^3 has the smallest value, the searching worker finds a senior job in a different firm and if τ_7^3 has the smallest value, the senior worker retires and the searching worker is promoted immediately. In both cases the firm becomes of d_{11}^{N3} type. Alternatively, if the non-searching junior worker achieves $\bar{x}_i^3$ level of experience first, the firm transitions into d_{21}^{SS} state. Finally, for a d_{21}^{SS} firm, two random draws τ_6^3 and τ_7^3 are compared. If $\min\{\tau_6^3, \tau_7^3\} = \tau_6^3$ one of the searching workers leaves the firm. Otherwise, if $\min\{\tau_6^3, \tau_7^3\} = \tau_7^3$, the senior worker retires and is replaced by one of the junior ones. In both cases the firm transitions into d_{11}^S state.

Once we know, all the states of the deviating vertical or pyramidal firm from its entry until its exit from the market and the time spent in each state, we can calculate the discounted sum of profits for this firm. The simulation is done by increasing the promotion cutoff of the deviating firm ($\bar{x}_i^j$) by a step of 5. As for the case of vertical firms, we take an average over the discounted sum of profits of 40000 instances of the hypothetical firm. This is repeated 100 times for all considered values of $\bar{x}_i^j$.

Chapter 3

Social Optimum in a Model with Hierarchical Firms and Endogenous Promotion Time

3.1 Introduction

Human capital is viewed as one of the main drivers of economic growth. Bassanini and Scarpetta (2002) find, for example, that an additional year of education is associated with 6% boost in output. Furthermore, attainment of higher education is on the rise. For instance, 28.7% of EU citizens had some tertiary educational level in 2018, compared to 22% in 2009 (EUROSTAT data). One could argue that besides school and university, on-the-job learning and human capital accumulation that occurs outside of formal education are also an important determinant of productivity. Professional tasks often rely on experience which is not taught in formal education, so a substantial part of human capital accumulation takes place during a worker's career. Moreover, technological advancements might render some knowledge obsolete so continued learning is needed. In an imperfect labour market, however, it is not guaranteed that the "right" level of human capital will be achieved. The aim of this study is to analyse the efficiency of the amount of human capital accumulation that is required for promoting a worker to a senior position.

To answer this question, we assume that the labour market is populated with hierarchical firms. Upon meeting an inexperienced worker who is applying for the lower-level, junior job, the firm and the worker sign a fixed-length binding contract which specifies the amount of time the worker will spend on level one before being eligible for promotion. During this period the worker accumulates human capital and once they reach the human capital level, specified in the contract, they are promoted instantaneously. If, however, the senior position in the firm is already taken, the firm is obliged to provide an experience evaluation which permits the workers to start searching for senior jobs on the external market. Under this framework, we look at firms' promotion decisions and analyse the efficiency of these decisions. The choice variable of all firms is the cutoff level of human capital required for promoting a worker from junior to senior level. The research question is then, if the decentralized equilibrium is also socially efficient. The welfare analysis is done in two steps where in the first, we fix the number of firms entering per period. We find that the decentralized equilibrium is inefficient in the sense that firms promote their junior worker to the senior level too late, compared to what would be socially optimal. A new firm chooses its promotion requirement taking into account the actions of other firms and the market conditions. The result is a Nash equilibrium characterized by a strategic complementarity of firms' promotion decisions for the given market transition rates which is the main reason for the inefficient outcome of firms' promotion choices. More specifically, higher average promotion timing of incumbent firms on the market, induces later promotions from entering firms. This is an inefficient outcome, because firms neglect the negative externalities that their decisions create. The delay of internal promotions reduces the pool of potential candidates to senior positions such that it becomes more difficult for firms to recruit workers for their high productivity senior jobs. This in turn suppresses firms' profits and overall output. This is an externality which the decentralized market cannot internalize. The resulting welfare loss is then due to the fact that workers are allocated inefficiently among the hierarchical levels. Moreover, the market outcome is inefficient for any value of worker's bargaining power which determines how the worker and the firm split the the output of the match.

In the second step of the welfare analysis, the equilibrium number of firms is determined by a free-entry condition. Here, the paper contributes to the literature on efficiency of search and matching models. In a labour market with search frictions, social optimum is not guaranteed and an intervention by a social planner could improve welfare. Hosios (1990) and later Pissarides (2000) demonstrate that in order for market entry and exit as well as match creation and destruction to be sociably desirable, the matching function has to have constant returns to scale and the sharing rule should be such that the bargaining power of the worker equals the elasticity of the matching function with respect to unemployment. Hence, there is a unique value of bargaining power parameter that internalizes the congestion externalities on both sides of the market and leads to an efficient outcome in the decentralized economy. We show that in a model with hierarchical firms and endogenous promotions, the Hosios conditions do not deliver a constrained efficient outcome. Under free-entry, the social planner chooses even earlier promotion timing compared to the case with fixed firm entry, which shows that the socially optimal equilibrium is even further away from the decentralized one. This reveals an additional inefficiency in the model, namely that firm creation is downward biased which exacerbates the allocative inefficiency in the market. High promotion requirement imply that filling a senior position is relatively difficult. This outweighs the benefit from employing a senior worker who is highly productive and in turn firms' profits are suppressed which leads to inefficiently low market entry. Next it is shown that the socially optimal and the decentralized equilibrium with free-entry could coincide if a higher fraction of the match output is obtained by junior workers while a lower fraction of the output is retained by senior workers. This reveals that firm are not adequately compensated for creating the high-productivity senior jobs.

Finally, the case when the social planner sets the promotion and the output sharing rules simultaneously is considered. Then, welfare is maximized for lower promotion requirement compared to the decentralized equilibrium and the optimal output sharing rule is such that a higher fraction of the output accrues to workers. Hence, assuming frictional labour markets and hierarchical firms with experience evaluation as a prerequisite for employment in senior-level jobs underlines the importance of turnover dynamics in multiple-worker firms with jobs with heterogeneous productivities in relation to the efficiency of human capital required for promotion.

Further implication of the model is connected to the perfect information which follows from the certification that workers need in order to be eligible for applying to senior jobs. The role of certification with respect to the under- or over-provision of training is debated in the literature. On the one hand, certificates reduces asymmetric information about workers' human capital. Katz and Ziderman (1990) argue that if workers' skills are easily observable to outside employers, current employers are deterred from investing in training. Acemoglu and Pischke (2000), on the other hand, argue that certification might be necessary to induce firms to sponsor training of their workers. The authors argue that the role of certificates is to provide incentive to workers to exert effort and "to balance the power between workers and firms evenly" (p. 919). Here, the focus is on the role of certification in the promotion decision of competing firms. The implication of the model is that while it removes possible uncertainty about the worker's human capital it also acts as a barrier that firms set preventing workers from advancing in their career. Also, certification reduces the threat of poaching since the workers are obliged to stay with the firm providing skill evaluation. Hence, certification gives too much power to the firms and contributes to the inefficient aggregate outcome that is found in the model.

The paper is related to several strands of the literature. On the one hand, to human capital theory as proposed by Becker (1962). In a perfectly competitive setting, in which workers are paid their marginal product, firms never have an incentive to invest in workers' general skills. Here the author distinguishes between two types of training: specific and general. Specific skills acquired by workers in a given company are not transferable to other employers. General skills, on the other hand, can be applied in all firms. Then, the socially efficient level of investment in training is achievable since workers are willing to pay the cost of training in the form of lower wages during the training period because they claim the benefit of general training. Since all returns to general training accrue to the worker, in a perfectly competitive market, there are no positive externality on future employers and there is no under-investment in training.

Some of the predictions of the competitive model of training have, however, not been supported by empirical findings. For example, using the Employer Opportunity Pilot Project (EOPP) survey and a 1992 survey of firms funded by the small Business Administration (SBA) Barron et al. (1999) find that employees bear a small fraction of the cost of training and that most of the training they receive can be interpreted as general human capital. Acemoglu and Pischke (1999) further argue that firms do invest in workers general training. Surveying literature on the topic of apprenticeship training in Germany, the authors find that German firms provide general training to their apprentices at a positive cost.

More recent contributions to the literature, highlight externalities which lead to inefficient human capital accumulation in markets which are not perfectly competitive. Surveys are given by Leuven (2005) and Brunello and De Paola (2004). One possibility to why workers would not receive an optimal amount of training is a liquidity constraint. It follows from the model of Becker (1962) that workers might not be able to finance their general training if they do not have enough funds and are not able to obtain them. Hence, credit constraints and capital market imperfections can lead to inefficient training in the labour market (Stevens, 2001). In an overlapping generations model, Galor and Zeira (1993) show that under the condition of indivisibility of investment in human capital if credit markets are imperfect, then children from poor families might be unable to invest in human capital. The initial wealth distribution then determines the aggregate level of human capital investment also in the long-run. Kaas and Zink (2011) further show that in a frictional labour market poor workers who take up loans to fund their education alter their search behaviour to prefer higher paying but riskier jobs. Higher unemployment risk among these workers then suppresses their returns to human capital which has a negative effect on their educational investment.

Minimum wages could also lead to under-investment in training if firms are not allowed to offer low enough starting wage (Mincer and Leighton, 1980). Hold-up problems have also been identified to lead to under-investment in firm-specific training. If renegotiation takes place after investment, the incentive to invest ex-ante is reduced which leads to a sub-optimal outcome (Brunello and De Paola, 2004). Moral hazard problems are another reason why firms would under-investment in training (Schlicht, 1996).

Further externalities associated with inefficient worker training in imperfect labour markets involve information asymmetries such as, if the firm has better information about the training of its workers or has better information about the abilities of its employees (Leuven, 2005). Katz and Ziderman (1990) argue that the recruiting firms are less likely to know the amount or type of training a worker has obtained. The difference in information on worker's training then translates into increased information-based cost of the recruiting firms and higher risk associated with hiring the worker. As a result, a worker with general training gains less from moving to a different firm. Asymmetric information can thus give incentive to firms to invest in workers' general training. Chun and Wang (1995), on the other hand, show that adverse selection provides further rationale for firms to invest in general training.

Another externality is associated with worker turnover and poaching. Under imperfect competition, training firms would have an incentive to provide suboptimal level of training if there is a positive probability that another firm would poach the worker (Stevens, 1994). This occurs because part of the returns associated with training would then be captured by future employers. Acemoglu (1997) shows that because of search frictions labour turnover creates positive externality on future employers. Even though in the initial period the worker and the firm can write a binding contract, the fact that an unknown different firm might benefit from the training the worker receives and the inability to involve this third party in the negotiations leads to under-investment in general training. In this respect, Moen and Rosén (2004) provide conditions under which the frictional labour markets can be organized so that there is no poaching externality. This involves directed search and the use of long-term contracts or efficient bargaining.

The paper is also related to literature that studies optimal contract length. In a frictional labour market with homogeneous firms and workers Burdett and Coles (2003) show that the optimal wage-tenure contract is such that it reduces employee's quitting probability by backloading wages but also takes into account worker's preferences. It is assumed that capital markets are imperfect, thus workers who are risk averse prefer a constant wage profile. As a result optimal contracts are such that wages increase smoothly with tenure. To study the relationship between optimal contract length and the provision of training Malcomson et al. (2003) take as a motivating example the German apprenticeship system and analyses training outcomes under two cases. Firstly, when there are no contracts and wages are determined on a period by period basis and firms make their offers as to discourage workers from quitting. And secondly, when firms offer a contract of specific length, according to which workers accept a lower wage during the training period but are promised a high wage if they continue to be employed after that period, similarly to the apprenticeship system. Then firms retain the more able workers after the end of the training period while the rest of the workers find a job at their marginal productivity. Malcomson et al. (2003) show that the apprentice contracts are more profitable for firms than the no contract scenario and in equilibrium more workers receive training. However, the authors argue that even with apprenticeship contracts, less than the efficient level of general training is achieved because there is still a probability that future employers or the workers themselves will capture some of the returns to training. Similarly, connected to the issues of contract length, worker heterogeneity and asymmetric information, Hermalin (2002) shows that under-provision of general training occurs as a result of the preference of short term contracts which are used for screening workers' abilities. Cantor (1990), on the other hand, focusing on firm specific training and the moral hazard problem shows that contracts with intermediate length and fixed wages are preferable to career long fixed-wage contracts or continuously renegotiable wage contracts as they induce higher efforts and more efficient training.

The model developed here is closest to Bernhardt and Scoones (1993) and Bernhardt (1995) who also model firm's promotion decision and derive results with respect to its efficiency. In the context of asymmetric learning, Bernhardt and Scoones (1993) and Bernhardt (1995) find that firm's promotion rules are inefficient. In both models employers face a trade-off between placing able workers in higher positions and revealing information about their abilities to competitors. Bernhardt and Scoones (1993) consider a two period model with two firms, each of which has two occupational levels. Worker's managerial potential is revealed to their employer during the first period and conditional on the worker-firm managerial match, the firm decides whether to promote the worker in the second period and what should be the wage offer. In case the the worker-firm managerial match is high firms offer a preemptive wage to deter the competitor from bidding for the worker. However, promotions are inefficient because for some marginally matched workers with managerial potential, the firm would decide not to promote them so as to not engage in bidding and to not lose the worker's firm-specific skills acquired during the first period. In a multi period setting, Bernhardt (1995) also shows that since current employers have information about the ability of their own employees, they strategically use this knowledge and delay promotions beyond the social optimum. Competitors can observe worker's employment but not ability and employers trade-off the productivity gain associated with promotion and the value of information on worker's ability. An implication is that promotions even for very able workers are delayed and that some workers are always inefficiently employed at the lower level even though they would be more productive as managers. The result that promotions are delayed above the social optimum is the closest to the one derived here, although the underlying mechanism is quite different.

The model proposed here takes a different approach to answering the question whether or not workers gain the optimal amount of human capital in the earlier stages of their careers and deviates from the above discussed modelling frameworks in several key aspects which renders direct comparison difficult. Firstly, a hierarchical firm structure is added to a frictional labour market similar to Dawid et al. (2019). It follows that human capital accumulation is important not only for productivity gains but is also a prerequisite for internal promotions. The longer firms let their junior worker gain experience, the higher future profits the firms can obtain after promotion. Moreover, firms' promotion choices induce feedback effects which shape the market conditions. Hence, the model focuses on the strategic interaction between firms when they optimally set the promotion timing of workers, rather than the strategic interaction between the firm and its employees.

Secondly, firms do not pay a direct cost for training their entry-level (junior) worker, but this cost can be interpreted in the sense of foregone profits that the firm bears, given that output in the second (senior) level is higher for each level of worker's human capital. Hence, firms "invest" in the training of their junior worker by letting her accumulate human capital while in the junior level. Furthermore, it is important to note that because workers need certification before applying in the senior market, there is no information asymmetry in the model, i.e. firms anticipate correctly the productivity of a senior worker hired from a different firm. Moreover, there is no adverse selection in the model and all workers are identical with respect to skills.

The rest of the paper has the following structure: section 3.2 describes the modelling framework while section 3.3 illustrates the decentralized equilibrium via a numerical example. Next, the welfare analysis is presented in section 3.4 and section 3.5 concludes. Details on the derivation of the decentralized equilibrium are shown in Appendix A, while additional figures are presented in Appendix B.

3.2 Economic framework: labour market flows

Firms and workers are risk-neutral and the mass of workers is normalized to 1. The economy is populated with hierarchical firms, each of which has two positions: one junior position which does not require professional experience, and one senior position for which only experienced candidates are accepted. There is a pool e_0 of inexperienced workers in simple jobs that do not provide a career advancement possibility and these workers search for their first professional job. Once young and inexperienced workers find a junior job they begin their career with no professional experience ($x = 0$) and starts accumulating it according to $\dot{x} = 1$. The experience is general and perfectly transferable between different employers. Here, the modelling framework of Dawid et al. (2019) is followed precisely. Similarly to them, it is assumed that each firm i chooses the experience level $\bar{x}_i$ which will be required for internal promotions. Once the worker reaches the predetermined level of human capital[1], s/he is promoted to the senior level, provided that the position is vacant. In the case that the senior

[1]Here, the terms "experience" and "human capital" are used interchangeably.

position is occupied, the firm is obliged to provide a certificate to the junior worker which in turn makes him/her eligible for applying to senior positions in other firms. Moreover, it is assumed that human capital accumulation is costly, so once workers reach the promotion threshold, they do not attempt to accumulate any more human capital. This implies that while productivity of workers is increasing at the early stages of their careers, it remains constant at the senior level. More precisely, the output at the junior level produced by a worker with human capital level x is $d_1 + c_1 e^{\gamma x}$, while the output of a senior worker employed at a senior job is $d_2 + c_2 e^{\gamma \bar{x}_i}$. It is assumed that $d_1 > d_2$ and $c_1 < c_1$ as in Gibbons and Waldman (1999) which implies that human capital is complementary to the hierarchical level.

Let $m_1 = m_1(e_0, d_{00} + d_{01})$ be the matching technology in the junior market. Here, the stock of available vacancies is $d_{00} + d_{01}$, where d_{00} is the stock of "empty" firms and d_{01} is the stock of firms with a senior worker only. It is assumed that $m_1(.,.)$ is increasing in both arguments and exhibits constant returns to scale. The tightness of the junior labour market (θ_1) is then $\frac{d_{00}+d_{01}}{e_0}$. The vacancy-filling ($q_1$) and job-finding ($\lambda_1$) rates can be expressed in terms of the market tightness such that:

$$q_1(\theta_1) = \frac{m_1(e_0, d_{00} + d_{01})}{d_{00} + d_{01}} = m_1\left(\frac{1}{\theta_1}, 1\right); \qquad \lambda_1(\theta_1) = \frac{m_1(e_0, d_{00} + d_{01})}{e_0} = \theta_1 q_1(\theta_1).$$

On the other hand, senior positions are available only for workers who have reached $\bar{x}_i$ level of experience. This leads to two distinct labour markets – one for junior workers without professional experience and one for experienced professionals. Similarly to m_1, let $m_2 = m_2(d_{11}^S, d_{00} + d_{10})$ be the matching technology in the senior market such that it is increasing in both arguments and has constant returns to scale. The first argument d_{11}^S, denotes the stock of firms with a junior worker who has already reached $\bar{x}_i$ experience but is not promoted because the senior position is occupied. These junior worker can thus apply for a senior position on the external market. The second argument $d_{00} + d_{10}$ is the stock of senior vacancies on the marker, where d_{10} are firms that have one junior but no senior worker. Hence, the senior vacancy-filling rate and the senior job-finding rate are given as:

$$q_2(\theta_2) = \frac{m_2(d_{11}^S, d_{00} + d_{10})}{d_{00} + d_{10}} = m_2\left(\frac{1}{\theta_2}, 1\right); \qquad \lambda_2(\theta_2) = \frac{m_2(d_{11}^S, d_{00} + d_{10})}{d_{11}^S} = \theta_2 q_2(\theta_2)$$

where $\theta_2 = \frac{d_{00}+d_{10}}{d_{11}^S}$ is the tightness of the senior market.

Assuming a Cobb-Douglas matching functions of the form $m_1(e_0, d_{00}+d_{01}) = \mu(e_0)^{\alpha_1}(d_{00}+d_{01})^{1-\alpha_1}$ and $m_2(d_{11}^S, d_{00}+d_{10}) = \mu(d_{11}^S)^{\alpha_2}(d_{00}+d_{10})^{1-\alpha_2}$ we find the following job-filling and job-finding rates in the two sub-markets:

$$q_1 = \mu\left(\frac{e_0}{d_{00} + d_{01}}\right)^{\alpha_1} \qquad q_2 = \mu\left(\frac{d_{11}^S}{d_{00} + d_{10}}\right)^{\alpha_2} \tag{3.1}$$

$$\lambda_1 = \mu\left(\frac{d_{00} + d_{01}}{e_0}\right)^{1-\alpha_1} \qquad \lambda_2 = \mu\left(\frac{d_{00} + d_{10}}{d_{11}^S}\right)^{1-\alpha_2} \tag{3.2}$$

where $0 < \alpha_1 < 1$ and $0 < \alpha_2 < 1$ are the elasticities of the junior and senior vacancy-filling

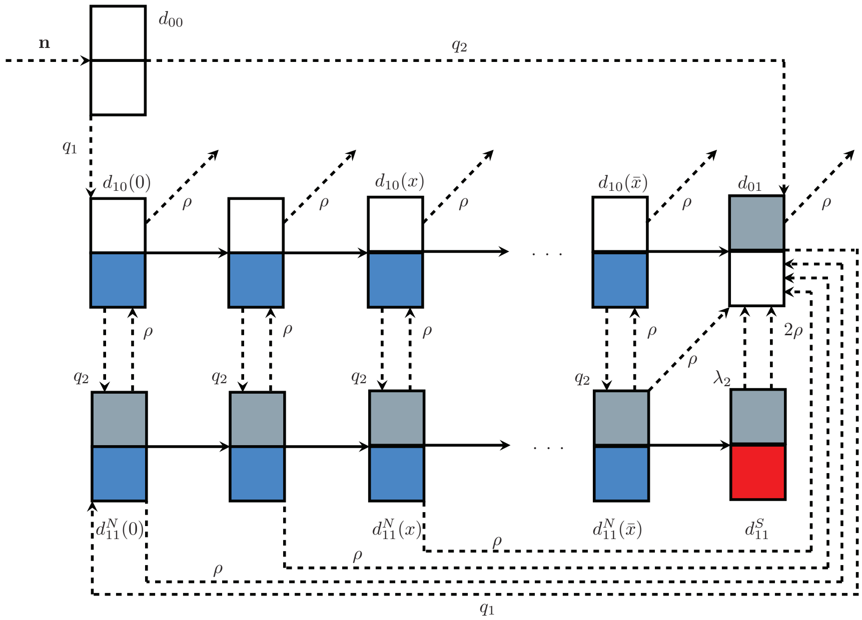


Figure 3.1: Firm transitions

rates (q_1 and q_2), respectively and μ is the efficiency of the matching function.

3.2.1 Firm dynamics

Next, dynamic equations which govern the transitions of firms between different states are described where a schematic representation is shown in figure 3.1. The model builds upon the one proposed in Dawid et al. (2019) with the exception that all types of workers, regardless of their status can exit the market at some exogenous separation rate ρ. Specifically, in each period there is an inflow $\mathbf{n}$ of new, "empty" d_{00} firms into the market. At a rate q_1 they find a junior worker and become of d_{10} type while at a rate q_2 they find a senior worker and transition into d_{01} state. At the steady state $\dot{d}_{00} = 0$ such that:

$$\dot{d}_{00} = n - (q_1 + q_2)d_{00} \quad \Rightarrow d_{00} = \frac{n}{q_1 + q_2} \tag{3.3}$$

Considering the stock of $d_{10}(x)$ firms, which have a junior worker with human capital level x, the inflow is given by firms with both positions filled, where the junior worker is not yet searching on-the-job for a senior position: $d_{11}^N(x)$, which lose their senior worker. The outflow occurs either if the junior worker exits (at a rate ρ) or if the firm finds a senior worker from the secondary market (at a rate q_2). The inflow into $d_{11}^N(x)$ state, on the other hand, comes from $d_{10}(x)$ firms that hire a senior worker, while the outflow occurs at a rate 2ρ since both workers can be exogenously separated with the firm. Hence, the system of first order linear differential equations is given by:

$$\begin{cases} \partial d_{10}(x)/\partial x &= -(\rho + q_2)d_{10}(x) + \rho d_{11}^N(x) \\ \partial d_{11}^N(x)/\partial x &= q_2 d_{10}(x) - 2\rho d_{11}^N(x) \end{cases}$$

The eigenvalues of the corresponding coefficient matrix are $-\rho$ and $-(q_2 + 2\rho)$ which leads to the following general solution:

$$\begin{cases} d_{10}(x) & = & k_1\rho e^{-\rho x} + k_2 e^{-(q_2+2\rho)x} \\ d_{11}^N(x) & = & k_1 q_2 e^{-\rho x} - k_2 e^{-(q_2+2\rho)x} \end{cases}$$

The total stock of d_{11}^N firms is found by integrating $d_{11}^N(x)$ over the interval $[0..\bar{x}]$ where $\bar{x}$ is the market promotion cutoff:

$$d_{11}^N = \int_0^{\bar{x}} d_{11}^N(x)dx = \frac{k_1 q_2}{\rho}(1 - e^{-\rho\bar{x}}) - \frac{k_2}{q_2 + 2\rho}(1 - e^{-(q_2+2\rho)\bar{x}}) \tag{3.4}$$

Similarly, the total stock of d_{10} firms is found by integrating $d_{10}(x)$ over the interval $[0..\bar{x}]$:

$$d_{10} = \int_0^{\bar{x}} d_{10}(x)dx = k_1(1 - e^{-\rho\bar{x}}) + \frac{k_2}{q_2 + 2\rho}(1 - e^{-(q_2+2\rho)\bar{x}}) \tag{3.5}$$

In order to find k_1 and k_2, we use the initial conditions $q_1 d_{00} = d_{10}(0)$ and $q_1 d_{01} = d_{11}^N(0)$, which state that the stock of d_{10} firms in which the junior worker has no professional experience equals the stock of "empty" firms who just found a junior worker. The second initial condition shows similarly that the stock of d_{11}^N firms in which the junior worker has 0 experience equals the the stock of d_{01} firms who just hired a junior worker from the pool of workers in simple jobs. The equations imply that $k_1\rho + k_2 = q_1 d_{00}$ and $k_1 q_2 - k_2 = q_1 d_{01}$, respectively. Let us first consider the stock of firms which have both positions filled and the junior worker is already searching on the external market: d_{11}^S. The outflow of firms from this state is $(\lambda_2 + 2\rho)d_{11}^S$ which is due to the junior worker moving to a different firm (λ_2) or due to either of the workers exiting the market (2ρ). The inflow, on the other hand, equals all $d_{11}^N(\bar{x})$ firms, i.e. d_{11}^N firms in which the junior worker becomes eligible for promotion. In the steady state, we get:

$$0 = \dot{d}_{11}^S = d_{11}^N(\bar{x}) - (\lambda_2 + 2\rho)d_{11}^S \quad \Rightarrow \quad d_{11}^S = \frac{d_{11}^N(\bar{x})}{\lambda_2 + 2\rho} = \frac{k_1 q_2 e^{-\rho\bar{x}} - k_2 e^{-(q_2+2\rho)\bar{x}}}{\lambda_2 + 2\rho} \tag{3.6}$$

Next, consider the stock of firms with senior workers only: d_{01}. Firms which employ a junior worker only promote this worker once s/he reaches $\bar{x}$ experience level. Hence, there is an inflow $d_{10}(\bar{x})$ into state d_{01}. Further, at a rate λ_2 searching junior workers find a senior position on the external market, change firms and the d_{11}^S firms enter d_{01} state. Additionally, d_{11}^S firms could lose both workers at a rate ρ due to exit. This implies that there is inflow $(\lambda_2 + 2\rho)d_{11}^S$ into d_{01} state. Next, ρd_{11}^N is the outflow of d_{11}^N firms due to exit of the junior worker. These firms then transition into d_{01} state. And finally, at a rate q_2 entrant firms d_{00} find a senior worker and become of type d_{01}. At a rate ρ, d_{01} firms lose their worker and at a rate q_1 they fill their junior vacancy. Hence, $(\rho + q_1)d_{01}$ is the outflow of state d_{01}. Combining all expression, substituting in (3.3), (3.4) ,(3.6) and evaluating d_{10} at $x = \bar{x}$ we find the steady state stock of d_{01} firms, $\dot{d_{01}} = 0$:

$$d_{01} = \frac{k_1(\rho e^{-\rho\bar{x}} + q_2)}{\rho + q_1} - \frac{\rho k_2(1 - e^{-(q_2+2\rho)\bar{x}})}{(\rho + q_1)(q_2 + 2\rho)} + \frac{q_2 n}{(\rho + q_1)(q_1 + q_2)} \tag{3.7}$$

	Value		Value		Value
r	0.010	γ	0.003	ρ	0.014
β	0.500	s	0.100	μ	0.069
c_1	0.500	c_2	2.000	α_1	0.500
d_1	0.200	d_2	0.100	α_2	0.500

Table 3.1: Values of exogenous parameters

The two initial conditions can be then re-written as:

$$\begin{cases} k_1\rho + k_2 &= \frac{nq_1}{q_1+q_2} \\ k_1 q_2 - k_2 &= q_1\left(\frac{k_1(\rho e^{-\rho\bar{x}}+q_2)}{\rho+q_1} - \frac{\rho k_2(1-e^{-(q_2+2\rho)\bar{x}})}{(\rho+q_1)(q_2+2\rho)} + \frac{q_2 n}{(\rho+q_1)(q_1+q_2)}\right) \end{cases}$$

Solving this system for k_1 and k_2 we find:

$$\begin{cases} k_1 &= \frac{nq_1\left(q_1\rho e^{-(q_2+2\rho)\bar{x}}+(q_2+\rho)(q_1+q_2+2\rho)\right)}{\rho(q_1+q_2)\left(q_1\rho_0 e^{-(q_2+2\rho)\bar{x}}-q_1(q_2+2\rho)e^{-\rho\bar{x}}+(\rho+q_2)(q_1+q_2+2\rho)\right)} \\ k_2 &= -\frac{nq_1^2(q_2+2\rho)e^{-\rho\bar{x}}}{(q_1+q_2)\left(q_1\rho e^{-(q_2+2\rho)\bar{x}}-q_1(q_2+2\rho)e^{-\rho\bar{x}}+(\rho+q_2)(q_1+q_2+2\rho)\right)} \end{cases}$$

Finally, the population is normalized to 1 such that:

$$e_0 + d_{10} + d_{01} + 2d_{11}^S + 2d_{11}^N = 1. \tag{3.8}$$

The stocks of junior and senior workers can be expressed as $e_1 = d_{10} + d_{11}^S + d_{11}^N$ and $e_2 = d_{01} + d_{11}^S + d_{11}^N$, respectively. On the other hand, the steady state stock of e_0 workers is: $\frac{\rho e_1+\rho e_2}{\lambda_1(\theta_1)}$.

3.3 Firm's promotion choice: decentralized equilibrium

In this section, the promotion choice of firms is endogenized using a similar approach to Dawid et al. (2019). Let β be the fraction of output that accrues to workers and $1-\beta$ be the rest of the output that firms get as profit. Then, $\pi_1(x) = (d_1 + c_1 e^{\gamma x})(1-\beta)$ denotes the flow profit of a firm from having its junior position filled where the junior worker has experience x. Next, let $\pi_2(y) = (d_2 + c_2 e^{\gamma y})(1-\beta)$ be the flow profit accruing to a firm with filled senior position and a senior worker with experience y. The present value equation of a firm which employs one junior worker rJ_{10} is given by:

$$rJ_{10}(x|x_i,\bar{x}) = \pi_1(x) - s - \rho J_{10}(x|x_i,\bar{x}) + q_2(J_{11}^N(x,\bar{x}|x_i,\bar{x}) - J_{10}(x|x_i,\bar{x})) + \frac{\partial J_{10}(x|x_i,\bar{x})}{\partial x} \tag{3.9}$$

where the first two terms capture the flow profit from the match and the cost of searching for a senior worker. At a rate ρ the junior worker quits and the firm exits the market while at a rate q_2 the firm is successful in finding a senior worker from the external market where applicants have $\bar{x}$ level of experience. That is why the present value of the firm depends not only on its choice for internal promotion $\bar{x}_i$ but also on the market promotion cutoff $\bar{x}$. The last term captures the marginal change of firm's profits stemming from increasing productivity of the junior worker.

Next, the present value of a firm with both positions filled with a junior worker with experience x and a senior worker with experience y is given by:

$$rJ_{11}^N(x,y) = \pi_1(x) + \pi_2(y) - \rho(J_{11}^N(x,y) - J_{10}(x)) - \rho(J_{11}^N(x,y) - J_{01}(y)) + \frac{\partial J_{11}^N(x,y)}{\partial x} \tag{3.10}$$

where the indirect dependence on $\{x_i, \bar{x}\}$ is suppressed for ease of notation. The first two terms are the flow profits of the firm, the third and the fourth capture the fact that at a rate ρ the firm loses its senior or its junior worker and moves to state $J_{10}(x)$ or $J_{01}(y)$, respectively. The last term, is the gain from increasing output of the junior worker over time. The present value of a firm with one senior worker with experience y is:

$$rJ_{01}(y) = \pi_2(y) - s - \rho J_{01}(y) + q_1(J_{11}^N(0,y) - J_{01}(y)). \tag{3.11}$$

At a rate ρ the worker retires and the firm exits the market, while at a rate q_1 the firm is successful in finding an inexperienced junior worker and transitions to state $J_{11}^N(0,y)$. Further, the present value of a firm that has both workers and the junior worker is already eligible for promotion rJ_{11}^S is:

$$rJ_{11}^S(\bar{x}_i,y) = \pi_1(\bar{x}_i) + \pi_2(y) - \rho(J_{11}^S(x,y) - J_{01}(\bar{x}_i)) - (\rho + \lambda_2)(J_{11}^S(x,y) - J_{01}(y)) \tag{3.12}$$

where $\pi_1(\bar{x}_i) + \pi_2(y)$ is the flow profit of the firm. At a rate ρ the senior worker exits, the junior one is instantaneously promoted and the firm transitions into state $J_{01}(\bar{x}_i)$. At a rate ρ the junior worker exits, while at a rate λ_2 the junior worker is finds a senior job in a different firm and quits. In both cases the firm transitions into state $J_{01}(y)$. Finally, the present value of a new firm which enters the market rJ_{00} is given by:

$$rJ_{00} = -2s + q_1(J_{10}(0) - J_{00}) + q_2(J_{01}(\bar{x}) - J_{00}) \tag{3.13}$$

where $-2s$ is the flow cost that the firm incurs from searching in both sub-markets. At a rate q_1 it finds an inexperienced junior worker and moves into state $J_{10}(0)$ and at a rate q_2 it finds a senior worker and moves to state $J_{01}(\bar{x})$. An entering firm maximizes its present value with respect to the promotion timing $\bar{x}_i$ and the optimal choice is:

$$\bar{x}_i^*(\bar{x}) = \underset{\bar{x}_i \geq 0}{\operatorname{argmax}}\, J_{00}(\bar{x}_i, \bar{x}). \tag{3.14}$$

Below, a symmetric Nash equilibrium $x_i^*(\bar{x}) = \bar{x}$ is analysed. The solution procedure for finding the decentralized equilibrium is discussed in detail in appendix A. In a nutshell, we find $J_{10}(x)$ and $J_{11}^N(x,\bar{x})$ from the first order linear differential equations in terms of two integration constants. The two integration constants are then found from two boundary conditions. The first one $J_{10}(\bar{x}_i) = J_{01}(\bar{x}_i)$ states that the present value of the firm with a junior worker with experience $\bar{x}_i$ and no senior worker is equal to the present value of the firm if the worker is immediately promoted. The second boundary condition $J_{11}^N(\bar{x}_i,\bar{x}) = J_{11}^S(\bar{x}_i,\bar{x})$

Variable	Value	Interpretation	Variable	Value	Interpretation
q_1	0.053	Junior vacancy-filling rate	$4(d_{10}(\bar{x}) + \rho d_{11}^S)/e_1$	0.026	Promotion rate
q_2	0.027	Senior vacancy-filling rate	$4\lambda_2 d_{11}^S/e_1$	0.042	Job-to-job trans. rate
λ_1	0.090	Junior job-finding rate	n	0.004	Entering firms
λ_2	0.177	Senior job-finding rate	d_{00}	0.049	Firm distribution
θ_1	1.696	Junior market tightness	d_{10}	0.102	Firm distribution
θ_2	6.544	Senior market tightness	d_{01}	0.179	Firm distribution
e_0	0.135	Workers in simple jobs	d_{11}^N	0.269	Firm distribution
e_1	0.394	Workers in junior jobs	d_{11}^S	0.023	Firm distribution
e_2	0.471	Workers in senior jobs	$\bar{x}$	40	Optimal prom. timing

Table 3.2: Decentralized equilibrium. Promotion and job-to-job transition rates are in annual terms.

states that at the promotion cutoff of firm i, the present value changes from $J_{11}^N(\bar{x}_i, \bar{x})$ to $J_{11}^S(\bar{x}_i, \bar{x})$ and that the junior worker starts searching for a senior job. Also, in order to find $J_{01}(y)$, we need an expression for $J_{01}(\bar{x})$. In equilibrium it must be then true that $J_{01}(\bar{x}) = J_{01}(y|_{y=\bar{x}})$. The decentralized equilibrium is found from (3.3)-(3.8) which determine the distribution of firms and workers, (3.1)-(3.2) which define the transition rates and the first order condition of the value function of an entering firm J_{00} with respect to the promotion timing.

Because of the complexity of the best response function, an analytical analysis is not feasible. Therefore, the decentralized equilibrium is characterized numerically. The values of the exogenous parameters are summarized in table 3.1. Most of them are chosen to be exactly the same as in the model of Dawid et al. (2019). The exceptions are provided in the last column of table 3.1. The exit rate ρ is slightly lower (compared to $\rho = 0.015$ in Dawid et al. (2019)) reflecting the fact that all workers exit the market, not only the senior ones. The next three parameters are due to the different matching technology. The efficiency of the matching function (μ) is chosen such that $\bar{x} = 40$ is the general equilibrium outcome of the model. This is also comparable to Dawid et al. (2019) where $\bar{x} = 45$ is a general equilibrium. Here, the equilibrium promotion timing is lower since there is a positive probability that the junior worker will be exogenously separated from the firm which gives an incentive to the firms to speed up promotions. The model is calibrated on quarterly basis, so $\bar{x} = 40$ corresponds to 10 years of professional experience which junior workers need before becoming eligible for promotion. Finally, recall that α_1 and α_2 are the elasticities of the junior and senior vacancy-filling rates, respectively. Their values are set $= \beta$ such that the Hosios conditions are fulfilled in both sub-markets. Then, the values of the resulting variables are summarized in table 3.2.

It is evident that hiring junior workers is much easier than finding senior workers from the external market ($q_1 > q_2$). This is reflected also in the job-finding rates, such that it is much easier for workers to find a senior position compared to finding their first professional job ($\lambda_2 > \lambda_1$). There are fewer workers competing for e_2 jobs compared to young and inexperienced workers, searching for e_1 positions ($e_0 > d_{11}^S$). Consequently, the senior market is approximately four times tighter than the junior one. Further, in equilibrium firms choose $\bar{x}$ such that there is high probability that they are in d_{11}^N state. This is favourable since in that state firms operate with both positions filled, while the treat of losing a worker comes

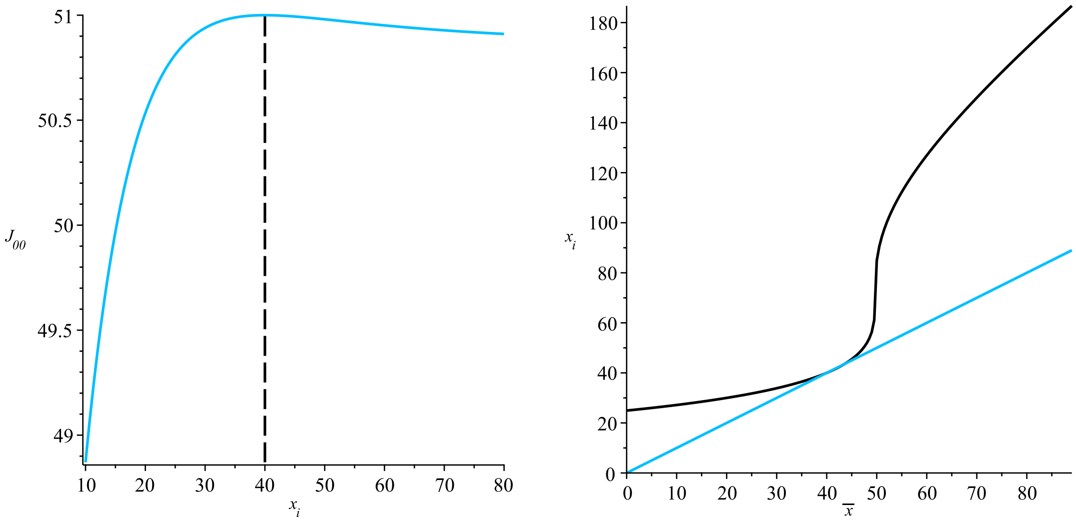


Figure 3.2: Left panel: Objective function of firm i and the optimal choice $\bar{x}_i(\bar{x})$ for a fixed market promotion cutoff $\bar{x} = 40$ and fixed transition rates. Right panel: Optimal response function $\bar{x}_i(\bar{x})$ for different values of $\bar{x}$ and constant transition rates.

only from the exogenous separation rate. The left panel of figure 3.2 displays the objective function J_{00} of an entering firm i, given that the market promotion cutoff is $\bar{x} = 40$. The right panel of the same figure shows the optimal response function of an entering firm (black curve) for varying market promotion timing and fixed transition rates (blue curve). First of all, it is evident that $x_i^*(\bar{x} = 40) = 40$ so that $\bar{x} = 40$ is a symmetric general equilibrium. Secondly, the result of Dawid et al. (2019) of strategic complementarity of firms' promotion choices is preserved under the current specification of the model. This can be inferred from the positively sloped response curve of an entering firm. If the average promotion time in the market is increasing, an entering firm has an incentive to also choose a higher promotion requirement. Given that external candidates have a higher experience level, the firm prefers to delay promoting its own junior worker provided that it can find a highly qualified worker from the market.

Furthermore, due to the strategic complementarity the equilibrium is not unique. The second equilibrium is at $\bar{x} \approx 43.55$ as can be seen in figure 3.17 in Appendix B. The right panel of the figure provides a close up of the optimal response function where the two equilibria can be distinguished. However, $\bar{x} \approx 43.55$ is not a stable equilibrium, therefore in the analysis we focus on the unique stable one: $\bar{x} = 40$.

3.3.1 Firm distribution and transition rates

Many of the main properties of the model are discussed in Dawid et al. (2019). However, here few of the modelling assumptions differ, so it is worth noting some of the main qualitative differences. Unlike Dawid et al. (2019), in this specification of the model, job-to-job transitions are the more important channel for upward mobility. This is the result of choosing a different matching technology which allows for higher elasticity of the job-finding rates with respect to the promotion timing compared to the urn-ball matching technology employed in Dawid et al. (2019) where the search intensity of workers determines to a great extend their job-finding

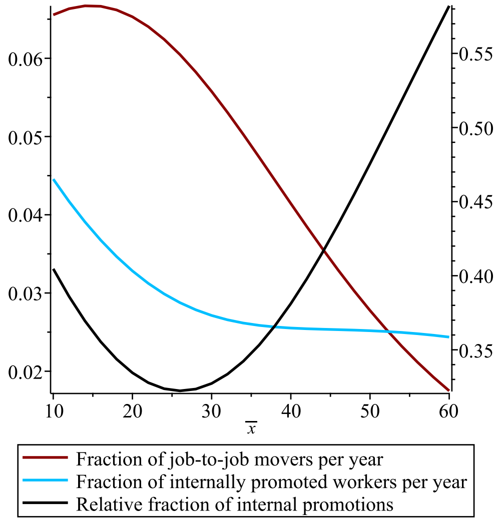


Figure 3.3: Relative importance of the different channels for upward mobility of junior workers.

probabilities. Also, the relative importance of internal promotions compared to job-to-job transitions is non-monotone in the promotion timing such that for low $\bar{x}$ the fraction of internally promoted workers relative to all promotions is decreasing and starts increasing for larger $\bar{x}$ (see fig 3.3). For low promotion requirement, junior workers are more likely to be in a firm where the senior position is already taken. Hence, they are more likely to have to search on the external market in order to gain promotion. On the contrary, with higher $\bar{x}$ the stock of workers eligible for promotion decreases since each junior worker has to attain a higher level of human capital. During this time, the senior worker in the firm might retire and the probability that s/he is replaced by another senior worker from the market is lower. Hence, the relative importance of promotions for upward mobility starts to increase, similarly to the result of Dawid et al. (2019).

3.4 Welfare analysis

Previously, we have derived the optimal promotion time that an entering firm chooses in order to maximize the present value of its profits. In this section, we investigate whether the firm's choice is also socially optimal. The welfare analysis proceeds in two steps. In the first we fix the inflow of new firms per period: **n**. In the second step, the stock of firms is determined via a free-entry condition.

3.4.1 Fixed firm entry

Since workers are risk-neutral, the social planner maximizes total output, which is the sum of the match surplus generated by all workers in junior and senior jobs as well as those at

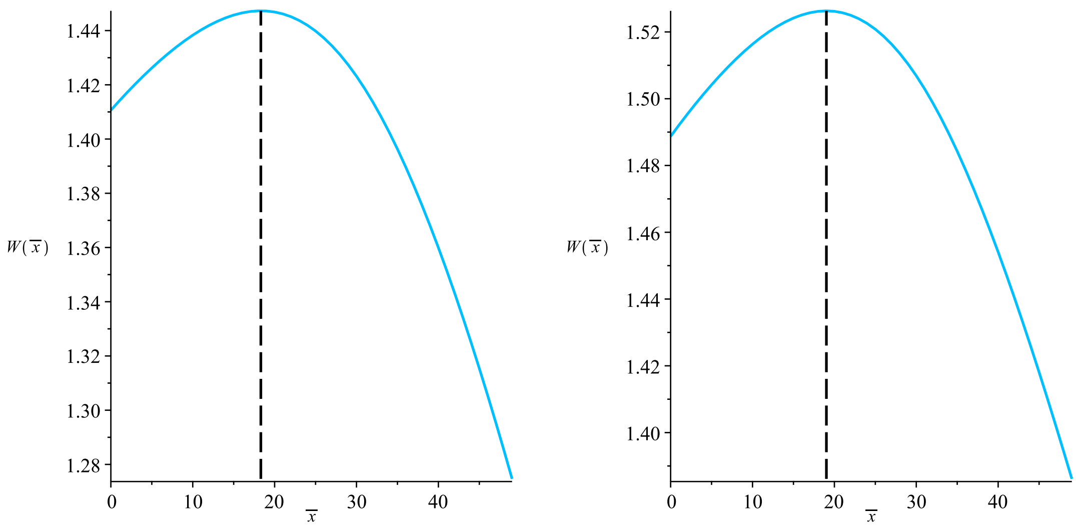


Figure 3.4: Left panel: Welfare for varying $\bar{x}$ and $y_0 = 0$. Maximum is achieved at $\bar{x}^S \approx 18.3$. Right panel: welfare for varying $\bar{x}^S$ and $y_0 = 0.7$. Maximum is achieved at $\bar{x}^S \approx 19$

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level e_0 net of costs:

$$\max_{\bar{x}} \quad \mathrm{W}(\bar{x}) = \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx + \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx + (d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S$$
$$+ (d_2 + c_2 e^{\gamma \bar{x}})(d_{01} + d_{11}^N + d_{11}^S) + y_0 e_0 - s(2d_{00} + d_{10} + d_{01})$$

The social planner chooses the optimal promotion timing $\bar{x}$ while facing the same matching constraints as firms and workers: $\{\dot{d}_{00}, \dot{d}_{10}, \dot{d}_{01}, \dot{d}_{11}^N, \dot{d}_{11}^S, \dot{e}_0\}$. At this stage we also impose a fixed number of entering firms per period n which ensures that the total number of firms does not vary by much for different promotion cutoffs. This restriction allows us to sequentially analyse the potential externalities that might drive an inefficient outcome in the model. The social planner's constrained maximization problem is solved numerically under the simplifying assumption that $r \to 0$ and we proceed the analysis by comparing welfare for different steady-states arising by varying the promotion cutoff.

First of all, looking at the different terms entering the welfare function, the first two determine the total output of junior workers who are still accumulating human capital and are not eligible for promotion. Output of junior workers in d_{10} firms is then:

$$\int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx = \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x})(k_1 \rho e^{-\rho x} + k_2 e^{-(q_2 + 2\rho) x}) dx$$
$$= d_1 \left[\frac{k_1 \rho}{\rho} (1 - e^{-\rho \bar{x}}) + \frac{k_2}{2\rho + q_2} (1 - e^{-(2\rho + q_2)\bar{x}}) \right]$$
$$+ c_1 \left[\frac{k_1 \rho}{\rho - \gamma} (1 - e^{(\gamma - \rho)\bar{x}}) + \frac{k_2}{2\rho + q_2 - \gamma} (1 - e^{-(2\rho + q_2 - \gamma)\bar{x}}) \right]$$

Decentralized eq.				Socially efficient eq.			
$\bar{x}$	40	e_0	0.135	$\bar{x}$	19	e_0	0.113
q_1	0.0531	e_1	0.394	q_1	0.0436	e_1	0.325
q_2	0.0271	e_2	0.471	q_2	0.1087	e_2	0.562
λ_1	0.0901	Promotion rate	0.026	λ_1	0.1099	Promotion rate	0.033
λ_2	0.1770	Job-to-job trans. rate	0.042	λ_2	0.0441	Job-to-job trans. rate	0.064
θ_1	1.696	θ_2	6.544	θ_1	2.523	θ_2	0.405
W	1.4541			W	1.5263		

Table 3.3: Decentralized vs. socially efficient equilibrium with fixed firm entry. Promotion and job-to-job transition rates are in yearly terms.

Similarly, the output of all junior workers employed in d_{11}^N firms is:

$$\int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx = \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x})(k_1 q_2 e^{-\rho x} - k_2 e^{-(q_2+2\rho)x}) dx$$
$$= d_1 \left[\frac{k_1 q_2}{\rho}(1 - e^{-\rho \bar{x}}) - \frac{k_2}{2\rho + q_2}(1 - e^{-(2\rho+q_2)\bar{x}}) \right]$$
$$+ c_1 \left[\frac{k_1 q_2}{\rho - \gamma}(1 - e^{(\gamma-\rho)\bar{x}}) - \frac{k_2}{2\rho + q_2 - \gamma}(1 - e^{-(2\rho+q_2-\gamma)\bar{x}}) \right]$$

Summing the two and simplifying leads to:

$$\int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx + \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx$$
$$= k_1(\rho + q_2) \left(\frac{d_1(1 - e^{-\rho \bar{x}})}{\rho} + \frac{c_1(1 - e^{(\gamma-\rho)\bar{x}}))}{\rho - \gamma} \right)$$

which is the total output of junior workers who are not yet searching for senior positions. Next, total output of those junior workers who are eligible for promotion is simply $(d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S$. On the other hand, the output of all senior worker is: $(d_2 + c_2 e^{\gamma \bar{x}})(d_{01} + d_{11}^N + d_{11}^S)$ and y_0 is the output of workers in e_0 jobs. Finally, we denote the socially efficient promotion cutoff as:

$$\bar{x}^S = \underset{\bar{x} \geq 0}{\operatorname{argmax}} \, W(\bar{x}).$$

Figure 3.4 plots the welfare function for two values of the productivity of workers in simple jobs: y_0. In the left-hand panel, y_0 is set to 0, which means that workers in e_0 jobs have no output, whereas in the right-hand panel it is assumed that $y_0 = d_1 + c_1$, i.e. their productivity is equal to that of a newly hired junior worker with zero professional experience. It is straightforward that increasing the productivity parameter y_0 quantitatively increases social welfare, measured on the y-axis. Further, higher y_0 induces later socially optimal promotion cutoff. Specifically, for $y_0 = 0$, $\bar{x}^S = 18.32$, while for $y_0 = d_1 + c_1 = 0.7$ it is $\bar{x}^S = 19.03$. This is due to the fact that $y_0 = 0$ is the extreme assumption that workers in simple jobs do not contribute at all to total output. Hence, the social planner puts higher weight on minimizing the stock of such workers. Quantitatively, however, the effect on $\bar{x}^S$ of relaxing $y_0 = 0$ is small. For the rest of the analysis, it will be assumed that $y_0 = d_1 + c_1$.

From welfare perspective it is not optimal to promote junior workers to senior positions

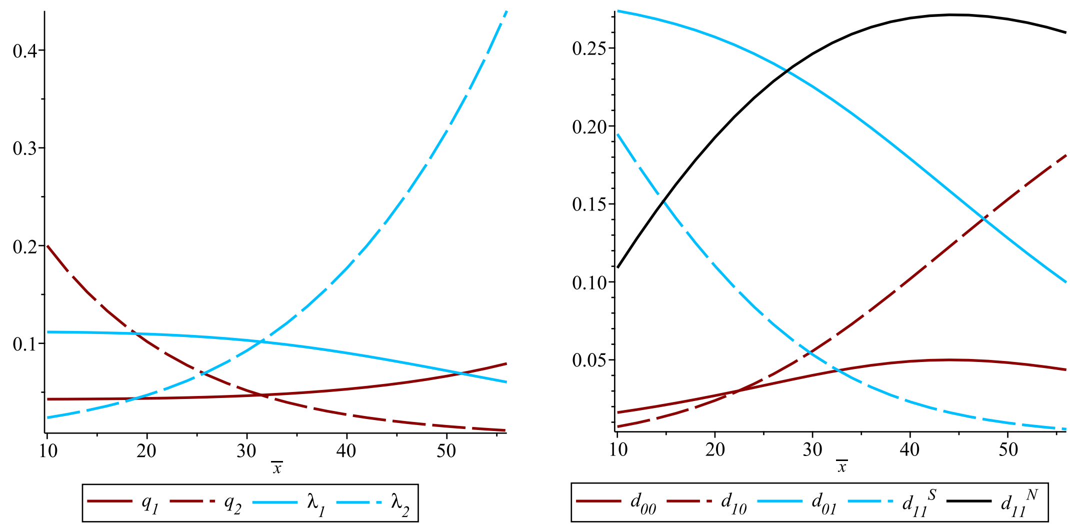

Figure 3.5: Comparative statics with respect to the promotion cutoff $\bar{x}$ and fixed firm entry. Left panel: transition rates. Right panel: firm distribution.

right away even though senior jobs are more productive, irrespective of worker's accumulated experience ($d_1 + c_1 < d_2 + c_2$). This is similar to the decentralized equilibrium. However, the social planner chooses an earlier promotion cutoff than firms do: $\bar{x}^S = 19.03$ vs. $\bar{x} = 40$. The two equilibria are compared side by side in table 3.3. At $\bar{x}^S \approx 19$, fewer workers are in e_0 and e_1 jobs while more are employed in senior positions. Furthermore, because of the lower promotion cutoff workers reach the promotion threshold faster and more of them are eligible for promotion. This substantially increases both the promotion and the job-to-job transition rates. In the decentralized equilibrium, 2.6% of junior workers are promoted internally per year while another 4.2% change employers to gain a promotion. In the socially optimal equilibrium those number increase to 3.3% and 6.4%, respectively, which corresponds 27% increase in annual promotion rate and 52.4% increase in annual job-to-job transitions.

Further, figure 3.5 displays the adjustment of transition rates (left panel) and firm types (right panel) as a function of promotion timing, with fixed inflow of new firms n. Higher promotion requirement reduces the stock of competing workers searching for senior jobs (d_{11}^S) and leads to more competing senior vacancies ($d_{00} + d_{10}$). Therefore, the senior job-finding rate λ_2 increases multiple-fold in $\bar{x}$. Also since competition between firms for senior workers increases, the senior vacancy-filling rate q_2 declines. In terms of the junior job-finding rate λ_1: lower stock of competing junior vacancies and more workers searching in the junior sub-market suppresses λ_1 as $\bar{x}$ increases. For the same reasons the junior job-filling rate q_1 increases in $\bar{x}$. The centralized equilibrium is thus characterized by lower promotion requirement, lower firm competition for senior workers, equivalently less tight senior market and higher firm competition for junior workers and a tighter junior market.

At $\bar{x} \approx 19$ total welfare is approximately 5% higher than at the decentralized equilibrium: $\bar{x} = 40$. This welfare gain can be decomposed into several parts. On the one hand, there is a change in workers' productivity resulting from the different promotion cutoffs. Particularly, earlier promotion requirement means that average productivity in the pool of junior worker will be lower. Similarly, the output of senior workers will also be lower if firms promote their junior workers at a lower human capital level. On the other hand, a change in $\bar{x}$ induces a redistribution of firm and worker types. While, lower $\bar{x}$ reduces average output per worker employed in a professional job it might induce higher welfare, provided it redistributes workers across hierarchical levels in a more efficient way. Finally, a change in the promotion cutoff leads to a new equilibrium number of firms. To quantify these effects, we decompose the difference in welfare under the socially optimal promotion cutoff $W(\bar{x}^S)$ and under the decentralized equilibrium $W(\bar{x})$ into gain (or loss) that is due to worker productivity differences in the two sub-markets, gain (loss) that is due to the different distribution of workers across hierarchical levels and gain (loss) that is due to change in the firm stock. The difference can be expressed with the following 15 elements:

$$\begin{aligned}
W(\bar{x}^S) - W(\bar{x}) &= \underbrace{(c_1(e^{\gamma c^S} - e^{\gamma c}))(p_1^N(\bar{x}))}_{\Delta(1)} + \underbrace{(d_1 + c_1 e^{\gamma c^S})(p_1^N(\bar{x}^S|_{nF(\bar{x})}) - p_1^N(\bar{x}))}_{\Delta(2)} \\
&+ \underbrace{(d_1 + c_1 e^{\gamma c^S})(p_1^N(\bar{x}^S) - p_1^N(\bar{x}^S|_{nF(\bar{x})}))}_{\Delta(3)} + \underbrace{(c_1(e^{\gamma\bar{x}^S} - e^{\gamma\bar{x}}))d_{11}^S(\bar{x})}_{\Delta(4)} \\
&+ \underbrace{(d_1 + c_1 e^{\gamma\bar{x}^S})(d_{11}^S(\bar{x}^S|_{nF(\bar{x})}) - d_{11}^S(\bar{x}))}_{\Delta(5)} + \underbrace{(d_1 + c_1 e^{\gamma\bar{x}^S})(d_{11}^S(\bar{x}^S) - d_{11}^S(\bar{x}^S|_{nF(\bar{x})})}_{\Delta(6)} \\
&+ \underbrace{(c_2(e^{\gamma\bar{x}^S} - e^{\gamma\bar{x}}))p_2(\bar{x})}_{\Delta(7)} + \underbrace{(d_2 + c_2 e^{\gamma\bar{x}^S})(p_2(\bar{x}^S|_{nF(\bar{x})}) - p_2(\bar{x}))}_{\Delta(8)} \\
&+ \underbrace{(d_2 + c_2 e^{\gamma\bar{x}^S})(p_2(\bar{x}^S) - p_2(\bar{x}^S|_{nF(\bar{x})}))}_{\Delta(9)} - \underbrace{s(v_1(\bar{x}^S|_{nF(\bar{x})}) - v_1(\bar{x}))}_{\Delta(10)} \\
&- \underbrace{s(v_1(\bar{x}^S) - v_1(\bar{x}^S|_{nF(\bar{x})}))}_{\Delta(11)} - \underbrace{s((v_2(\bar{x}^S|_{nF(\bar{x})}) - v_2(\bar{x})))}_{\Delta(12)} - \underbrace{s(v_2(\bar{x}^S) - v_2(\bar{x}^S|_{nF(\bar{x})}))}_{\Delta(13)} \\
&+ \underbrace{y_0(e_0(\bar{x}^S|_{nF(\bar{x})}) - e_0(\bar{x}))}_{\Delta(14)} + \underbrace{y_0(e_0(\bar{x}^S) - e_0(\bar{x}^S|_{nF(\bar{x})}))}_{\Delta(15)}
\end{aligned} \tag{3.15}$$

where $p_2(\bar{x}) = d_{01}(\bar{x}) + d_{11}^N(\bar{x}) + d_{11}^S(\bar{x})$ is the stock of firms that have the senior position filled, given the market promotion time: $\bar{x}$ and $p_2(\bar{x}^S) = d_{01}(\bar{x}^S) + d_{11}^N(\bar{x}^S) + d_{11}^S(\bar{x}^S)$ is the stock of such firms under the socially efficient promotion timing. Next, we denote with $p_2(\bar{x}^S|_{nF(\bar{x})})$ the stock of firms with senior workers given that the total number of firms is fixed to its decentralized equilibrium value but the promotion cutoff is the socially efficient one. For all following definitions, the same distinctions hold: $(\bar{x})$ denotes the value of the variable under the decentralized equilibrium while $(\bar{x}^S)$ stands for its value in the socially efficient steady-state and $(\bar{x}^S|_{nF(\bar{x})})$ evaluates the value of the variable under the socially optimal promotion but assuming the total stock of firms found in the decentralized equilibrium. Next, $p_1^N = d_{10} + d_{11}^N$ is the stock of firms with junior workers who are not yet searching. On the other hand, the total stock of firms which have the junior position filled is $p_1^N + d_{11}^S$. Further, $v_1 = d_{00} + d_{01}$ and $v_2 = d_{00} + d_{10}$ are the stocks of vacancies in the junior and senior market, respectively.

Let us first consider the difference in total output of senior jobs under the two equlbria: $(d_2 + c_2 e^{\gamma\bar{x}^S})p_2(\bar{x}^S) - (d_2 + c_2 e^{\gamma\bar{x}})p_2(\bar{x})$. Rearranging the terms and adding and subtracting $c_2 e^{\gamma\bar{x}^S} p_2(\bar{x})$ and $(d_2 + c_2 e^{\gamma\bar{x}^S})(p_2(\bar{x}^S|_{nF(\bar{x})})$, the difference can be re-written as parts (7),

$\frac{W(\bar{x}^S)-W(\bar{x})}{W(\bar{x})}(\%)$	$\Delta(1)$	$\Delta(2)$	$\Delta(3)$	$\Delta(4)$	$\Delta(5)$	$\Delta(6)$	$\Delta(7)$	$\Delta(8)$
	≈ -0.39	≈ -7.98	≈ -0.055	-0.05	4.5	0.23	-4.46	15.1
	$\Delta(9)$	$\Delta(10)$	$\Delta(11)$	$\Delta(12)$	$\Delta(13)$	$\Delta(14)$	$\Delta(15)$	**Total**
	-1.3	0.5	-0.11	-0.68	-0.03	-1.27	0.23	$\approx 5\%$

Table 3.4: Numerical decomposition of the welfare gain

(8) and (9) of the decomposition. Component (7) is interpreted as the productivity effect contributing to the change in welfare. The next term of the decomposition: (8) fixes the productivity of workers to the one under the socially efficient equilibrium, and traces the change in worker distribution assuming that total number of firms does not alter. This can be interpreted as the worker and firm re-distribution effect resulting from the new promotion cutoff. The final component: (9) captures the welfare change which is due to firm stock change. Similarly, the difference in total output of junior workers in d_{11}^S firms: $(d_1 + c_1 e^{\gamma \bar{x}^S}) d_{11}^S(\bar{x}^S) - (d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S(\bar{x})$ can be re-written as parts (4), (5) and (6) of the decomposition. Again, the first term is the change in welfare due to productivity differences, the second is the gain or loss that stems from worker re-distribution, while the third reveals the effect of change in the total stock of firms.

In order to decompose the welfare change that is due to difference in productivity and stock of e_1 workers who are still accumulating experience, we use the mean value theorem to approximate the mean human capital level of such workers employed in d_{10} and d_{11}^N firms. Let $e_1^N(x)$ be the stock of e_1 non-searching workers with experience x. The first order linear differential equation that characterizes changes in $e_1^N(x)$, $0 \leq x \leq \bar{x}$ is: $\partial e_1^N(x)/\partial x = -\rho e_1^N(x)$. At a rate ρ such workers exit the market. The solution is then $e_1^N(x) = N e^{-\rho x}$ where N can be found from the initial condition $e_1^N(0) = \lambda_1 e_0$, i.e. at a rate λ_1 workers in e_0 employment find a professional junior job and start their career with no professional experience. This implies that $N = \lambda_1 e_0$ and the general solution to the first order linear differential equation is written as: $e_1^N(x) = \lambda_1 e_0 e^{-\rho x}$. This expression is equivalent to $d_{10}(x) + d_{11}^N(x)$, i.e. the stock of firms which have a junior worker who is still accumulating experience. By the mean value theorem since $e_1^N(x)$ is continuous on the interval $[0, \bar{x}]$ and differentiable on $(0, \bar{x})$, there exists c such that $e_1^{N'}(c) = (e_1^N(\bar{x}) - e_1^N(0))/(\bar{x})$. For the decentralized equilibrium, we find that $c \approx 19.07$ while for the socially efficient equilibrium $c^S \approx 9.3$. We then use these numerical values to estimate the three effects of switching between the decentralized and socially optimal steady states with respect to e_1 employment of non-searching workers. This results in components (1), (2) and (3) of the decomposition. Even though this is an approximation, it can give us an indication to which of the effects is quantitatively larger.

Next, we need to account for changes in the stock of vacancies and its contribution to welfare. Firstly, $-s(v_1(\bar{x}^S|_{nF(\bar{x})}) - v_1(\bar{x}))$ shows the change in total junior vacancy cost stemming only from the new promotion cutoff. Secondly, the term $-s(v_1(\bar{x}^S) - v_1(\bar{x}^S|_{nF(\bar{x})}))$ accounts for the firm stock adjustment. Similar calculations are done for the contribution of total senior vacancy cost (components (12) and (13)). Finally, we take into account the effect of adjustment of the number of workers in simple jobs where the term $y_0(e_0(\bar{x}^S|_{nF(\bar{x})}) - e_0(\bar{x}))$ shows the change in output of such workers holding the number of firms fixed, while $y_0(e_0(\bar{x}^S) - e_0(\bar{x}^S|_{nF(\bar{x})}))$ allows for changes in the firm stock.

Table 3.4 summarizes the value of each term in the decomposition in percentage terms. Components (1) + (4) + (7) $\approx -4.94\%$ can be interpreted as the total *productivity effect* of changing the promotion timing. Further, (2) + (5) + (8) + (10) + (12) + (14) $\approx 10.51\%$ is the total *redistribution of workers effect* of switching between the two steady states. Finally, (3) + (6) + (9) + (11) + (13) + (15) $\approx -0.76\%$ is the *stock of firms adjustment effect.* It is evident that the welfare gain stems from the redistribution of workers across hierarchical levels and predominantly from employing more workers in senior jobs (component (8)). Even though there is lower average output per worker, in the socially efficient equilibrium, this negative effect is outweighed by the gain from having more e_2 workers. Furthermore, due to higher junior job-finding rate in the socially efficient equilibrium, workers move out of e_0 jobs faster, which leads to fewer workers at the e_0 level. This is associated with loss of output and a corresponding welfare decline of 1.27% (component (14)). However, this effect is dominated by the fact that the difference in e_0 workers has moved into professional jobs which are at least as productive as the simple jobs. Finally, there is a 0.76% welfare loss associated with smaller equilibrium number of firms (nF) under socially efficient equilibrium ($nF(\bar{x}^S) = 0.609$ vs. $nF(\bar{x}) = 0.622$). However, this effect is quantitatively small and is driven by the fixed firm entry. Overall, we can conclude under the decentralized equilibrium, there is loss in allocative efficiency, i.e. workers are inefficiently distributed across hierarchical levels, because firms choose a promotion requirement that is too high.

In order to identify the drivers of this inefficient outcome, note that firm's incentive to delay internal promotions is two-fold. On the one hand, firms would like to reduce turnover on level one. Turnover on level one increases with earlier promotion and with higher senior job-finding rate. So, a straightforward way for firms to retain junior workers is to delay promoting them. However, choosing higher promotion requirement induces general equilibrium effects which mitigate firm's incentive to delay internal promotions. Firstly, when a single firm decides to promote later, it imposes a negative externality on all other firms because its higher promotion choice reduces the number of potential candidates in the external market for experienced workers, or in other words, reduces the senior vacancy-filling rate q_2. Strategic complementary implies that other firms then also increase their promotion threshold in response. When all firms delay promotions the senior vacancy-filling rate is substantially suppressed which leads to many unfilled, competing senior vacancies. This externality is not internalized by firms as shown by the social planner's solution.

The second general equilibrium effect is associated with the senior job-finding rate and is the following: higher promotion requirement reduces the number of applicants on the secondary market so whenever the junior worker reaches the cutoff experience s/he finds a senior job with a different firm much faster in case promotion is not possible. This is evident by the steeply increasing senior job-finding rate λ_2 in $\bar{x}$ (see the left panel of figure 3.5). Hence, once the worker reaches $\bar{x}$ there is a very high probability of separation which is not favourable for the firm. To illustrate this, figure 3.6 show comparative statics with respect to λ_2 keeping all other rates equal to the ones under the decentralized equilibrium. The blue curve shows the benchmark scenario. The black curve is the optimal response of an individual firm assuming $\lambda_2 > \lambda_2^{eq}$, i.e separation probability once the worker reaches $\bar{x}$ increases. The firm's optimal response is then to delay internal promotions even further in order to keep its

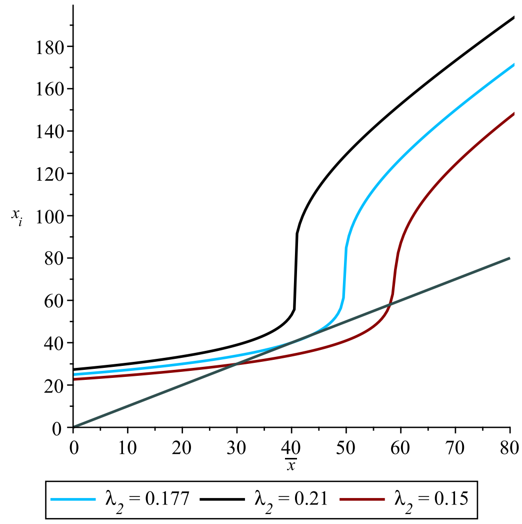

Figure 3.6: Comparative statics with of the effect of the senior job-finding rate on firm's promotion decision.

worker over a longer period. The opposite is true if $\lambda_2 < \lambda_2^{eq}$. Firm's optimal strategy is then to choose earlier promotion cutoff since the treat of losing the worker once s/he is eligible for promotion is reduced.

Second incentive of firms to delay internal promotions comes from the expected profit associated with hiring a senior worker from the external market. Note that the expected output of a senior match depends on the average promotion timing on the market. Higher experience level of potential external candidates gives incentive to firms to delay internal promotions since the gains associated with hiring a senior worker from the market increase. Overall, even though general equilibrium effects mitigate to some extent the incentive of firms to delay promotions too much, it is evident that the decentralized market cannot internalize the negative externality associated with the strategic complemetarity of firms' promotion decisions. This leads to inefficiently high equilibrium promotion cutoff under which too many senior positions are vacant which in turn suppresses total output. Thus the paper identifies a novel externality in the context of human capital accumulation that leads to an inefficient market outcome, namely in a setting with competitive firms and endogenous promotion decisions, strategic complemetarity of promotion choices pushes up the promotion requirements "too high" than what would be optimal from output maximizing perspective. This result also highlights that certification gives to much power to firms since junior workers have to stay with the employer that provides their evaluation. Because of their strategic considerations, firms exploit the power that certification gives them which leads to an inefficient aggregate outcome.

Effects of productivity and educational parameters

Next, we explore the effect of education, which is proxied by the parameters c_1 and c_2. On the one hand, assuming higher c_1 would correspond to higher general schooling attainment such that new workers, just starting their professional career are more productive. Similarly, higher c_2 can be interpreted as higher competence among professional workers, regardless

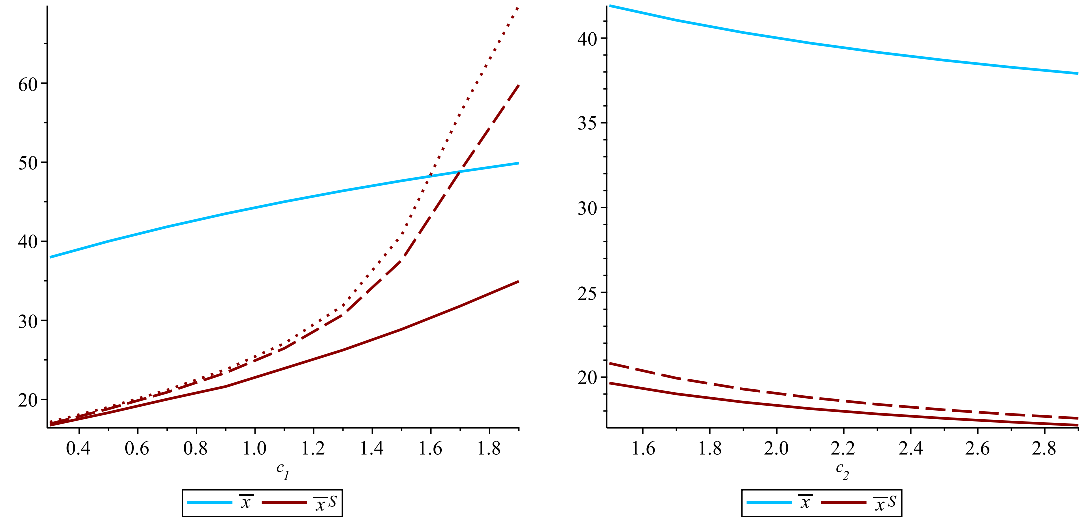

Figure 3.7: Left panel: comparative statics of the effect of productivity parameter c_1 on firm's promotion and socially optimal promotion cutoffs for fixed n and $y_0 = 0$ (red solid curve), $y_0 = c_1$ (red dashed curve) and $y_0 = d_1 + c_1$ (red dotted curve). Right panel: comparative statics of the effect of productivity parameter c_2 on firm's promotion and socially optimal promotion cutoffs for fixed n and $y_0 = 0$ (red solid curve), $y_0 = d_1 + c_1$ (red dashed curve).

of their practical experience. In our benchmark scenario $c_1 = 0.5$ while $c_2 = 2$ and in this section we vary the two parameters and compare how the decentralized ($\bar{x}$) and the socially efficient ($\bar{x}^S$) equilibria respond to the changes. Figure 3.7 displays the result.

As expected, the two parameters have an opposite effect on the optimal promotion timing. Higher c_1 means that workers in e_1 jobs are more productive so firms can afford to keep them longer in junior jobs. On the other hand, increasing c_2 leads to earlier promotion since the foregone profits associated with keeping the workers at level one increase. Qualitatively, the socially optimal $\bar{x}^S$ responds in the same way with respect to the two parameters. However, it is evident from the left panel of figure 3.7 that it is crucially important how productivity of young workers in simple jobs is defined. The solid red curve plots the case where $y_0 = 0$, i.e. those workers have 0 output. In this case $\bar{x}^S < \bar{x}$ for all plausible values of c_1[2]. Since e_0 workers do not contribute to overall output, it is optimal to put a high weight on minimizing the stock of such workers. If the promotion threshold is set too high that would mean that workers will spend a lot of time in the junior jobs, reducing the vacancies on that level. Thus, finding a professional job for e_0 workers will be more difficult, which implies that high promotion requirement is not optimal. On the other hand, the dashed red curve plots the case $y_0 = c_1$ while the dotted red curve assumes that $y_0 = d_1 + c_1$ such that output of e_0 workers is the same as the one of a junior worker who just got hired and has no professional experience. We see that depending on the assumption on y_0 there are parameter settings for which it is possible that the socially optimal and decentralized equilibrium coincide. For very high values of c_1 and corresponding high productivity of workers in simple jobs we could also have that case $\bar{x}^S > \bar{x}$, i.e. firms would promote inefficiently early. However, this would require a substantial increase in c_1 compared to the benchmark scenario and effectively assuming that productivity at the two hierarchical layers is almost identical for a given level of human

[2]Note that c_1 has to be smaller than c_2.

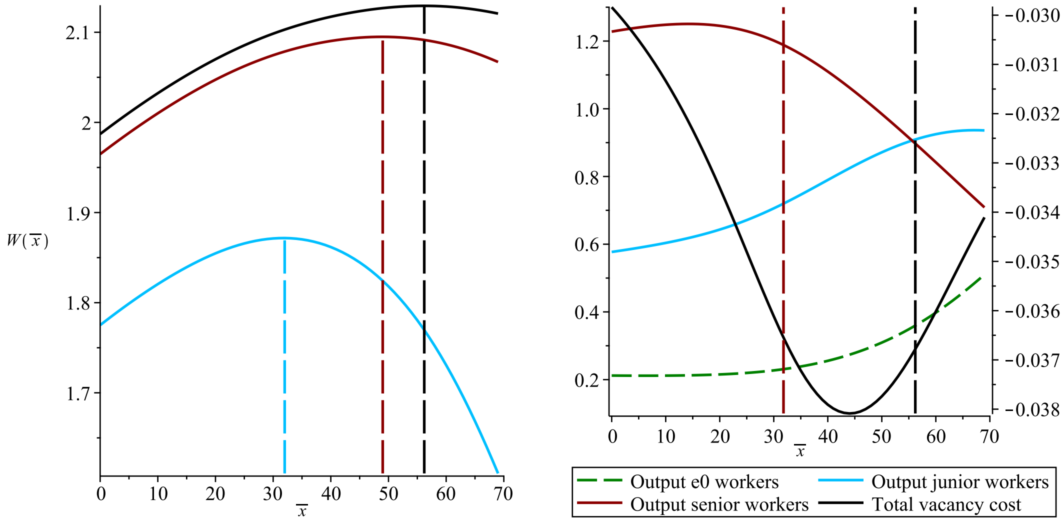

Figure 3.8: Left panel: Comparative statics of welfare with respect to productivity of workers in simple jobs: y_0 and $c_1 = 1.7$. Blue curve: $y_0 = 0$: $x^S \approx 31.8$; red curve: $y_0 = c_1$: $x^S \approx 48.9$; black curve: $y_0 = d_1 + c_1$: $x^S \approx 56.2$. Right panel: Welfare decomposition into output from workers at all possible states and vacancy cost for $c_1 = 1.7$.

capital.

More specifically, if we look into the case $c_1 = 1.7$, we can graphically disentangle the effect of y_0 on the optimal promotion timing. Figure 3.8 displays the welfare function $W(\bar{x})$ for the three specifications of y_0: $y_0 = 0$ (blue curve), $y_0 = c_1$ (red curve) and $y_0 = d_1 + c_1$ (black curve). It is straightforward that $y_0 > 0$ quantitatively increases overall welfare for all considered cutoff options. In order to illustrate the effect of y_0 on $\bar{x}^S$ we can look at the four main components that enter the welfare function. On the one hand, total output of junior workers increases as $\bar{x}$ increases (see figure 3.8, right panel, blue curve). This comes from both the fact that these workers are on average more productive and also because the stock of such workers increases. On the other hand, we can see that the output of senior workers increases at first too. This is because their productivity increases in $\bar{x}$. However, the stock of e_2 workers decreases which eventually suppresses total output of e_2 jobs (see figure 3.8, right panel, red curve).

Further, total vacancy cost (black curve in the right panel of figure 3.8, measure on the right axis) initially increases in $\bar{x}$ but the effect is quantitatively small. If $y_0 = 0$, then maximum sum of the three components is at $\bar{x}^S \approx 31.8$ (red vertical line). The green dashed line plots the output of e_0 workers for the case $y_0 = d_1 + c_1$. The stock of e_0 workers slightly declines for $\bar{x}$ close to 0 but increases after. It is evident that output of workers in simple jobs, together with the higher output of of junior workers can, under this parameter setting, compensate the loss associated with lower e_2 employment, so in order to maximize total output the planner delays internal promotions until $\bar{x}^S \approx 56.2$ (black vertical line). This implies that if jobs in the economy are fairly homogeneous with respect to their productivity, then a large increase in human capital leads to overall welfare improvements. If jobs are more heterogeneous in terms of productivity, which would be a more plausible assumption in the context of human capital accumulation and assigning workers to different hierarchical levels,

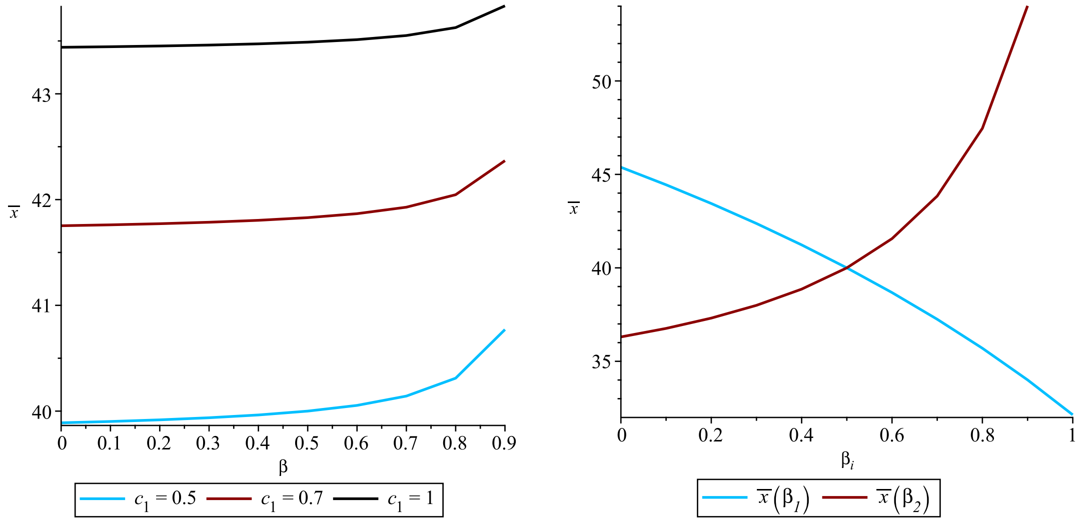

Figure 3.9: Optimal promotion and the bargaining power.

then concerns in regards to the efficient allocation of workers to jobs also play a dominant role.

Effects of workers' bargaining power

Next, we consider the effect of the parameter β which determines how the firm and the worker split the output of the match, where a share β accrues to the worker and a fraction $1-\beta$ is retained by the firm as profits. From output maximizing perspective, the social planer is not concerned with how the output is divided between the economic agents, so potentially, there is scope for welfare improvement with respect to β.

Recall that $\alpha_1 = -(\partial q_1(\theta_1)/\partial\theta_1)(\theta_1/q_1(\theta_1))$ and $\alpha_2 = -(\partial q_2(\theta_2)/\partial\theta_2)(\theta_2/q_2(\theta_2))$ are the elasticities of the vacancy-filling rates in the junior and senior market, respectively. So far we have assumed that the Hosios condition $\beta = \alpha_i$ $i = 1, 2$ is satisfied in both sub-markets. The left panel of figure 3.9 shows comparative statics of the optimal promotion timing of firms and the bargaining power for varying c_1. As discussed in the previous section, higher c_1 is associated with later promotion. This is true for all feasible values of workers' bargaining power which is evident from the upward shift of the promotion timing curves. Further, $\partial\bar{x}/\partial\beta > 0$ such that we can conclude that lower bargaining power of workers ($\beta < \alpha_i,\ i = 1, 2$) leads to welfare improvement since it induces earlier promotion. Lower β means that firms earn higher profits for a given level of human capital of the workers. This implies that they can reduce their promotion requirement without sacrificing profits even though worker productivity will on average be lower. On the other hand, as β increases, firm profits per match decrease. In order to compensate for this effect firms require higher experience level before promotion which means that on average total output per match in both sub-markets will be higher.

However, even for $\beta \to 0$ the welfare improvement would be only marginal since the change in $\bar{x}$ is quantitatively small. If we consider a scenario where workers' share of the match surplus differs in the two hierarchical levels, such that β_1 is the bargaining power of junior workers and β_2 is the bargaining power of senior workers, a different picture is

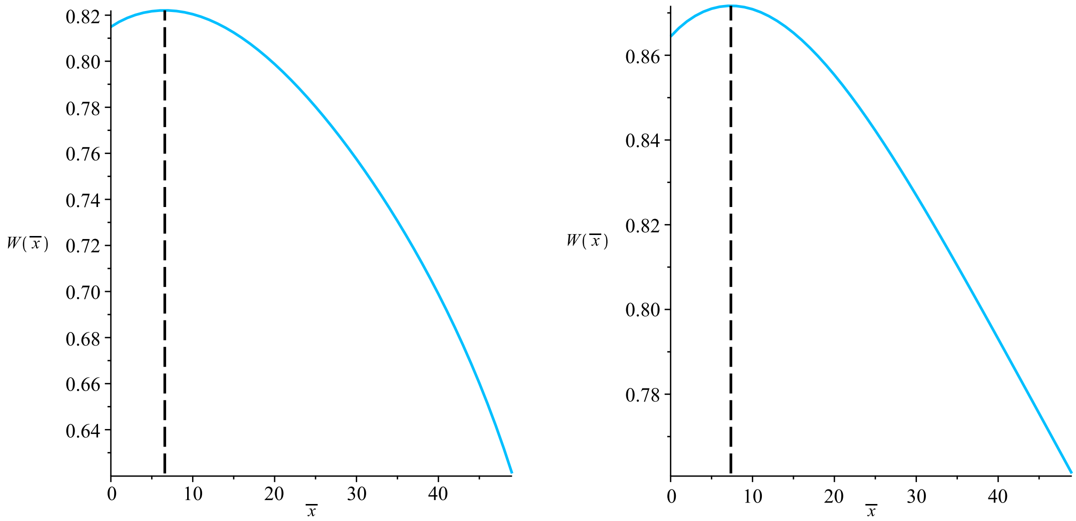

Figure 3.10: Left panel: Welfare for varying $\bar{x}$ and $y_0 = 0$. Maximum is achieved at $\bar{x}^S \approx 6.6$. Right panel: welfare for varying $\bar{x}^S$ and $y_0 = 0.7$. Maximum is achieved at $\bar{x}^S \approx 7.4$

revealed. The right panel of figure 3.9 plots the case where one of the $\beta_i,\ i = 1, 2$ is fixed at its benchmark value, while the other is varied and the optimal promotion timing. We see that for fixed $\beta_2 = \alpha_2$, $\partial\bar{x}/\partial\beta_1 < 0$ (blue curve). With higher bargaining power of junior workers, firms speed up promotions since profits associated with having a worker on the lower hierarchical level decline. Hence, we can conclude that ($\beta_1 > \alpha_1$) leads to welfare improvement. The opposite is true for the relationship between $\bar{x}$ and β_2. We have that for fixed $\beta_1 = \alpha_1$, $\partial\bar{x}/\partial\beta_2 > 0$ (red curve). Firms compensate for the lower profits from senior jobs by delaying promotions. Hence, ($\beta_2 < \alpha_2$) leads to welfare improvement since it induces earlier promotions. Overall, however, the numerical simulations show that for the benchmark parameter setting and fixed firm entry, there is no combination of β_1 and β_2 that will lead to the socially efficient promotion cutoff.

3.4.2 Free-entry

In this section we let the stock of firms be determined from a free-entry condition. It is assumed that firms have to pay an entry cost K upon entering the market which can be interpreted as the cost needed for buying equipment and capital. In equilibrium this implies that the number of firms is determined at the point where $J_{00} = K$, i.e. firms enter until there are no positive profits to be gained by creating a new firm. The social planner then solves the following problem:

$$\max_{\bar{x},n} \mathrm{W}(\bar{x}) = \beta \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx + \beta \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx + \beta (d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S$$
$$+\beta (d_2 + c_2 e^{\gamma \bar{x}})(d_{01} + d_{11}^N + d_{11}^S) + y_0 e_0$$

subject to the matching frictions and the free-entry condition: $\{\dot{d}_{00}, \dot{d}_{10}, \dot{d}_{01}, \dot{d}_{11}^N, \dot{d}_{11}^S, \dot{e}_0\}$ and $J_{00} = K$. Since the free-entry condition ensures that in equilibrium the profits of firms are driven down to zero, the objective of the social planner is to maximize the surplus that does

Decentralized eq.: $\bar{x} = 40$				Socially efficient eq.: $\bar{x} = 7.36$			
n	0.0039	e_0	0.135	n	0.0065	e_0	0.071
q_1	0.0531	e_1	0.394	q_1	0.0261	e_1	0.243
q_2	0.0271	e_2	0.471	q_2	0.1154	e_2	0.686
λ_1	0.0901	Promotion rate	0.026	λ_1	0.1833	Promotion rate	0.055
λ_2	0.1770	Job-to-job trans. rate	0.042	λ_2	0.0414	Job-to-job trans. rate	0.104
θ_1	1.696	θ_2	6.544	θ_1	7.019	θ_2	0.359
W	0.793			W	0.872		

Table 3.5: Decentralized vs. socially efficient equilibrium with free-entry condition. Promotion and job-to-job transition rates are in yearly terms.

not accrue to the firms. That is, the planner chooses the promotion cutoff that maximizes the steady-state wage bill together with the output of e_0 workers. The first four terms of W($\bar{x}$) are then the total output produced by e_1 and e_2 workers that is paid out as wages while the last term is the productivity of those agents who are not yet in professional employment.

Figure 3.10 plots the welfare function for $y_0 = 0$ (left panel) and $y_0 = d_1 + c_1$ (right panel). Similarly to the fixed-entry case, the quantitative difference between the two cases is very small, so subsequently it will be assumed $y_0 = d_1 + c_1$. Also similarly to the results from the previous section, the socially optimal promotion time $\bar{x}^S$ is earlier than the one chosen by the firms in the decentralized equilibrium. Further, note that in the decentralized equilibrium $J_{00}(\bar{x}) = 51$, so the entry cost K is set to 51. Table 3.5 displays the comparison between the two equilibria. In the socially efficient equilibrium, the number of workers in simple jobs is almost halved, while much more workers are employed in professional jobs and particularly, in senior ones. The lower promotion requirement leads to substantially larger senior vacancy-filling rate. Moreover, the low stock of workers competing for level one jobs, means that it is much more difficult for firms to fill their junior positions which leads to lower junior vacancy-filling rate. On the other hand, both promotions and job-to-job transitions occur more often, which is again a straightforward result from the lower promotion timing.

Further, figure 3.11 displays the adjustment of transition rates and firm stocks under free-entry as the promotion timing increases. Qualitatively, the direction of change of the transition rates in response to increasing the promotion cutoff is the same as to the one discussed for the case of fixed firm entry (see figure 3.5). Notably, the magnitude of change in the junior job-filling and finding rates: q_1 and λ_1 is much larger under firm free-entry. This is the result of labour demand effects that correspond to the change in firm stock. Figure 3.18 in Appendix B displays the adjustment of number of firms for varying promotion cutoff under fixed firm entry (left panel) and free-entry (right panel). We observe that for larger $\bar{x}$ the stock of active firms under free-entry declines substantially which magnifies the effects of promotion timing on the transition rates, particularly in the junior market. Firstly, an increase in $\bar{x}$ is associated with fewer workers in senior jobs and higher firm competition in that sub-market. Since it becomes relatively more difficult for firms to fill e_2 vacancies, profits are suppressed and fewer firms stay active on the market. In terms of the junior sub-market, the decrease in firm stock, together with the higher promotion requirement means that the market tightness decreases, with high worker competition for junior jobs, a steeper decline in junior job-finding rate (λ_1) and corresponding steeper increase in junior job-filling rate

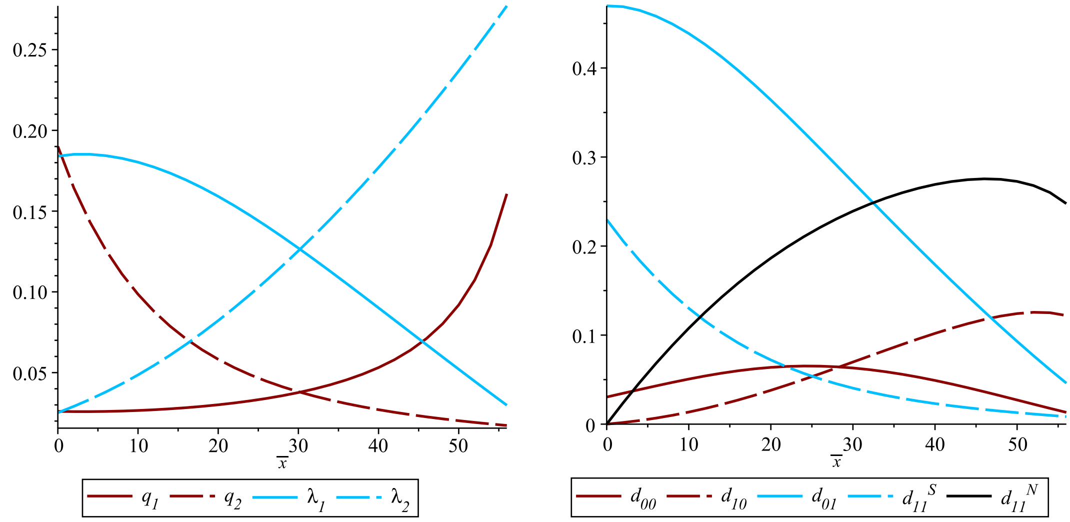

Figure 3.11: Comparative statics with respect to the promotion cutoff $\bar{x}$ under free-entry. Left panel: transition rates. Right panel: firm distribution.

(q_1). Due to free-entry then, the changes in λ_1 and q_1 are much stronger. On the flip side, because there is fewer firms for large $\bar{x}$, workers who are eligible for promotion compete for fewer vacancies and the senior job-finding rate λ_2 increases less compared to the fixed firm entry scenario. Finally, the firm distribution adjustment is also comparable to the fixed firm entry scenario. Notably, however, there are larger quantitative changes as $\bar{x}$ increases.

In terms of overall welfare, we see that the socially optimal $\bar{x}^S$ leads to approximately 10% welfare improvement compared to the decentralized equilibrium. Table 3.6 shows the decomposition of welfare difference between the two steady-states (see equation (3.15)). Note that the output from professional firms enters the respective components multiplied with β and that the vacancy cost does not enter the consideration of the social planner since it is captured by the free-entry condition. Looking at the three major effects, we observe that the productivity effect (1) + (4) + (7) leads to 6.89% welfare loss[3]. This is due to the fact that workers on both hierarchical levels are on average less productive. Moreover, this effect is larger compared to the fixed firm entry scenario since the promotion timing in the socially efficient equilibrium with free-entry is lower. Next, the redistribution of workers effect: (2) + (5) + (8) + (14) accounts for 10.33% increase in welfare due to higher professional employment and larger number of senior workers. This effect is quantitatively similar to the one found under the fixed firm entry case. Finally, the stock of firms adjustment effect: (3) + (6) + (9) + (15) contributes to further 6.48% welfare increase. In contrast to the fixed firm entry scenario, here the last effect is quantitatively large and positive. In the decentralized equilibrium, the total stock of firms is $nF(\bar{x}) = 0.622$ while it increases to $nF(\bar{x}^S) = 0.741$ in the socially efficient steady-state. This reveals that firm creation is distorted downwards compared to what would be socially optimal, which is a further source of inefficiency in the model. The reason behind this distortion will be discussed in more detail in the next sub-section.

Further, we consider the effect of the entry cost K on the market outcomes. Figure 3.12

[3]Here, $c^S \approx 3.648$.

	$\Delta(1)$	$\Delta(2)$	$\Delta(3)$	$\Delta(4)$	$\Delta(5)$	$\Delta(6)$	$\Delta(7)$	$\Delta(8)$
$\frac{W(\bar{x}^S)-W(\bar{x})}{W(\bar{x})}(\%)$	≈ -0.56	≈ -12.597	≈ 0.135	-0.08	8.4	-2.63	-6.25	17.4
	$\Delta(9)$	$\Delta(10)$	$\Delta(11)$	$\Delta(12)$	$\Delta(13)$	$\Delta(14)$	$\Delta(15)$	**Total**
	11.7	-	-	-	-	-2.87	-2.73	≈ 9.9

Table 3.6: Numerical decomposition of the welfare gain with free-entry

displays the equilibrium promotion cutoff as a function of K (left panel) and the corresponding equilibrium stock of firms (right panel). As expected, the number of active firms declines as the entry cost increases. Considering the effect of higher K on the optimal promotion timing, then there are several effects. Firstly, higher entry cost means that the present value of an entering firm must also increase. In order to achieve that firms must earn higher profits. Assuming market conditions remain constant otherwise and under fixed match output sharing rule, this is possible only if the average output per match is increased. Hence, firms have to let their junior workers accumulate more experience and delay internal promotions.

Secondly, there is a labour demand effect coming from decreasing firm competition as the equilibrium number of firms declines. Since there are less competing vacancies in both sub-markets, it is easier to fill an open vacancy and both q_1 and q_2 go up (see figure 3.19 in Appendix B). The effect of a simultaneous increase of both of those variables on $\bar{x}$ is, however, ambiguous since they have an opposite effect on the optimal promotion timing. Higher junior vacancy-filling rate is associated with earlier promotions while higher senior vacancy-filling rate leads to later internal promotions[4]. Overall, the effect of lower competition in the senior market dominates in this setting and optimal promotion timing rises in response to higher entry cost.

Similarly to the decentralized equilibrium, the socially optimal $\bar{x}^S$ increases in K. As it will be discussed below, if the condition are relatively favourable for firms, implying that many firms can stay active on the market, the social planner can maximize welfare by choosing immediate or very fast promotion and employing many workers at the high productivity senior jobs. If, however, there are few active firms because of unfavourable market conditions, such as in this case, a high entry cost, welfare is maximized by delaying promotions and increasing average match output. In the next section we explore the relationship between firm entry and the socially optimal promotion timing in more detail.

3.4.3 Constraint efficient firm entry and the bargaining power

As it has been shown in the previous section, welfare is not maximized at the Hosios level of bargaining power: $\beta = \alpha_i,\ i = 1, 2$. In this section, we numerically explore the effect of this key model parameter. Given the objective function of the social planner under free-entry, changing β influences both the decentralized and the socially optimal equilibrium. Figure 3.13 plots the comparative statics of the promotion timing in the decentralized equilibrium: $\bar{x}$ and the socially optimal one: $\bar{x}^S$ with respect to different values of β. Similarly to the fixed-entry scenario, discussed above, $\bar{x}$ is increasing in β for low values of β. However, as workers' bargaining power increases, this relationship is reversed which is in contrast to the firm fixed-entry case.

[4]This result and the intuition behind it are discussed in greater detail in Dawid et al. (2019).

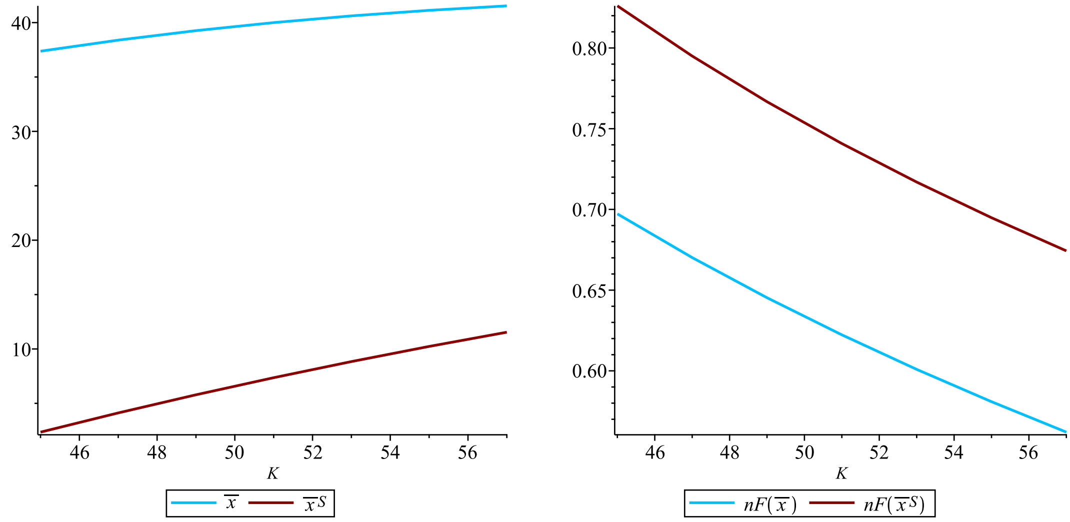

Figure 3.12: Left panel: Optimal $\bar{x}$ and $\bar{x}^S$ as a function of entry cost. Right panel: Number of firms under decentralized and socially optimal equilibrium with free-entry.

Increasing β has several effects on firms' promotion decisions. On the one hand, if a higher share of the output goes to workers, firms could compensate by delaying promotions and thus increasing output per worker. Also, as β increases, firms profits decline and fewer firms are able to stay active. Hence, many workers compete for few vacancies and the vacancy-filling rates increase. As discussed above, a simultaneous increase in both q_1 and q_2 has an ambiguous effect on $\bar{x}$. We see that for low to middling values of β the effect of decreasing firm competition on the senior market dominates, so firms delay promotions. For higher values of β, the equilibrium number of firms declines so much that the effect on promotions is reversed, i.e. increasing β is associated with a decrease in promotion timing. The stock of firms at $\beta = 0.75$ is $nF = 0.261$ which is more than twice less than in the case $\beta = 0.5$ and for $\beta > 0.75$, it approaches 0, so $\bar{x}$ cannot be computed. For such high values of workers' bargaining power, there are even fewer firms and potential vacancies and many competing searching workers in the market. Consequently, the job-filling rates increase steeply in β (see figure 3.20 in Appendix B). Also, we observe that q_1 increases faster compared to q_2. This combined with the decreasing senior job-finding rate λ_2 becomes the dominant effect and so for high values of workers' bargaining power, promotion timing in the decentralized equilibrium decreases.

Next, note that the socially efficient promotion timing also depends on β. The red curve in figure 3.13 plots $\bar{x}^S$ for different values of β. If $\beta = 0$, then the social planner maximizes the stock of e_0 workers given the matching frictions and the free-entry condition. This is the extreme case in which firms retain all of the output from the match and is not of interest for the analysis. For $\beta \in [0.3, 0.4]$ immediate promotion is optimal. Since firms retain a larger share of the total output, many firms enter the market, there is a high firm competition in both submarkets and the vacancy-filling rates are low. By choosing immediate promotions the social planner is thus able to employ many workers at the high productivity senior positions. Even though increasing $\bar{x}$ also translates into higher output once the workers are at the e_2 level, the firm competition effect dominates here. Increasing $\bar{x}$ in this case reduces q_2

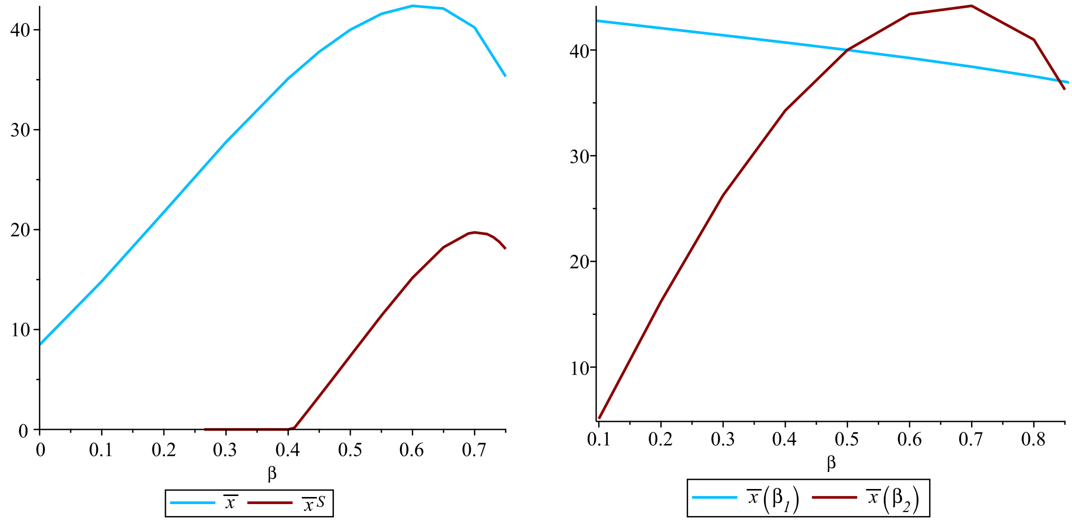

Figure 3.13: Optimal promotion and the bargaining power.

even further which suppresses the profits of firms and drives some firms out of the market. Hence, setting higher promotion requirement acts as a barrier to entry for new firms and the equilibrium stock of firms monotonically decreases. To illustrate this figure 3.21 in Appendix B displays the social planner's objective function, the firm stock and the job-filling rates for varying $\bar{x}$ and $\beta = 0.35$.

At $\beta = 0.5$, we have $\bar{x}^S = 7.4$ which is the case depicted in figure 3.10. As β increases further, so does the socially optimal promotion timing. Figure 3.22 in Appendix B display the case $\beta = 0.75$. Comparing it to the case $\beta = 0.35$, here the stock of firms is much lower for all considered promotion cutoffs. This implies that firm competition is lower and the the vacancy-filling rates are higher (right panel of figure 3.22). Setting a higher promotion requirement then increases the average output per match which leads to higher firm profits and consequently higher entry up to a certain value of $\bar{x}$. Hence, here the productivity effect dominates and welfare rises as promotions increase up from $\bar{x} = 0$. Choosing too high promotion requirement, however, suppresses q_2 drastically so it becomes difficult for firms to fill their high productivity senior jobs and again welfare starts to decline.

These considerations imply that the way firms and workers split the match output is crucial in determining the social efficiency of firm's promotion timing and entry. To explore this relationship deeper, we next assume that β_1 is the share of output that goes to junior workers and β_2 is the share of output that accrues to senior workers. In what follows, the aim is to answer the question whether there is a pair $\{\beta_1, \beta_2\}$ under which the socially optimal and the decentralized equilibrium coincide. Firstly, assuming $\beta_2 = 0.5$ is constant, then the firm's promotion choice is decreasing in β_1: $\partial\bar{x}/\partial\beta_1 < 0$ (see right panel of figure 3.13, blue curve) which is similar to the fixed entry case. Further, for fixed $\beta_1 = 0.5$, $\partial\bar{x}/\partial\beta_2$ is non-monotone mirroring the overall relationship between β and $\bar{x}$ (see right panel of figure 3.13, red curve). In the following step, we plot the decentralized and socially optimal values for the promotion timing against the bargaining power of the junior worker for fixed bargaining power of senior workers. The result is shown in figure 3.14 which plots the cases $\beta_2 = 0.35$, $\beta_2 = 0.38$ $\beta_2 = 0.4$ (top row, left to right) and $\beta_2 = 0.5$, $\beta_2 = 0.7$ $\beta_2 = 0.8$ (bottom row, left to right) . The

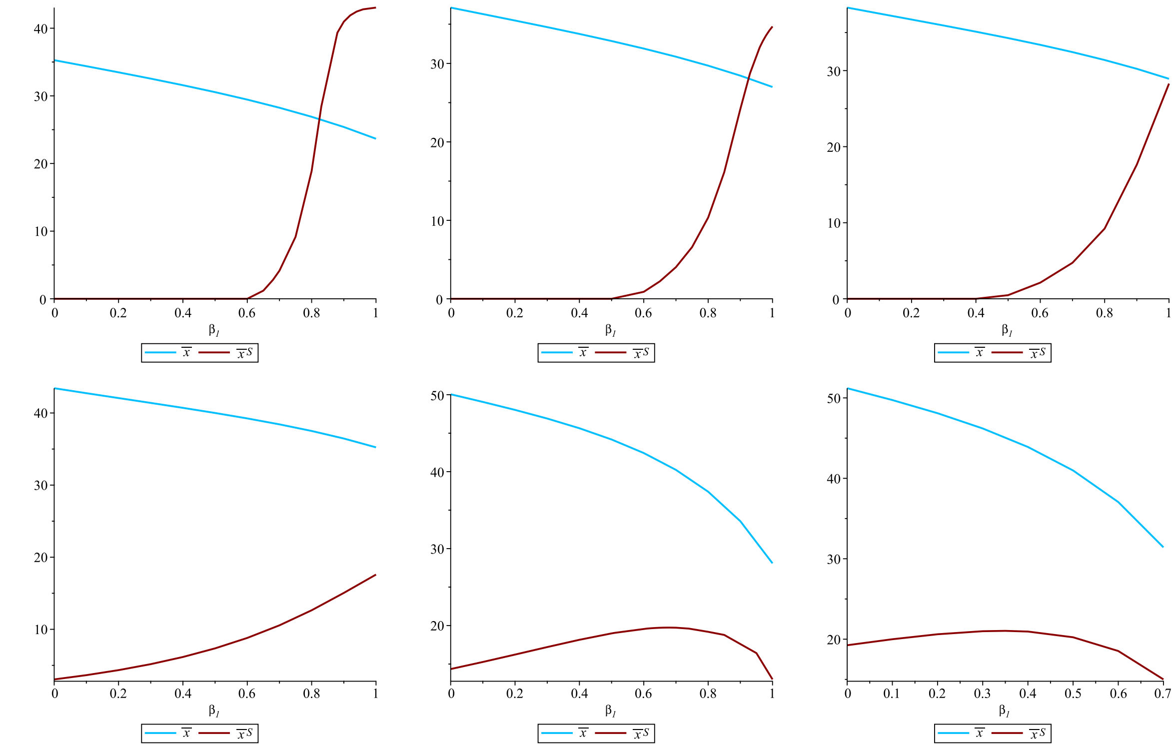

Figure 3.14: Comparative statics of decentralized and socially optimal promotion cutoffs $\bar{x}$, $\bar{x}^S$ with respect to β_1 for fixed β_2. Top row: left panel: $\beta_2 = 0.35$, middle panel: $\beta_2 = 0.38$, right panel: $\beta_2 = 0.4$.Bottom row: left panel: $\beta_2 = 0.5$, middle panel: $\beta_2 = 0.7$, right panel: $\beta_2 = 0.8$

benchmark case: $\beta_2 = 0.5$ is depicted in the left panel, bottom row of the figure. We see that there is no value of β_1 for which the social planner's promotion timing coincides with the decentralized equilibrium if $\beta_2 = 0.5$. Also, $\bar{x}$ is decreasing in the bargaining power of junior workers β_1, while $\bar{x}^S$ is increasing in it for low to middling values of β_2 (top row of the figure). Since, the social planner maximizes the total wage bill together with the output of workers in simple jobs, it follows that if the share of output that workers retain at a certain hierarchical level increases, welfare can be improved if more workers are employed in those jobs. So here, since β_2 is fixed, increasing β_1 leads to later promotions. Firms have, however, the opposite response, such that $\bar{x}$ decreases in β_1. This is the case because for higher β_1 it becomes less profitable to retain a worker at the junior level so firms choose earlier promotion timing.

Furthermore, increasing β_2 we see that the $\bar{x}$ curve shifts outwards. If senior workers receive a larger share of the match output, firms optimally slow down promotions for all plausible values of β_1. Qualitatively, the socially optimal promotion timing still increases in β_1 for lower values of β_2 (see top row of figure 3.14). The intercept and the slope of $\bar{x}^S$, however, vary greatly. For $\beta_2 = 0.38$, for instance, immediate promotions are socially optimal for low values of β_1 (middle panel, top row). The intuition behind is similar to above: since both β_1 and β_2 are relatively low, welfare is maximized by setting immediate promotions and employing more workers in senior jobs. As β_1 increases, however, the $\bar{x}^S$ curve begins to increase steeply. The numerical simulations show that there exists a pair (β_1, β_2) such that $\beta_1 > \alpha_1$ and $\beta_2 < \alpha_2$ for which the decentralized and the socially optimal equilibrium coincide.

Moreover, the pair is not unique. For instance, at $(\beta_1, \beta_2) = (\approx 0.82, 0.35)$ and $(\beta_1, \beta_2) = (\approx 0.92, 0.38)$, depicted in the left and middle top row panels of figure 3.14, the socially optimal and decentralized equilibrium coincide. In the first case: $(\beta_1, \beta_2) = (\approx 0.82, 0.35)$, we have $\bar{x} = \bar{x}^S \approx 26.5$, while for $(\beta_1, \beta_2) = (\approx 0.92, 0.38)$ it follows: $\bar{x} = \bar{x}^S \approx 28$. Out of those two, however, only the equilibrium corresponding to the pair $(\beta_1, \beta_2) = (\approx 0.82, 0.35)$ is stable. The optimal response functions for the two cases are displayed in figure 3.24 in Appendix B.

For higher values of β_2 (middle and right panel of bottom row of figure 3.14) the promotion timing that firms choose is still decreasing in β_1. The socially efficient promotion cutoff, on the other hand, exhibits a non-monotone relationship with the bargaining power of junior workers, such that it is increasing at first and starts to decline for higher values of β_1. Furthermore, the intercept of the curve increases with higher β_2 such that immediate promotion is not efficient for any value of β_1. The reason is similar to the one discussed above for the case that workers on both hierarchical levels have the same bargaining power. Further, when both β_1 and β_2 are high, $\bar{x}^S$ declines in β_1 since the number of active firms approaches 0. Figure 3.23 in Appendix 3.7 plots $\bar{x}$ and $\bar{x}^S$ for $\beta_2 = 0.9$. We see that in this case the slope of $\partial \bar{x}^S / \partial \beta_1$ is negative over the whole range where the socially optimal and decentralized equilibrium could be computed. Very few firms are active in the market if $\beta_2 = 0.9$, so increasing β_1 leads to decreasing promotion timing as the social planner maximizes the wage bill given the very few employment opportunities. However, this indicates that if $\beta_2 \geq \alpha_2$, the socially optimal and decentralized equilibrium never coincide.

The above discussion highlights that the share of output accruing to senior workers is above the value needed so that the socially optimal and decentralized equilibrium coincide, while the opposite is true for the share of output earned by junior workers. This contributes to firms' incentives to delay promotions inefficiently long which leads to under-entry of firms and a stock of e_0 workers which is above the socially efficient level. This reveals that firms are not adequately compensated for creating the high productivity e_2 jobs and therefore firm entry is biased downwards. High wages in the senior market suppress firm creation which implies that the optimal bargaining power in that market has to be below the traditional Hosios value. Moreover, the adverse effect of strategic complementary can be neutralized if the bargaining power of workers in the junior market is set above the Hosios value as to deter firms from delaying promotion inefficiently long. Under those two conditions we can find multiple equilibria for which the decentralized equilibrium is also constrained efficient. The effects on workers in different hierarchical levels, however, are diverse. If we consider the case $(\beta_1, \beta_2) = (\approx 0.82, 0.35)$, then the resulting vector of transition rates is: $\{\lambda_1 = 0.17, \lambda_2 = 0.16, q_1 = 0.03, q_2 = 0.03\}$. Comparing these values to the ones in table 3.5 implies that workers in simple jobs gain from having a higher job-finding rate compared to the decentralized equilibrium in the case $(\beta_1, \beta_2) = (0.5, 0.5)$. Workers who are searching for a senior job are in a less favourable position since their job-finding rate has decreased slightly. Finally, the wage gain associated with being promoted, either internally or via changing firms is smaller due to the fact that β_1 has increased and β_2 is lower.

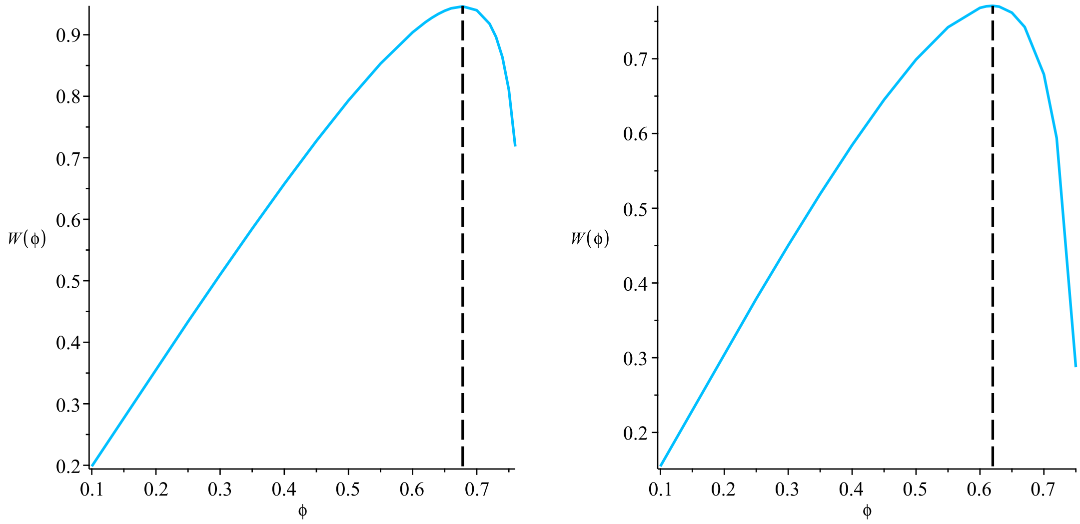

Figure 3.15: Left panel: optimal sharing rule under fixed $\bar{x} = 40$ and $y_0 = d_1 + c_1$. Maximum is achieved at $\phi = 0.678$ Right panel: optimal sharing rule under fixed $\bar{x} = 40$ and $y_0 = 0$. Maximum is achieved at $\phi = 0.619$

3.4.4 Optimal sharing rule

In the final step we relax the assumption that the social planner is constrained by the bargaining power parameter. To do so, it is assumed that the planner can choose the fraction of output that accrues to workers: ϕ. First, we fix the promotion timing to its value under the decentralized equilibrium, assuming that it remains firm's choice. Then the optimization problem becomes:

$$\max_{\phi,n} \mathrm{W}(\phi) = \phi \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx + \phi \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx + \phi(d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S$$
$$+ \phi(d_2 + c_2 e^{\gamma \bar{x}})(d_{01} + d_{11}^N + d_{11}^S) + y_0 e_0$$

subject to the matching frictions and the free-entry condition: $\{\dot{d}_{00}, \dot{d}_{10}, \dot{d}_{01}, \dot{d}_{11}^N, \dot{d}_{11}^S, \dot{e}_0\}$ and $J_{00} = K$. The left panel of figure 3.15 shows the objective function of the social planner for varying values of ϕ and fixed $\bar{x} = 40$. The maximal value is achieved at $\phi^* \approx 0.678$. Under a fixed promotion requirement, altering the sharing rule has several effects. Wages increase as ϕ increases but also the number of entering firms and consequently the vacancy-filling and job-finding rates adjust. We see that here the social planner chooses to allocate a larger fraction of the output to the workers. Hence, the direct increase in the wage bill outweighs the loss from lower firm entry. However, it is not optimal to choose values of ϕ close to 1 because the negative effect associated with the decreasing stock of firms as ϕ increases becomes too large. At $\phi^* \approx 0.678$, there are $nF(\phi*) = 0.404$ firms, compared to $nF(\phi = 0.5) = 0.622$ under the decentralized equilibrium.

Further, since under the optimal sharing rule the stock of e_0 workers increases due to the smaller number of firms, we check how much the assumption that $y_0 = d_1 + c_1$ contributes to the outcome and set $y_0 = 0$. The result, displayed in the right panel of figure 3.15, shows that setting $y_0 = 0$ reduces the optimal value of ϕ slightly to $\phi^*|_{y_0=0} \approx 0.619$, since the social planner puts a higher weight on minimizing the stock of e_0. However, qualitatively it remains

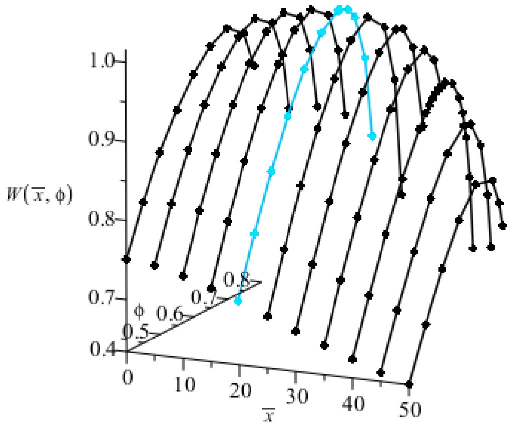

Figure 3.16: Objective function of the social planner in the space $\{\bar{x}, \phi\}$. Maximum is achieved at $\{\bar{x}^S, \phi^*\} = \{19.728, 0.706\}$.

true also under this assumption that the optimal ϕ is such that the bigger fraction of output accrues to workers.

Finally, the case when the social planner sets the sharing rule ϕ and promotion rule $\bar{x}$ simultaneously is characterized. The problem is then:

$$\max_{\phi,\bar{x},n} \mathrm{W}(\bar{x}, \phi) = \phi \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{10}(x) dx + \phi \int_0^{\bar{x}} (d_1 + c_1 e^{\gamma x}) d_{11}^N(x) dx + \phi(d_1 + c_1 e^{\gamma \bar{x}}) d_{11}^S$$
$$+\phi(d_2 + c_2 e^{\gamma \bar{x}})(d_{01} + d_{11}^N + d_{11}^S) + y_0 e_0$$

again subject to the matching frictions and the free-entry condition. The optimal pair of promotion timing and output sharing rule is given by: $\{\bar{x}^S, \phi^*\} = \{19.728, 0.706\}$ and is depicted in figure 3.16. As expected, the social planner chooses a lower promotion requirement compared to the decentralized equilibrium so as to reduce the allocative inefficiency in the economy. Hence, the stock of firms associated with the optimal pair increases compared to the case where promotion timing was kept as firm's private decision to $nF(\bar{x}^S, \phi^*) = 0.46$. Similarly to the case of fixed promotion timing, also here choosing a sharing rule is such that $\phi^* > 0.5$ is optimal.

In the previous sections it was shown that if the bargaining power of workers is relatively low, then many firms enter the market. High firm competition then implies that filling open vacancies is relatively difficult and welfare is maximized by setting immediate or very fast promotions and filling the high productivity senior jobs. However, if workers' bargaining power is relatively high, then welfare is maximized by letting workers accumulate more human capital and thus increasing average match output. Here, the results suggest that comparing the different types of allocations, the highest welfare can be achieved when workers accumulate more human capital, retain the bigger share of the match output, but the firm stock is lower compared to the cases with very high firm entry and immediate promotions.

3.5 Conclusion

This paper investigates the efficiency of the promotion choices of competing firms in a frictional labour market. Once a new firm enters the market it chooses the human capital level at which it will promote a worker from the junior to the senior level such as to maximize present value of profits. From the discussion presented in the introduction and the results of the model it is evident that different model specifications imply various possible externalities which distort human capital accumulation. Which of these are empirically relevant is still an open question. Viewing human capital accumulation from the lens of strategic interaction between firms rather than between the firm and its workers gives a different perspective to the question of over- or under-accumulation of human capital. In this paper, it has been shown that competing firms have incentive to set promotion requirements that are too high resulting in a population of workers who are inadequately distributed across hierarchical levels. The allocative inefficiency in turn suppresses overall output and welfare.

Human capital accumulation at a specific hierarchical level is one component which leads to productivity improvements. One has to also acknowledge the role of firm and worker heterogeneity, or for example, match quality. The model abstracts from those aspects of the relationship of human capital accumulation and the efficient market outcome. However, even with these limitations, it provides insight on externalities which deliver an inefficient outcome. Assuming fixed firm entry, it has been shown that the main reason for the inefficiency of the decentralized equilibrium is the strategic complementarity of firms promotion choices. Firms end up in a symmetric Nash equilibrium which is characterized by a promotion threshold that is too high compared to a socially efficient benchmark. Even though general equilibrium effects mitigate firm's incentive to delay promotions even further, the analysis shows that the negative externalities caused by the strategic complementarity of firms' promotion choices are not internalized. Comparative statics further reveal that there is no value of workers' bargaining power that can induce firms to choose the socially optimal promotion cutoff. However, welfare improvements can be achieved if workers on the senior level have a lower bargaining power while workers on the junior level have a higher bargaining power compared to the standard Hosios value.

Secondly, the model has been extended to implement a free-entry condition. As it was hinted in the fixed firm entry scenario, it has been shown that the Hosios conditions do not deliver an efficient market entry. Specifically, wages in the senior hierarchical layer are too high which suppresses profits and leads to under-entry of firms. The numerical results reveal that reducing the bargaining power of senior workers below the standard Hosios value while simultaneously increasing the bargaining power of junior workers above that value can lead to firm entry which ensures that the decentralized equilibrium is also efficient. This is the case because firms are then compensated for creating the high productivity senior jobs while their incentive to keep workers on the junior level inefficiently long is reduced. Moreover, there are multiple constrained efficient decentralized equilibria arising from different pairs of the bargaining power parameters.

Finally, allowing for simultaneous setting of the promotion timing and the output sharing rule shows that the welfare maximizing pair is such that workers retain a larger share of the output compared to firms and the promotion threshold is lower than the one chosen by firms under the decentralized equilibrium but higher than the one found when the Hosios condition is satisfied. Further insight into the efficiency of firms' promotion choices can be gained by extending the analysis in several possible directions. Endogenizing the wage bargaining mechanism is one of them. Considering worker or firm heterogeneity would be a second.

3.6 Appendix A: Calculations for the decentralized equilibrium

First, we define $\Delta J(x,\bar{x}) = J_{11}^N(x,\bar{x}) - J_{10}(x)$. Hence,

$$(r+2\rho+q_2)\Delta J(x,\bar{x}) = \pi_2(\bar{x}) + s + \rho J_{01}(\bar{x}) + \frac{\partial \Delta J(x,\bar{x})}{\partial x}$$

Denoting with K the constant of integration, the solution to this first order linear differential equation is:

$$\Delta J(x,\bar{x}) = \frac{\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x})}{r+2\rho+q_2} + Ke^{(r+2\rho+q_2)x} \tag{3.16}$$

Substituting (3.16) into (3.9), we get:

$$(r+\rho)J_{10}(x) = \pi_1(x) - s + q_2\frac{(\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x}))}{r+2\rho+q_2} + q_2Ke^{(r+2\rho+q_2)x} + \frac{\partial J_{10}(x)}{\partial x} \tag{3.17}$$

The solution is given by:

$$J_{10}(x) = \frac{d_1(1-\beta)-s}{r+\rho} + \frac{c_1(1-\beta)e^{\gamma x}}{r+\rho-\gamma} - \frac{q_2Ke^{(r+2\rho+q_2)x}}{\rho+q_2} + q_2\frac{(\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x}))}{(r+\rho)(r+2\rho+q_2)} + Ae^{(r+\rho)x}$$

where A is the constant of integration. Since, $J_{11}^N(x,\bar{x}) = \Delta J(x,\bar{x}) + J_{10}(x)$, $J_{11}^N(x,\bar{x})$ is given by the following equation:

$$\begin{aligned} J_{11}^N(x,\bar{x}) = {} & \frac{(r+\rho+q_2)(\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x}))}{(r+\rho)(r+2\rho+q_2)} + \frac{\rho Ke^{(r+2\rho+q_2)x}}{\rho+q_2} \\ & + \frac{d_1(1-\beta)-s}{r+\rho} + \frac{c_1(1-\beta)e^{\gamma x}}{r+\rho-\gamma} + Ae^{(r+\rho)x} \end{aligned}$$

Next, inserting $J_{10}(x)$ into (3.10), we have:

$$\begin{aligned} (r+2\rho)J_{11}^N(x,y) = {} & \pi_1(x) + \pi_2(y) + \rho J_{01}(y) + \frac{\partial J_{11}^N(x,y)}{\partial x} + \rho\frac{d_1(1-\beta)-s}{r+\rho} + \frac{\rho c_1(1-\beta)e^{\gamma x}}{r+\rho-\gamma} \\ & - \frac{\rho q_2 Ke^{(r+2\rho+q_2)x}}{\rho+q_2} + q_2\rho\frac{\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x})}{(r+\rho)(r+2\rho+q_2)} + \rho Ae^{(r+\rho)x} \end{aligned}$$

Denoting with D the constant of integration, the general solution is given by:

$$\begin{aligned} J_{11}^N(x,y) = {} & \frac{\pi_2(y) + \rho J_{01}(y)}{r+2\rho} + \frac{d_1(1-\beta)}{r+\rho} - \frac{s\rho}{(r+\rho)(r+2\rho+q_2)} + \frac{c_1(1-\beta)e^{\gamma x}}{r+\rho-\gamma} \\ & + \frac{\rho K}{\rho+q_2}e^{(r+2\rho+q_2)x} + Ae^{(r+\rho)x} + \frac{\rho q_2}{(r+\rho)(r+2\rho)}\left(\frac{\pi_2(\bar{x}) + \rho J_{01}(\bar{x})}{r+2\rho+q_2}\right) + De^{(r+2\rho)x} \end{aligned}$$

This equation, evaluated at $y = \bar{x}$ should return $J_{11}^N(x,\bar{x})$. We find that $D = 0$, because:

$$\frac{(\pi_2(\bar{x}) + \rho J_{01}(\bar{x}))}{r+2\rho} + \frac{\rho q_2(\pi_2(\bar{x}) + \rho J_{01}(\bar{x}))}{(r+\rho)(r+2\rho)(r+2\rho+q_2)} = \frac{(\pi_2(\bar{x}) + \rho J_{01}(\bar{x}))(r+\rho+q_2)}{(r+\rho)(r+2\rho+q_2)}$$

The present value of a d_{01} firm with a manager with experience y is given as:

$$rJ_{01}(y) = \pi_2(y) - \rho J_{01}(y) - s + q_1(J_{11}^N(0, y) - J_{01}(y))$$

which can be written as:

$$J_{01}(y) = \frac{\pi_2(y) - s + q_1 J_{11}^N(0, y)}{r + \rho + q_1} \tag{3.18}$$

Next, in order to find an expression for $J_{01}(\bar{x})$ we first evaluate $J_{11}^N(x, y)$ at $x = 0$ and $y = \bar{x}$:

$$J_{11}^N(0, \bar{x}) = \frac{(\pi_2(\bar{x}) + \rho J_{01}(\bar{x}))(r + \rho + q_2)}{(r + \rho)(r + 2\rho + q_2)} + \Theta$$

where $\Theta = \frac{d_1(1-\beta)}{r+\rho} - \frac{s\rho}{(r+\rho)(r+2\rho+q_2)} + \frac{c_1(1-\beta)}{r+\rho-\gamma} + \frac{\rho K}{\rho+q_2} + A$. Hence, substituting this into (3.18) and solving for $J_{01}(\bar{x})$, we find:

$$J_{01}(\bar{x}) = \frac{[(\pi_2(\bar{x}) - s)(r + \rho)(r + 2\rho + q_2) + q_1(r + \rho + q_2)\pi_2(\bar{x}) + q_1(r + \rho)(r + 2\rho + q_2)\Theta]}{(r + \rho)(r + \rho + q_1)(r + 2\rho + q_2) - q_1\rho(r + \rho + q_2)}$$

On the other hand, in order to find $J_{01}(y)$, we need to evaluate $J_{11}^N(x, y)$ at $x = 0$, which gives:

$$J_{11}^N(0, y) = \frac{\pi_2(y) + \rho J_{01}(y)}{r + 2\rho} + \Theta + \frac{\rho q_2}{(r + \rho)(r + 2\rho)} \left(\frac{\pi_2(\bar{x}) + \rho J_{01}(\bar{x})}{r + 2\rho + q_2} \right) \tag{3.19}$$

Plugging this in (3.18) and solving for $J_{01}(y)$, we get:

$$\begin{aligned} J_{01}(y) = & \frac{(\pi_2(y) - s)(r + 2\rho) + q_1\pi_2(y)}{(r + \rho)(r + 2\rho + q_1)} + \frac{q_1(r + 2\rho)\Theta}{(r + \rho)(r + 2\rho + q_1)} \\ & + \frac{\rho q_1 q_2(\pi_2(\bar{x}) + \rho J_{01}(\bar{x}))}{(r + \rho)(r + \rho)(r + 2\rho + q_1)(r + 2\rho + q_2)} \end{aligned}$$

Next, the present value of a d_{11}^S firm: rJ_{11}^S can be written as:

$$rJ_{11}^S(x_i, y) = \pi_1(x_i) + \pi_2(y) - \rho(J_{11}^S(x_i, y) - J_{01}(x_i)) - (\rho + \lambda_2)(J_{11}^S(x_i, y) - J_{01}(y))$$

Evaluating for $y = \bar{x}$, this gives us:

$$J_{11}^S(x_i, \bar{x}) = \frac{\pi_1(x_i) + \pi_2(\bar{x}) + \rho J_{01}(x_i) + (\rho + \lambda_2)J_{01}(\bar{x})}{r + 2\rho + \lambda_2}$$

The first boundary condition $J_{10}(x_i) = J_{01}(x_i)$ is given as:

$$\begin{aligned} J_{10}(x_i) = & \frac{d_1(1 - \beta) - s}{r + \rho} + \frac{c_1(1 - \beta)e^{\gamma x_i}}{r + \rho - \gamma} - \frac{q_2 K e^{(r+2\rho+q_2)x_i}}{\rho + q_2} + q_2\frac{(\pi_2(\bar{x}) + s + \rho J_{01}(\bar{x}))}{(r + \rho)(r + 2\rho + q_2)} \\ & + A e^{(r+\rho)x_i} = \frac{\pi_2(x_i) - s + q_1 J_{11}^N(0, x_i)}{r + \rho + q_1} = J_{01}(x_i) \end{aligned}$$

Where $J_{11}^N(0, x_i)$ is equivalent to (3.19) for $x_i = y$.

The second boundary condition $J_{11}^N(x_i,\bar{x}) = J_{11}^S(x_i,\bar{x})$ can be written as:

$$J_{11}^N(x_i,\bar{x}) = \frac{(r+\rho+q_2)(\pi_2(\bar{x})+s+\rho J_{01}(\bar{x}))}{(r+\rho)(r+2\rho+q_2)} + \frac{\rho K e^{(r+2\rho+q_2)x_i}}{\rho+q_2} + \frac{d_1(1-\beta)-s}{r+\rho}$$

$$+\frac{c_1(1-\beta)e^{x_i}}{r+\rho-\gamma} + Ae^{(r+\rho)x_i} = \frac{\pi_1(x_i)+\pi_2(\bar{x})}{r+2\rho+\lambda_2} + + \frac{\rho(\pi_2(x_i)-s+q_1 J_{11}^N(0,x_i))}{(r+2\rho+\lambda_2)(r+\rho+q_1)}$$

$$+\frac{(\rho+\lambda_2)(\pi_2(\bar{x})-s+q_1 J_{11}^N(0,\bar{x}))}{(r+2\rho+\lambda_2)(r+\rho+q_1)} = J_{11}^S(x_i,\bar{x})$$

3.7 Appendix B: Additional figures

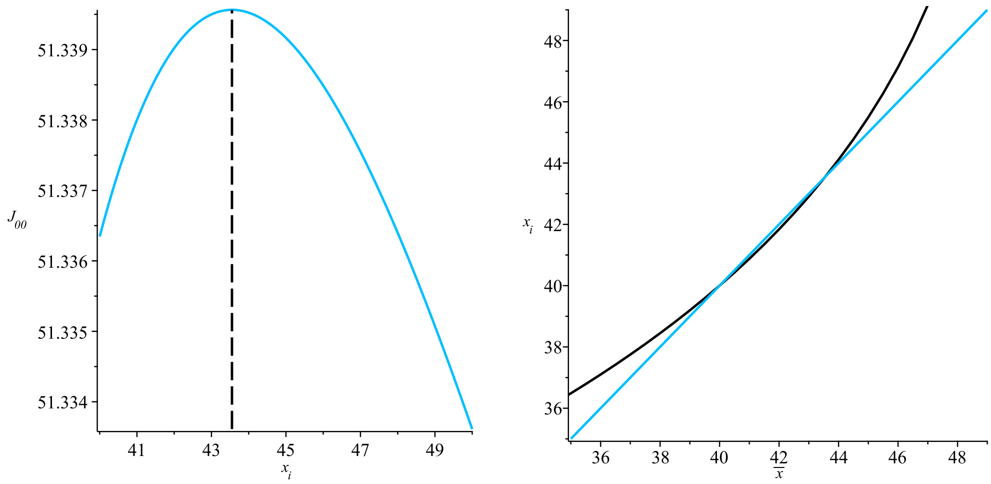

Figure 3.17: Left panel: Objective function of firm i and the optimal choice $\bar{x}_i(\bar{x})$ for a fixed market promotion cutoff $\bar{x} = 43.55$ and fixed transition rates. Right panel: Optimal response function $\bar{x}_i(\bar{x})$ for different values of $\bar{x}$ and constant transition rates.

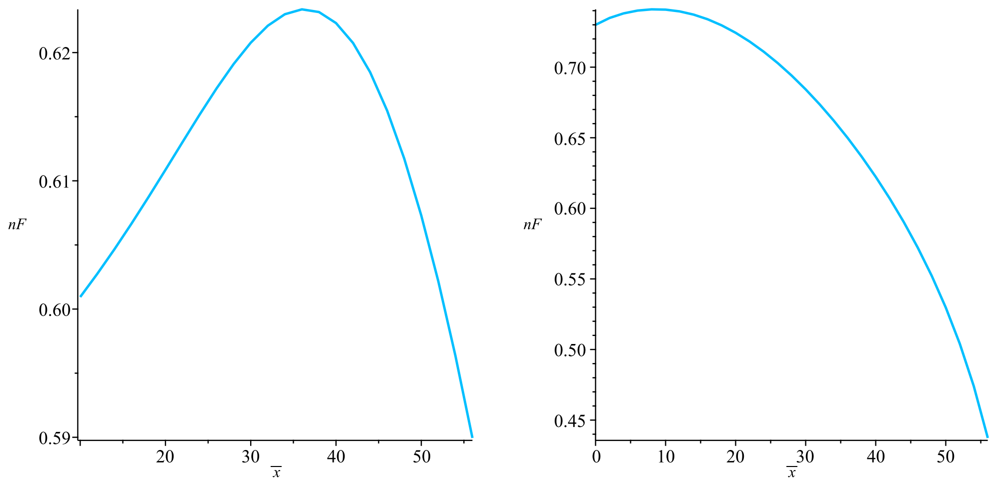

Figure 3.18: Left panel: Number of firms for fixed firm entry: $n \approx 0.004$. Right panel: Number of firms with free-entry.

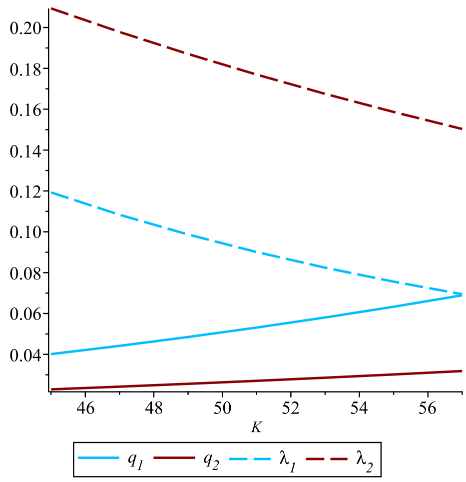

Figure 3.19: Comparative statics: equilibrium transition rates as functions of the entry cost K.

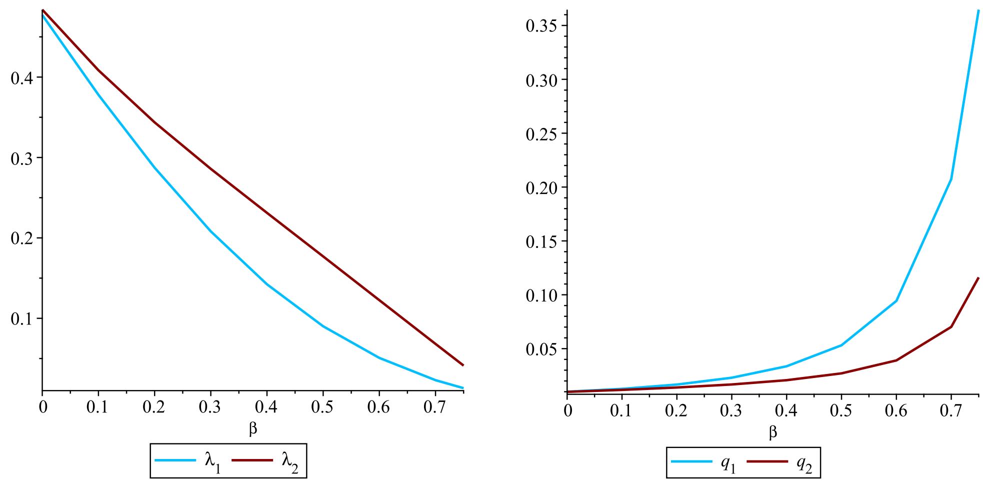

Figure 3.20: Left panel: Job-finding rates as a function of workers' bargaining power β. Right panel: Job-filling rates as a function of workers' bargaining power β.

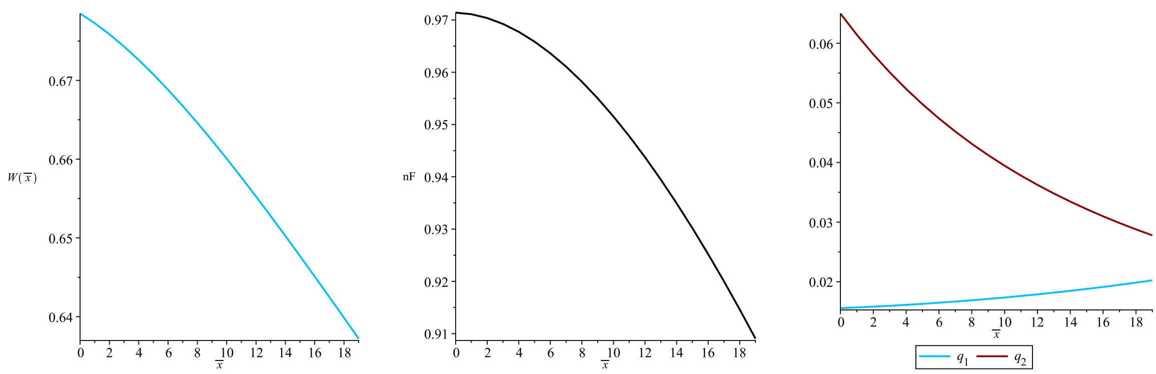

Figure 3.21: Comparative statics with respect to promotion timing $\bar{x}$ for $\beta = 0.35$ and free-entry. Left panel: overall welfare. Middle panel: stock of firms. Right panel: junior vacancy-filling rate (blue curve) and senior vacancy-filling rate (red curve).

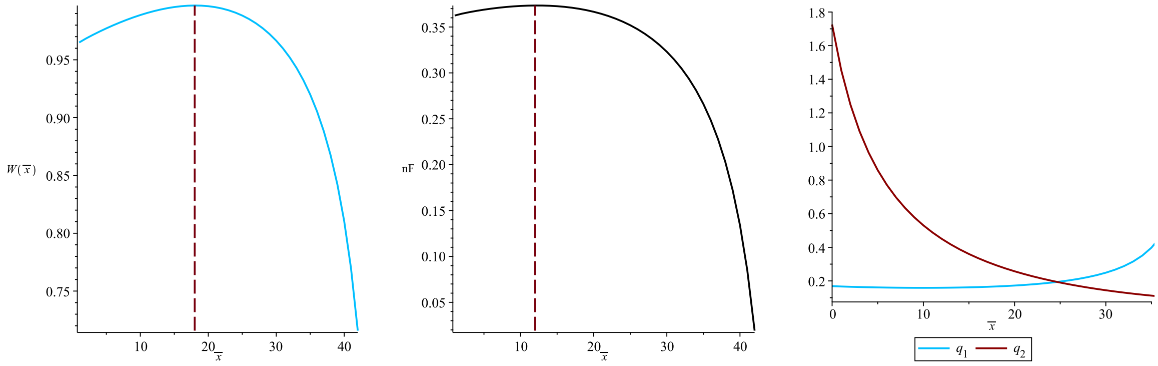

Figure 3.22: Comparative statics with respect to promotion timing $\bar{x}$ for $\beta = 0.75$ and free-entry. Left panel: overall welfare. Middle panel: stock of firms. Right panel: junior vacancy-filling rate (blue curve) and senior vacancy-filling rate (red curve).

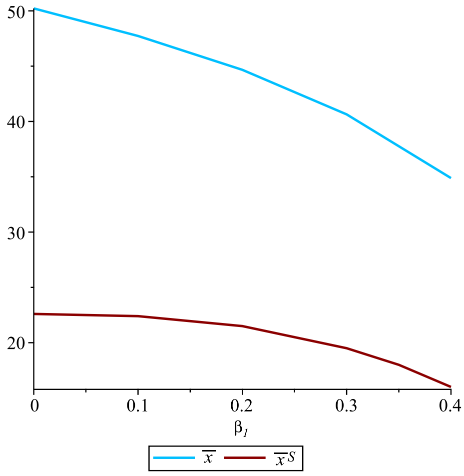

Figure 3.23: Decentralized and socially efficient equilibrium as a function of the bargaining power of junior workers: β_1 for $\beta_2 = 0.9$.

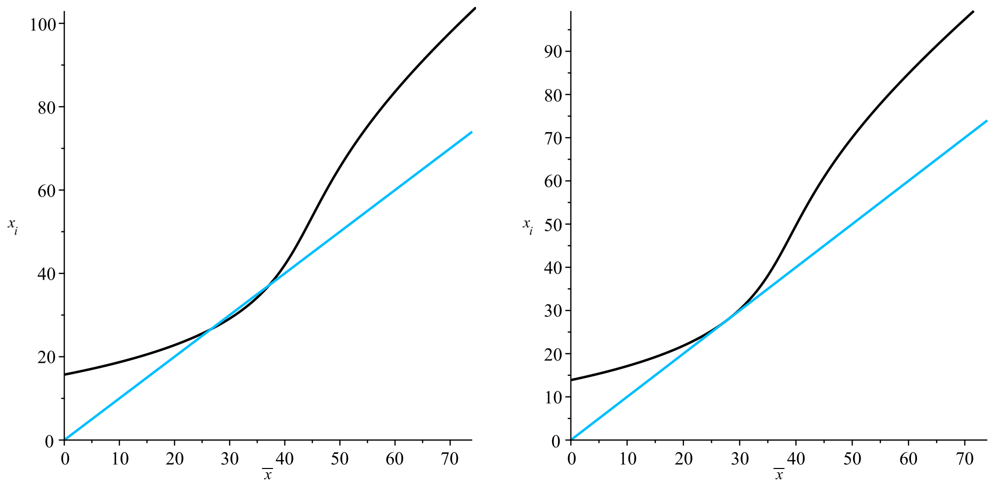

Figure 3.24: Left panel: best response function in the case $(\beta_1, \beta_2) = (\approx 0.82, 0.35)$. $\bar{x} = \bar{x}^S \approx 26.5$ is a stable equilibrium. Right panel: best response function in the case $(\beta_1, \beta_2) = (\approx 0.92, 0.38)$. $\bar{x} = \bar{x}^S \approx 28$ is *not* a stable equilibrium.

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