Wage Dynamics along the Life-Cycle of Manufacturing Plants*

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Abstract

This paper explores the evolution of wages along the life-cycle of U.S. manufacturing plants. Real wages start out low for new plants, and increase along with productivity as plants survive and age. As plants experience productivity decline and approach exit, real wages fall. However, for failing plants wages do not fall as quickly as they rise in the case of surviving new entrants. These empirical regularities are captured in a dynamic model of labor quality and quantity choice by plants subject to adjustment costs in wages and employment. The model's parameters are estimated to assess the magnitude of adjustment costs and the degree of asymmetry in the cost of upward versus downward adjustments.

JEL Codes: J31, J21, J24, L60, L23, L11, D24

*Any opinions and conclusions expressed herein are those of the authors and do not necessarily represent the views of the U.S. Census Bureau. All results have been reviewed to ensure that no confidential information is disclosed.

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1 Introduction

This paper provides evidence on the evolution of wages along the life-cycle of manufacturing plants using comprehensive data from U.S. Census Bureau's Census of Manufactures over the period 1963-1997. It first presents some facts on how the average wage paid by a plant to its employees changes as the plant enters an industry, grows, and ages, and as it approaches exit. It then builds and estimates a dynamic model of plant-level wage adjustment to account for the asymmetric pattern observed in the evolution of wages for growing versus declining plants. Using the estimated adjustment costs from the model, the extent of plant level real wage rigidity is assessed.

The analysis is motivated by the evolution of key plant-level variables in the U.S. quinquennial Census of Manufactures (CM). The CM waves were linked at the plant level to form an unbalanced panel over the period 1963 through 1997. A plant is observed at most eight times, when it appears in all waves of the CM. Using a plant's deflated revenue (total value of shipments), its deflated wage bill, and its employment, three ratios were constructed for each plant-CM wave observation:[1] (a) average wage – the ratio of wage bill to employment, (b) labor productivity – the ratio of revenue to employment, and (c) the ratio of wage bill to revenue, equivalent to the ratio of (a) to (b). Each ratio was then regressed on life-cycle indicators – a set of dummy variables indicating the number of CM waves a plant has been observed prior to its exit and after its entry, up to five each.[2] The omitted category contains the plants that are more than twenty years away from their entry or exit, and the plants for which entry or exit do not fall into the sample period.[3] Each regression also includes dummies for 4-digit SIC industry - CM wave interactions, to control for industry and time effects. The coefficient estimates for the life-cycle indicators are in Figure I.

First, consider the evolution of average wage in Figure Ia. New plants begin with an average wage roughly $2,700 lower than that of the omitted category. It takes at least twenty years for

[1] Both wages and revenue are expressed in 1987 dollars. Wages were deflated by the Consumer Price Index (CPI) from the Bureau of Labor Statistics (BLS), and revenue was deflated using industry-level deflators from the NBER-CES Manufacturing Industry Database (http://www.nber.org/data/nbprod2005.html).

[2] Entry and exit events are defined as the first observation of a plant in an economic census and the last observation, respectively. The exact entry and exit dates are not observed, and may fall in between two census years.

[3] These plants are those which enter before 1963 CM, and those that are still in operation as of 1997 CM.

this gap to drop below $300. Average wage starts to fall as a plant approaches exit. Plants twenty years away from exit have about $200 lower average wage than the omitted category. This gap grows to $2,000 by the time of exit. Average wage for exiting plants is about $700 higher than that of new entrants. Wages tend to rise faster for surviving entrants than they fall for plants approaching exit, as indicated by the slopes of the two average wage profiles.

Next, turn to the evolution of labor productivity in Figure Ib. Compared to the omitted group, new plants start off with approximately $5,700 productivity disadvantage that diminishes over time. However, failing plants exhibit a much larger productivity disadvantage. Exiting plants have about $10,000 lower productivity. Even as early as ten years prior to exit, plants that eventually exit have around $4,000 lower productivity. Labor productivity tends to fall faster for plants nearing exit than it rises for aging entrants.

The findings in Figures Ia-b together suggest the evolution of the ratio of a plant's wage bill to its revenue, equivalent to the percent of a worker's productivity provided to the worker in the form of wages. The estimated life-cycle pattern for this ratio is shown in Figure Ic. New plants spend a lower fraction of their revenue on wage bill compared to the omitted category, although this wage advantage largely disappears over the next fifteen years for surviving plants. Plants approaching exit, however, exhibit a small but statistically significant increase in this ratio. During their last three censuses, failing plants on average spend a higher fraction of their revenue on wages compared to the omitted category.

Figure I reveals that the evolution of average wages tends to roughly mimic the evolution of labor productivity at the plant level. New plants have increasingly higher average wage as they age and their labor productivity improves. Failing plants have both lower average wage and productivity as they approach exit. Yet, there is a fundamental asymmetry: wages do not fall as fast as labor productivity does for plants approaching exit, but they rise faster than labor productivity for new plants that survive and age. The model in this paper considers the role of wage adjustment costs as a potential explanation for these observations.

The connection between firm tenure and wages arises for several reasons. Older firms may have higher wages because their workers tend to be more experienced, and have more human capital and better skills. Established firms with higher survival likelihood are more likely to honor long-term wage contracts, which induce higher worker effort and lead to higher wages. On the other hand, young firms that face significantly lower probability of survival may offer higher or lower wages than established firms, depending on whether they compensate their workers for the shorter tenure prospects they face or promise future rewards if the firm is successful. Wages deemed fair by workers can also be higher in firms that are actually profitable enough to offer such wages. For instance, models of industry dynamics with persistent firm-level productivity, such as that of Jovanovic (1982), imply that established firms can afford higher wages because of their higher productivity – equivalent to profitability in some models.[4]

Using survey data on employees, Brown and Medoff (2003) find that older firms pay higher wages, but this premium disappears after controlling for several worker characteristics. Older firms also offer steeper wage-tenure profiles. Their analysis is based on a relatively small number of workers, and highly established firms with an average age of forty years.[5] Kölling, Schnabel and Wagner (2002) largely confirm Brown and Medoff's (2003) findings using a larger dataset that links establishments to workers in Germany, while Heyman (2007) finds some limited evidence in favor of a positive firm size-age relationship using Swedish data. These studies do not track firms or plants over time, and do not explicitly consider wage dynamics along the firm life-cycle. While age measures a firm's distance from entry, it does not contain information on its distance to exit, and cannot properly account for where a firm stands in its life-cycle. The samples used in these previous studies also do not adequately represent the age distribution of firms, especially the left tail of this distribution which consists of young plants that constitute a large fraction of firm population. This paper uses the entire population of U.S. manufacturing plants. It characterizes the evolution of wages not only for established plants, but also as new plants move away from their entry point, and as plants approach exit. The knowledge of entry and exit episodes and the ability to track plants over time allow for a more comprehensive understanding of wage dynamics.

The analysis also adds to the growing literature on microeconomic foundations of wage rigidities. A large body of work has considered both nominal and real wage rigidity, mostly at

[4]The distinction between productivity and profitability was highlighted by Foster, Haltiwanger and Syverson (2008), who disentagle the price and output components of revenue in a set of narrowly defined, homogeneous goods manufacturing industries and show that younger plants have higher 'physical' productivity but tend to charge lower prices, implying lower profitability does not imply lower productivity.

[5]Their sample consists of 1,067 workers, corresponding to at most as many firms. See Brown and Medoff (2003) for details.

the worker level.[6] The focus here is on plant-level rigidities in real wage movements. Forward-looking plants anticipate the effects of inflation on output and factor prices in making decisions. Nevertheless, the model and its estimation can readily accommodate nominal terms.

Given that productivity dynamics is a fundamental driver of firm and plant dynamics, it is also important to understand how changes in productivity or profitability are connected to changes in wages. The model in this paper makes this connection explicit.[7] The specific mechanism that drives the evolution of wages is a plant's choice of the quality of its labor force in the presence of productivity shocks. The emphasis on labor quality is inspired by the findings of Brown and Medoff (2003) and Kölling, Schnabel and Wagner (2002) which suggest that worker quality accounts for a considerable portion of wage differential across plants of different ages.[8] A further motivation is the strong positive association at the firm level between labor quality and labor productivity (see, e.g. Griliches and Regev (1995)).

In the model, labor quality is a factor of production, in addition to the quantity of labor. The premise is that labor is not homogeneous, and changes in worker quantity along a plant's life-cycle are likely associated with changes in average quality of a plant's workforce, and vice versa. Worker quality can have alternative interpretations, such as a worker's skill level, effort level, the quality of a worker's output, or the degree of essentiality of a worker in the production process, all of which may be positively associated with wage. While a plant takes as given the wage per unit of labor quality in the economy, it can alter the average quality of its labor force, and hence, its total wage bill and average wage. This mechanism is embedded into a model of plant dynamics driven by idiosyncratic shocks to plant profitability and common shocks to wage per unit of worker quality. Under certain specifications of production technology, when a plant's profitability increases, the plant desires to increase both its employment and average quality of its labor force, and a decline in profitability induces a downward pressure on both labor quality

[6] See, among others, Altonji and Devereux (1999), Bewley (1999), McLaughlin (1994, 2000), Hall (2005a,b), Blanchard and Gali (2007).

[7] Some recent studies tie firm-level productivity movements to wage changes using reduced-form econometric models. See, e.g., Fuss and Wintr (2009).

[8] The analysis here, however, does not attempt to disentangle the effect of worker versus plant characteristics on wage dynamics. The goal is not to explain away the differences in wages across plants at different stages of their life-cycles, but rather to explore the link between plant-level productivity dynamics and the evolution of wages along a plant's life-cycle.

and employment. These implications emerge in the data studied here. Adjustments in wages, however, have costs associated with them. These costs may curtail the extent to which wages can be changed. Plants make their labor quantity and quality choices considering the effects of these choices on current and future adjustment costs.

Adjustment costs in wages may arise due to a variety of reasons. Exogenous shocks to wages can force a plant to alter its wages at a cost. For instance, some workers can exercise their outside options if their wages are not adjusted adequately when demand for their services rises in the economy. New plants experiencing favorable profitability shocks and fast growth may need to reorganize their labor force and adjust compensation to increase the average quality and, therefore, output. Similarly, as a plant experiences persistent episodes of low profitability, it may be forced to shed some of its employees with high quality, but who may be non-essential for the main activity of the plant, and in some cases, it may even reduce compensation for some workers. There need not be a reduction in nominal compensation. For instance, if a plant freezes nominal wages, real wages would fall when there is inflation. Some workers may also quit in anticipation of exit and the plant may then have to reorganize its labor force to maintain production. All of such changes and events, however, require costly adjustment to wages. Changing the average quality of a plant's workers entails costly training and search for workers with desired levels of quality. Unions can resist or prevent a reduction in average wage level, whether the reduction is direct through a cut in real wages and benefits, or indirect through firing workers at a particular quality level.

To uncover the underlying wage adjustment costs, as well as the shares of labor quantity and quality in the production function of a plant, the model's parameters are estimated using generalized method of moments. The estimates reveal that labor quality, implicitly inferred from wages, is an important input to production. Furthermore, there are statistically and economically significant asymmetric adjustment costs associated with wages. Using the largest estimated adjustment cost parameters, upper bounds can be calculated for the share of wage adjustment costs in a plant's revenue. The average annual cost of wage adjustment in any direction (up or down) over a 5-year period between two consecutive census years constitutes around 1.6% of a plant's initial revenue at the median of the adjustment cost distribution, when only the continuing plants are considered. For continuing plants experiencing a fall in average wage, the average annual adjustment costs claim about 3.6% of initial revenue at the median. For continuing plants experiencing an increase in average wage, the average annual adjustment costs make up around 0.8% of revenue at the median. These shares are higher when only the exiting plants are considered: 3%, 6.6%, 1.2%, respectively. The revenue share of adjustment costs is even higher for plants in the higher quartiles of the adjustment cost distribution. Furthermore, wage adjustment costs tend to decline as a percentage of revenue as new plants survive and age, and increase as plants approach exit.

A version of the model with both wage and employment adjustment costs is also estimated. Consideration of adjustment in worker quantity next to adjustment in worker quality addresses the issue that labor is not homogeneous. The effect on plant value of a given change in employment depends on the corresponding change in worker quality associated with the employment adjustment. In other words, a plant may not be able to adjust employment up or down holding worker quality constant. Incorporating adjustments in worker quality can therefore account for some of the potential bias in the measurement of employment adjustment costs when all labor is treated homogeneous. Similarly, not accounting for adjustment costs in quantity margin may bias adjustment costs in the quantity margin. In the estimates obtained here, both margins of adjustment appear to be important.

Adjustment costs associated with factors of production have been studied in the context of plant, firm, industry, and aggregate dynamics.[9] These studies mainly consider adjustment costs for labor or capital, or those with different types of labor, but rarely focus on any adjustment costs associated with factor prices, such as wages. The approach here differs from the previous literature in a number of important dimensions. First, it introduces wage adjustment costs explicitly at the plant level, allowing for adjustments both in response to exogenous changes in wages and to changes through the plant's choice of labor quality. Second, it considers the dynamic interaction between the choices of labor quality and quantity at the plant level. This interaction has implications not only for the time-paths of wages and employment, but also on the adjustment costs associated with both wages and employment. Third, it quantifies the relative significance of wage and employment adjustment costs. Finally, the data used here is much richer than those in previous studies. With the exception of Cooper et al. (2004,

[9]See, among others, Cooper and Willis (2011), Cooper, Haltiwanger, and Willis (2006), Bloom (2009), Merz and Yashiv (2007), Cooper and Haltiwanger (2004), Hall (2004), Alonso-Borrego (1998), and Pfann and Palm (1993).

2006, 2011) who use plant level data, most studies at the firm level either use relatively small samples of firms (e.g. Alonso-Borrego (1998) – about 1,080 firms in Spanish manufacturing) or non-representative samples of U.S. plant or firm population (e.g. Bloom (2009) – relatively large publicly-traded firms in S&P's Compustat Database), whereas other studies (e.g. Shapiro (1986), Pfann and Palm (1993), Hall (2004), and Merz and Yashiv (2007)) use more aggregated data, which may hide patterns at the level of micro-units. Furthermore, prior studies, in part because of data restrictions, do not analyze how adjustment costs change with age along the plant or firm life-cycle.

The rest of the paper is organized as follows. Section 2 describes the data and presents some observations regarding the evolution of wages along a plant's life-cycle. Section 3 introduces the model. The estimation methodology is presented in Section 4. The estimation results are discussed in Section 5. Section 6 offers concluding remarks.

2 The evolution of wages

2.1 Data

The empirical work uses the Longitudinal Research Database (LRD), maintained at the Center for Economic Studies of the US Census Bureau. The LRD describes aspects of manufacturing plants' production. Output data include total value of shipments and value added. Data on inputs include information on capital, labor, energy, materials, and selected purchased services. The LRD also contains information on classification and identification of plants, such as plants' ownership, location, and industry, as well as various status codes that identify birth, death, and ownership changes. These identifying codes are used in developing the longitudinal plant linkages.[10]

The analysis focuses on a subset of the LRD that includes eight waves of Census of Manufactures (CM): 1963, 1967, 1972, 1977, 1982, 1987, 1992 and 1997. The number of plants in CM range from 305,691 in 1967 to 400,036 in 1997. Using permanent plant numbers, plants were linked from these CM's to form an unbalanced panel for the period 1963-1997. Plant entry, exit, and continuation were identified.

[10] For further information on the LRD, visit http://www.census.gov/ces/dataproducts/economicdata.html.

The key plant-level variables are revenue, employment, and average wage. A plant's revenue is its value of shipments deflated to 1987 dollars using 4-digit SIC level industry price deflators from NBER-CES Manufacturing Industry Database based on 1987 SIC code definitions. Employment is a plant's total number of workers engaged in production and non-production activities. The wages of individual workers in a plant are not observed, only the total wage bill is available. To obtain average wage, a plant's total wage bill was deflated to 1987 dollars using CPI from Bureau of Labor Statistics and then divided by the plant's total employment. Wages do not include benefits.[11] Labor productivity is defined as the ratio of a plant's revenue to its total employment. Finally, wage-bill-to-revenue ratio is a plant's total wage bill divided by its revenue.

2.2 Main findings

Underlying the evolutions of the three basic ratios described in Figure I is Table I, which contains the OLS estimates from several specifications of the following regression

$$Y_{it} = \alpha + \sum_{\tau} \beta_X^{\tau} X_{it}^{\tau} + \sum_{\tau} \beta_E^{\tau} E_{it}^{\tau} + \boldsymbol{\beta}_Z \mathbf{Z}_{it} + \sum_{I} \sum_{T} \beta_{IT} T_t I_i + \varepsilon_{it}, \tag{1}$$

where i indexes plants, t indexes census years, Y_{it} is either average wage, labor productivity, or wage-bill-to-revenue ratio, X_{it}^{τ} is an indicator of whether a plant is $\tau \in \{0, 5, 10, 15, 20\}$ years *to* its exit point (the last census it is observed), E_{it}^{τ} is an indicator of whether a plant is $\tau \in \{0, 5, 10, 15, 20\}$ years away *from* its entry point (the first census it is observed), $\mathbf{Z}_{it}$ is a vector of additional plant-level controls, T_t is a census year fixed effect, and I_i is a 4-digit SIC industry fixed effect.[12,13] The interaction term $T_t I_i$ is added to control for any industry-time specific effects, such as the effects of industry life-cycles. The omitted category, referred to as mature plants, contains the plants that are more than twenty years away from their entry or exit, and the plants whose entry or exit dates do not fall into the sample period.[14] The error

[11] Changes in benefits is another source of adjustments to compensation. The data contain information on benefits, which can be used to extend the definition of labor compensation beyond salary and wages.

[12] The total employment of a plant was restricted to the range 5 to $10,000$ employees. In addition, the top and bottom percentiles of the three dependent variables were trimmed to reduce the influence of any outliers on the estimated coefficients.

[13] Note that some plants indicated by a given E_{it}^{τ} may also be in the set of plants indicated by some X_{it}^{τ}'s.

[14] The regression specifications are similar to those used in Foster, Haltiwanger, and Syverson (2008).

term ε_{it} is assumed to have an unobserved firm specific component and estimation allows for clustered errors at the firm level to correct for standard errors.

The indicator variables X_{it}^{τ} and E_{it}^{τ} capture life-cycle effects. They track the evolution of Y_{it} as a plant moves away from entry into maturity, and also as it approaches exit. Of interest are the coefficients β_X^{τ} and β_E^{τ} that quantify the magnitudes of these life-cycle effects. β_X^{τ} is the effect on Y_{it} of being τ years away from exit, controlling for time from entry as identified by the indicators E_{it}^{τ}, in addition to other controls. Similarly, β_E^{τ} measures the effect on Y_{it} of being τ years from entry, controlling for time to exit identified by X_{it}^{τ}, in addition to other controls.

Specification I in Table I generates Figure I, without the plant-level controls $\mathbf{Z}_{it}$. Average wage is low for entering plants and gradually approaches that of mature plants. As plants get closer to exit, wages start to fall, but not as fast as they increase for surviving and aging entrants. Labor productivity is also much lower for entering plants, but improves as they age. Plants nearing exit have a much more substantial productivity disadvantage, visible even twenty years prior to exit. Griliches and Regev (1995) find a similar pattern in a study of Israeli firms and dub this effect "the shadow of death": firms that will exit in the future are less productive in the present. However, the pace of labor productivity growth in young plants exceeds the pace it declines in failing plants. This asymmetry manifests itself in the evolution of wage-bill-to-revenue ratio. For young plants, wages constitute a smaller fraction of revenue compared to mature plants, and for plants approaching exit wage bill claims an increasingly larger fraction of revenue.

The findings largely continue to hold when plant-level controls, $\mathbf{Z}_{it}$, are added. In specification II, plant size, which has been found to be highly positively associated with wages (see, e.g., Brown and Medoff (1989)), is included, in addition to an indicator of whether the plant is part of a multi-unit firm. Plant size is measured by total employment and specified as a cubic polynomial. While the magnitudes of life-cycle effects in average wage are now somewhat smaller in absolute value, their signs and significance resemble those in specification I. The most important difference is in the case of labor productivity for young plants. Compared to specification I, young plants now exhibit a much faster productivity growth, and seem to wipe out their productivity disadvantage vis á vis mature plants by their fifth year after entry. As a result, wage-bill-to-revenue ratio for entering plants is even lower, and stays lower longer as they age.[15]

The results in Table I point to a fundamental asymmetry in how plant-level labor productivity is connected to wages. Wages rise faster than labor productivity does for young plants as they survive and age, and they fall slower than labor productivity does for failing plants. Consequently, wages represent a smaller share of revenue for young and surviving plants, but a higher share of revenue for those plants nearing exit. Surviving plants appear to have a payroll advantage: they pay their workers a smaller share of their revenues compared to mature plants. Plants approaching exit, however, are burdened with a wage bill that claims a larger fraction of their revenue compared to mature plants.

Does the evolution of key variables in Figure I vary across different worker types? A broad categorization of a plant's labor force into production versus non-production workers is available in the data. Table II shows the evolution of average wage and other key variables for these two worker types, based on regressions (1) ran separately for each type. This breakdown is only a crude distinction of function among workers. Non-production workers category lumps together white-collar workers, including managers, sales, legal, and professional personnel, as well as many other types of employees who are not directly involved in production.[16] The average wage of non-production workers is roughly double that of production workers, a difference that is also highly statistically significant.[17] As suggested by this large gap, non-production workers may embody more skill, education, or human capital than production workers, at least on the average.

The first two columns of Table II present the evolution of the ratio of the number of non-production workers to the total number of workers, which is a proxy for a plant's skill com-

[15] The findings are also similar if unconditional estimates of the life-cycle effects (β^{τ}_{X} and β^{τ}_{E}) are used. Unconditional estimates are obtained from the regressions (1) by using on the right hand side either only the indicators for the number of years to exit (X^{τ}_{it}), or only the indicators for the number of years from entry (E^{τ}_{it}), in addition to time-industry interactions. The unconditional estimates capture the effect of being a certain number of years from entry (to exit) without conditioning on the number of years to exit (from entry). These estimates allow making statements about the evolution of the key variables without explicit conditioning. The unconditional estimates are available upon request.

[16] See Gujarati and Dars (1972) for a detailed description of these two types of workers, as defined by the US Census Bureau.

[17] In 1997 CM, the average wage for production workers was about \$21,000, compared to about \$39,000 for non-production workers.

position. Regressions of the form in (1) were rerun with this ratio as the dependent variable Y_t. New plants have a low ratio relative to mature plants, but as plants age, the ratio increases. However, even twenty years after entry plants exhibit lower ratio relative to mature plants. As plants near exit, this ratio tends to go down, but not as fast as it rises in the case of young plants, implying some asymmetry in the evolution of worker composition along the plant life-cycle. Figure II depicts these patterns compactly.

Average wages for both types of workers start out low for new plants relative to mature ones, but increase as plants age. Twenty years after entry, plants have about the same average wage for non-production workers as mature plants, whereas they exhibit about $200 lower average wage compared to mature plants for production workers. As a plant approaches exit, the average wages of both types of workers fall, with a larger decline for non-production workers. Plants in their last census year on average pay about $1,500 less to their production workers and about $4,500 less to their non-production workers, compared to the mature plants. These movements in average wages are shown in Figure III. One concern is that the estimated magnitudes are in absolute terms – not measured relative to the average wage in each category of workers. The regressions using logarithm of average wage address this issue. Even when the change in average wage for a worker type is measured as a percentage of the average wage for that type, the pattern remains the same: the average wage of non-production workers rises faster than that of production workers as a new plant ages, and it also declines faster as a plant approaches exit. The relatively higher inertia in production workers' wages may stem from several reasons. One reason is that they are more likely to be unionized. Another may be that they perform essential tasks for production and are harder to dispense with if a plant is to continue production during episodes of persistent low profitability. It may also be easier for highly-skilled non-production workers to quit and find alternatives when a plant approaches failure.

The last four columns of Table II present the evolution of wage-bill-to-revenue ratio for production and non-production workers. For both types of workers, this ratio starts out low in new plants compared to mature plants and gradually increases. However, failing plants seem to have a higher payroll share of revenue compared to mature plants when production workers are considered. This pattern does not apply to non-production workers. The evolutions of average wage and wage-bill-to-revenue ratio in Table I appear to be driven by two factors: (i) the asymmetry in the evolution of worker composition – a shift towards non-production workers as young plants age, and a shift towards production workers as plants approach exit, and (ii) the slower rise and decline in the average wage of production workers compared to that of non-production workers.

3 The model

The model is motivated by the empirical findings in the previous section. It considers both the quantity and quality of labor as factors of production. Worker quality can have alternative interpretations, such as a worker's skill level, effort level, the quality of a worker's output, or the degree of essentiality of a worker in the production process, all of which may be positively associated with wage. A key ingredient of the model is the ability of plants to alter their wages through adjustment of worker quality. The main premise is that such wage adjustments have costs associated with them. Plants take unit wages per worker quality as given in a labor market, where workers are heterogeneous with respect to quality. There are two distinct channels through which wage adjustments can occur. First, a plant can adjust its wages in response to changes in the exogenous wage rate per unit of worker quality. For instance, if the wages rise in the economy in general, a plant has to increase compensation to its workers in order to be able to retain them. The second channel is the ability of a plant to alter its wage bill through adjustment of its average worker quality. The higher the average quality of labor, the larger the output, but also the higher the wage bill. Labor quality can be altered by a plant through hiring, firing, and other means, such as investment into a worker's skill acquisition or training.

Consider now an industry with a large number of plants, each of which is too small to influence industry aggregates. Plants can be price-takers in the market for their output, or they may be local monopolies and can set prices given their downward sloping demand functions. There is an infinite number of discrete time periods. Plants receive random shocks to their profitability each period. Plants are also exposed to economy and industry-wide shocks to an exogenous wage rate per unit of labor quality. There is a large number of workers with varying quality levels available for hire by plants at that exogenous wage rate.

3.1 Adjustment cost for wages

A plant chooses the quantity and average quality of its labor force, as well as other inputs, to generate output through a Cobb-Douglas production technology.[18] The profit function of a plant in period t is

$$\begin{aligned}\Pi(q_t, L_t; q_{t-1}, L_{t-1}, w_t, w_{t-1}, \theta_t) &= \theta_t L_t^{\alpha} q_t^{\gamma} - w_t q_t L_t \\ &- \left[I_t^U \frac{\lambda^U}{2} + I_t^D \frac{\lambda^D}{2} \right] \left(\frac{w_t q_t - w_{t-1} q_{t-1}}{w_{t-1} q_{t-1}} \right)^2 w_{t-1} q_{t-1} L_{t-1} - F.\end{aligned} \tag{2}$$

In the production function represented by the first term on the left hand side of (2), L_t is the quantity of labor, q_t is the average quality or skill level per unit of labor, and $\theta_t \geq 0$ is a profitability shock that includes aggregate and idiosyncratic shocks, as well as the output price. The parameters of the production function satisfy the restrictions $\alpha, \gamma \in (0, 1)$ and $\alpha + \gamma < 1$. These parameters are determined by the underlying importance of L_t, q_t, and other inputs in production.[19]

In the cost function represented by the remaining terms on the left hand side of (2), w_t is the wage per unit of labor quality that evolves exogenously, and $\lambda^U \geq 0$ and $\lambda^D \geq 0$ are the parameters of the quadratic adjustment costs associated with upward and downward adjustments in average wage, $w_t q_t$, indicated by $I_t^U \equiv I(w_t q_t > w_{t-1} q_{t-1})$ and $I_t^D \equiv I(w_t q_t \leq w_{t-1} q_{t-1})$. The quadratic is in terms of the conventional growth rate of $w_t q_t$.[20] The adjustment in average wage applies to total wage bill from the previous period $w_{t-1} q_{t-1} L_{t-1}$, implying that the adjustment cost is proportional to plant size measured by L_{t-1}. The dependence of wage

[18] Cobb-Douglas technology, frequently used in studies assessing adjustment costs, restricts the elasticity of substitution between quantity and quality to one. More general specifications of technology would allow this elasticity to differ from unity, and the adjustment costs would then reflect the value of the elasticity. For instance, if the elasticity of substitution between quality and quantity is 0.5 conditional on output, then the adjustment cost for quality would be multiplied by 2.

[19] Suppose the plant is a price-taker and the underlying production function is given by $\widetilde{\theta}_t \left(M_t^{1-\widetilde{\alpha}-\widetilde{\gamma}} L_t^{\widetilde{\alpha}} q_t^{\widetilde{\gamma}} \right)^{\delta}$, where M_t is some other input that can be costlessly adjusted, $\widetilde{\alpha}, \widetilde{\gamma} \in (0, 1)$ are the shares of labor quantity and quality in output such that $\widetilde{\alpha} + \widetilde{\gamma} < 1$, and $\delta \in (0, 1)$ reflects decreasing returns at the plant level to some fixed input (such as capital or physical space). If the unit price of M_t is m_t, the optimization only with respect to M_t leads to the production function in (2) where $\alpha = \frac{\delta\widetilde{\alpha}}{1-\delta(1-\widetilde{\alpha}-\widetilde{\gamma})}$, $\gamma = \frac{\delta\widetilde{\gamma}}{1-\delta(1-\widetilde{\alpha}-\widetilde{\gamma})}$, and θ_t is a function of $\widetilde{\theta}_t, \widetilde{\alpha}, \widetilde{\gamma}, \delta, m_t$ and output price p_t. A similar interpretation applies if a plant has local market power, in which case δ is a function of the elasticity of demand.

[20] An alternative growth rate is also used for robustness, as explained below.

adjustment cost on previous plant size introduces a dynamic link between a plant's employment and average wage choices, in addition to the interaction of these two choices in the production function and wage bill. The adjustment in average wage has two sources: exogenous changes in w_t, and the plant's choice of q_t, which also depends on w_t and θ_t. When the unit cost of worker quality changes, the plant has to incur an adjustment cost in wages even when it does not alter the average quality of its labor force. These two dimensions of adjustment are not separately identified. Finally, F is a fixed cost of operation that is avoidable only if the plant exits.

Labor quality q_t can alternatively be interpreted as the idiosyncratic component of a plant's average wage, which can be positively associated with the quality of the job a worker produces or the effort that the worker exerts. If the idiosyncratic component is lower, the worker exerts less effort and the quality of his output declines, resulting in lower output for the plant. The average wage $w_t q_t$ is then a multiplicative representation of its exogenous common (w_t) and endogenous idiosyncratic (q_t) components.[21]

The distribution of θ_t is given by the *c.d.f.* $H(\theta_t|\theta_{t-1})$, which specifies the general dependence of a period's profitability shock on its previous value. Similarly, the distribution of w_t is given by the *c.d.f.* $G(w_t|w_{t-1})$. The random variables w_{t+j} and θ_{t+k} are assumed to be independent for $j \neq k$. The distributions H and G are assumed to satisfy certain monotonicity properties with respect to θ_{t-1} and w_{t-1}, respectively.[22] Such monotonicity is satisfied by *i.i.d.* distributions, as well as by more persistent processes. The exact forms of H and G are not specified.[23] In the estimation, the profitability and wage processes are driven by the data, instead of being specified as part of the model.

It can be verified that the profit function Π is strictly increasing in θ_t, and strictly decreasing

[21] An additive form, $w_t + v_t$, can also be specified, where v_t is the plant-specific component of wage. Now, write $w_t + v_t = w_t\left(1 + \frac{v_t}{w_t}\right)$ and define a worker's effort or the quality of his output proportional to wage as $e_t = kv_t$. Letting $q_t = \left(1 + \frac{e_t}{kw_t}\right)$, one can obtain the multiplicative specification $w_t q_t = w_t + v_t$. Because w_t is common across firms, q_t preserves the ranking of the idiosyncratic component across plants. Choice of q_t by a plant is equivalent to choice of e_t in this case.

[22] Specifically, for any non-decreasing function u, $\int u(\theta_t)dH(\theta_t|\theta_{t-1})$ is non-decreasing in θ_{t-1}. Similarly, for any non-increasing function v, $\int v(w_t)dH(w_t|w_{t-1})$ is non-increasing in w_{t-1}. These assumptions are needed for the existence and monotonicity of a plant's value function.

[23] Prior evidence suggests that θ_t is persistent. A frequent specification (see, e.g., Hopenhayn (1992), Fishman and Rob (2002)) is for any two shocks $\theta_{t-1} > \theta'_{t-1}$, $H(\theta_t|\theta_{t-1})$ first order stochastically dominates $H(\theta_t|\theta'_{t-1})$. Some studies (e.g., Abraham and White (2006)) find high persistence in productivity at the firm level.

in L_{t-1} and w_t.[24] Define the state variable for a plant as $\mathbf{s}_t = (q_{t-1}, L_{t-1}, w_t, w_{t-1}, \theta_t)$. The plant's decision to exit after observing θ_t is denoted by the discrete choice X_t such that $X_t = 1$ if the plant exits, and $X_t = 0$ if the plant continues. Letting β denote the discount factor, the value of a plant is

$$V_t(\mathbf{s}_t) \equiv \max_{X_t, L_t, q_t} (1 - X_t) \left(\Pi(q_t, L_t; \mathbf{s}_t) + \beta E\left[V_{t+1}(\mathbf{s}_{t+1})\right]\right), \tag{3}$$

where the plant's exit value is normalized to zero. The expectation in (3) is taken over all possible values of θ_{t+1} conditional on θ_t, and over all possible values of w_{t+1} conditional on w_t.

Given the assumptions of the model, dynamic programming arguments in Stokey and Lucas (1989) guarantee the existence of a unique time-invariant value function V, which is strictly increasing in θ_t and strictly decreasing in L_{t-1} and w_t.[25] Because V is monotonic in θ_t, exit occurs the first time θ_t is such that $V(\mathbf{s}_t) \leq 0$.

At the beginning of every period, there is a large number (a continuum) of ex-ante identical potential entrants which can enter the industry as long as it is profitable to do so. The expected value from entry is $V_t^e = E[V(\mathbf{s}_t)]$, where an entrant's initial state $\mathbf{s}_t = \{0, 0, w_t, w_{t-1}, \theta_t\}$ reflects the fact that its prior labor quality and quantity are both zero, and the initial profitability draw after entry comes from a continuous distribution. There is a one-time sunk entry cost of $\kappa > 0$. Positive entry in period t implies $V_t^e = \kappa$, and no entry occurs when $V_t^e < \kappa$.

Let V_i denote the derivative of V with respect to its i'th argument.[26] A continuing plant's choice of L_t satisfies

$$\alpha \theta_t L_t^{\alpha-1} q_t^{\gamma} - w_t q_t + \beta E\left[V_2(\mathbf{s}_{t+1})\right] = 0, \tag{4}$$

where

$$E\left[V_2(\mathbf{s}_{t+1})\right] = -E\left[\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right)\left(\frac{w_{t+1}q_{t+1} - w_t q_t}{w_t q_t}\right)^2\right] w_t q_t. \tag{5}$$

The first term on the left hand side of (4) is the marginal benefit from a small change in the quantity of labor, and the second and third terms give the associated marginal cost: the change

[24] Monotonicity in θ_t, w_t, and L_{t-1} follow from straightforward differentiation, except at $w_t = \frac{q_{t-1}}{q_t} w_{t-1}$, where Π is non-differentiable with respect to w_t when $\lambda^U \neq \lambda^D$.

[25] Assumptions 9.4, 9.5, 9.6, and 9.7 in Stokey and Lucas (1989) are satisfied for the firm's dynamic programming. Furthermore, Assumptions 9.8 and 9.9 are satisfied for the state variables L_{t-1} and w_t. Monotonicity then follows from Theorem 9.7. Similarly, assumptions 9.13-9.15 are satisfied for the state variable θ_t. Monotonicity then follows from Theorem 9.11.

[26] Note that the derivative of V with respect to q_t does not exist at $q_t = \frac{w_{t-1}}{w_t} q_{t-1}$ when $\lambda^U \neq \lambda^D$.

in current wage bill and the change in the next period's expected adjustment cost. A continuing plant's choice of q_t satisfies

$$\gamma\theta_t L_t^{\alpha} q_t^{\gamma-1} - w_t L_t - \left[I_t^U \lambda^U + I_t^D \lambda^D\right]\left(\frac{w_t q_t - w_{t-1}q_{t-1}}{w_{t-1}q_{t-1}}\right) w_t L_{t-1} + \beta E\left[V_1(\mathbf{s}_{t+1})\right] = 0, \tag{6}$$

where

$$E\left[V_1(\mathbf{s}_{t+1})\right] = E\left[\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right)\frac{L_t}{w_t^2 q_t^2}\left(w_{t+1}^2 q_{t+1}^2 - w_t^2 q_t^2\right) w_t\right]. \tag{7}$$

Once again, the first term on the left hand side of (6) is the marginal benefit from a small change in quality of labor and the remaining terms are the associated marginal cost: the change in current wage bill, the change in current adjustment cost, and the change in the next period's expected adjustment cost. The first order conditions (4) and (6) implicitly determine the policies $L(\mathbf{s}_t)$ and $q(\mathbf{s}_t)$. Let $\Pi^*(\mathbf{s}_t)$ be the period profit function evaluated at $L(\mathbf{s}_t)$ and $q(\mathbf{s}_t)$. The exit policy is then given by the following

$$X(\mathbf{s}_t) = \begin{cases} 0 & \text{if } \Pi^*(\mathbf{s}_t) + \beta E\left[V(\mathbf{s}_{t+1})\right] > 0, \\ 1 & \text{otherwise.} \end{cases}$$

One can assess the implications of the model on wage bill-to-revenue ratio. Using (4), the wage bill can be expressed as a percentage of revenue as

$$f_t = \frac{L_t w_t q_t}{\theta_t L_t^{\alpha} q_t^{\gamma}} = \alpha + \beta \frac{E\left[V_2(\mathbf{s}_{t+1})\right] L_t}{\theta_t L_t^{\alpha} q_t^{\gamma}}. \tag{8}$$

Using (5) in (8) one then obtains

$$f_t = \frac{\alpha}{1 + \beta a_{t+1}}, \tag{9}$$

where

$$a_{t+1} = E_{w_t}\left[E_{\theta_{t+1}}\left[\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right)\left(\frac{w_{t+1}q_{t+1} - w_t q_t}{w_t q_t}\right)^2 \middle| \theta_t\right] \middle| w_t\right], \tag{10}$$

is the expected value of the squared percent adjustment in the next period conditional on θ_t and w_t. An implication of (9) is that higher absolute expected percent adjustment in average wage in the next period is accompanied by a lower share of labor in current period revenue. This result follows because the plant's current wage bill and its expected cost of adjustment in wages next period must be compensated by the labor's share of current revenue.

The expectations in (10) are taken over w_{t+1} and θ_{t+1}, conditional on θ_t and w_t. If a_{t+1} is strictly increasing in θ_t conditional on w_t, better profitability shocks (higher θ_t) imply a lower

f_t. The outer expectation in (10) applies to the stochastic process w_t, which is common to all plants and independent of θ_t. Thus, in comparing the value of (9) across plants, one can focus on the inner expectation over θ_{t+1} conditional on θ_t. Consider the case where the policies $L(\mathbf{s}_t)$ and $q(\mathbf{s}_t)$ are both strictly increasing in θ_t. The appendix shows that such monotonicity holds under certain conditions. If θ_t follows an *i.i.d.* process, the expected average wage for the next period is the same for all plants, implying that a_{t+1} is higher, and f_t is lower, for values of θ_t away from the mean $E[\theta_t|\theta_{t-1}]$. However, if θ_t is persistent over time, e.g. if higher values of θ_t makes even higher values of θ_{t+1} more likely, then a high value of θ_t can lead to a higher expected θ_{t+1}, and, hence, a lower f_t, especially when $\lambda^U < \lambda^D$.

3.2 Adjustment costs for wages and employment

Consider now adjustment cost for employment, in addition to that for wages. Consideration of adjustment in worker quality next to adjustment in worker quantity addresses the issue that labor is not homogeneous. The effect on plant value of changes in employment depends on the associated changes in worker quality. Incorporating adjustments in worker quality can therefore account for some of the potential bias in the measurement of employment adjustment costs when all labor is treated homogeneous. Similarly, a change in employment rarely can be accomplished holding average wage constant. For instance, hiring or firing a worker changes the average quality of the remaining workers. Including adjustment costs in both quality and quantity helps adress the effect of changes in one on the other. The period profit function of a plant is now

$$\begin{aligned}\Pi(q_t, L_t; w_t, q_{t-1}, w_{t-1}, L_{t-1}, \theta_t) &= \theta_t L_t^\alpha q_t^\gamma - w_t q_t L_t \\ &\quad - \left[I_t^U \frac{\lambda^U}{2} + I_t^D \frac{\lambda^D}{2}\right] \left(\frac{w_t q_t - w_{t-1} q_{t-1}}{w_{t-1} q_{t-1}}\right)^2 w_{t-1} q_{t-1} L_{t-1} \\ &\quad - \left[J_t^U \frac{\nu^U}{2} + J_t^D \frac{\nu^D}{2}\right] \left(\frac{L_t - L_{t-1}}{L_{t-1}}\right)^2 L_{t-1} - F,\end{aligned} \tag{11}$$

where $\nu^U \geq 0$ and $\nu^D \geq 0$ are the parameters of the quadratic adjustment cost associated with upward and downward employment adjustments, indicated respectively by $J_t^U \equiv I(L_t > L_{t-1})$ and $J_t^D \equiv I(L_t \leq L_{t-1})$. The employment adjustment cost function follows the quadratic formulation also used by Cooper and Haltiwanger (2005) and Cooper and Willis (2009). Both the wage and employment adjustment costs are proportional to previous plant size, L_{t-1}. The specification of adjustment costs takes into account two margins of adjustment: an intensive margin of adjustment that applies only to average wage, and an extensive margin that applies only to employment. However, these two margins are not independent. Adjustment in average wage affects a plant's current and future employment decision, and adjustment in employment in turn influences current and future choices of average wage.

For a continuing plant, the first order condition for q_t is the same as (6). For L_t, the first order condition now becomes[27]

$$\alpha\theta_t L_t^{\alpha-1} q_t^{\gamma} - w_t q_t - \left[J_t^U \nu^U + J_t^D \nu^D\right] \left(\frac{L_t - L_{t-1}}{L_{t-1}}\right) + \beta E\left[V_2(\mathbf{s}_{t+1})\right] = 0. \tag{12}$$

3.3 Adjustment costs with alternative growth rates

As an alternative to the adjustment cost specification used so far, an adjustment cost which allows for symmetric and bounded growth rates can also be considered. The alternative adjustment cost specifications for average wage and employment are given by replacing the denominators of the squared terms in (2) and (11) with $\frac{1}{2}(w_t q_t + w_{t-1} q_{t-1})$ and $\frac{1}{2}(L_t + L_{t-1})$, respectively. These alternative specifications restrict the growth rates in average wage or employment to the interval $[-2, 2]$. These growth rates have some desirable features compared to the conventional growth rate, such as robustness to outliers and boundedness for the case of new entrants whose initial average wage and employment are both zero.[28] The appendix contains the first order conditions for the adjustment costs with alternative growth rates.

4 Estimation

4.1 Estimation with adjustment cost for wages

Consider first the model with adjustment cost for wages only. Condition (6) can be rewritten after multiplying through by q_t as

$$\gamma\theta_t L_t^{\alpha} q_t^{\gamma} - w_t q_t L_t - \left[I_t^U \lambda^U + I_t^D \lambda^D\right] \left(\frac{w_t q_t - w_{t-1} q_{t-1}}{w_{t-1} q_{t-1}}\right) w_t q_t L_{t-1} + \beta E\left[V_1(\mathbf{s}_{t+1})\right] q_t = 0. \tag{13}$$

[27] Note that V is now non-differentiable with respect to L_t at $L_t = L_{t-1}$ when $\nu^U \neq \nu^D$.

[28] See Davis, Haltiwanger, and Schuh (1996) for a discussion of this growth measure.

Multiplication by q_t ensures that average wage $w_t q_t$ appears in the first order condition, rather than just w_t. The former can be calculated using a plant's wage bill and employment, whereas the latter is not directly observed. Note that the labor quality q_t is also unobserved. Consequently, the parameter γ, as well as λ^U and λ^D, are going to be implicitly inferred from wages and output. The implicit assumption is that the endogenous part of the wages at the plant level is proportional to labor quality. This approach differs from those that use direct measures of labor quality based on observable worker characteristics, such as education and experience. The advantage of this approach is that the the estimation of returns to labor quality here does not require a specific measure or index of labor quality, or the estimation of an earnings function.[29]

Profit maximizing conditions are not likely to be exactly fulfilled for several reasons, such as managerial errors originating from inertia and ignorance. Such errors can result in deviations from the plant's ideal choices. Another source of ex-post deviations from optimality is the difference between anticipated and realized output price and exogenous wage rate per unit of quality. These idiosyncratic errors and deviations are assumed to be randomly distributed over plants. Following Hansen and Singleton (1982), the ex-post error can be expressed, using (7) and (13), as a function of the parameters $\Phi = \{\alpha, \gamma, \lambda^U, \lambda^D\}$

$$\begin{aligned} \varepsilon_{t,t+1}(\Phi) &= -\gamma\theta_t L_t^{\alpha} q_t^{\gamma} + w_t q_t L_t + \left[I_t^U \lambda^U + I_t^D \lambda^D\right] \left(\frac{w_t q_t - w_{t-1}q_{t-1}}{w_{t-1}q_{t-1}}\right) w_t q_t L_{t-1} \\ & \quad -\beta \left[I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right] \frac{L_t}{w_t q_t} \left(w_{t+1}^2 q_{t+1}^2 - w_t^2 q_t^2\right), \end{aligned} \tag{14}$$

The ex-post error in labor choice, after using (4) and (5), is

$$\eta_{t,t+1}(\Phi) = -\alpha\theta_t L_t^{\alpha-1} q_t^{\gamma} + w_t q_t + \beta \left[I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right] \left(\frac{w_{t+1}q_{t+1} - w_t q_t}{w_t q_t}\right)^2 w_t q_t. \tag{15}$$

Equations (14) and (15) are used in a generalized method of moments (GMM) framework to estimate the parameters $\Phi = \{\alpha, \gamma, \lambda^U, \lambda^D\}$. The discount factor is set to $\beta = 0.78$ for the quinquennial data, which corresponds to a 95% discount rate for annual data.

The estimation can be readily applied to continuing plants. For exiting plants, the decision variables are not observed for the period after they exit. However, the event of exit contains additional information about the parameters of interest, as exit probability depends on the

[29] For instance, Griliches and Regev (1995) offer a direct link between labor productivity and a labor quality index within the framework of a reduced form linear specification of labor productivity.

parameters

$$\Pr(X(\mathbf{s}_t) = 1) = \Pr(V(\mathbf{s}_t) \leq 0) = \Pr(\theta_t < \theta^*(q_{t-1}, L_{t-1}, w_t, w_{t-1})),$$

where $\theta^*(q_{t-1}, L_{t-1}, w_t, w_{t-1})$ is the threshold profitability shock such that a plant with $\mathbf{s}_t = (\theta_t, q_{t-1}, L_{t-1}, w_t, w_{t-1})$ and $\theta_t < \theta^*$ exits. Pakes (1994) shows that one can substitute the discrete exit policy $X(\mathbf{s}_t)$ into the expected discounted future profits, and proceed as in the case of continuing plants. Thus, for a plant that continues from time $t+1$ to $t+2$, $X(\mathbf{s}_{t+1}) = 0$ and the ex-post errors are as defined earlier. For a plant that exits at time $t+1$, $X(\mathbf{s}_{t+1}) = 1$ and the ex-post errors become

$$\varepsilon_{t,t+1}(\Phi) = -\gamma\theta_t L_t^{\alpha} q_t^{\gamma} + w_t q_t L_t + \left[I_t^U \lambda^U + I_t^D \lambda^D\right] \left(\frac{w_t q_t - w_{t-1} q_{t-1}}{w_{t-1} q_{t-1}}\right) w_t q_t L_{t-1}, \tag{16}$$

$$\eta_{t,t+1}(\Phi) = -\alpha\theta_t L_t^{\alpha-1} q^{\gamma} + w_t q_t. \tag{17}$$

The GMM estimation can be carried out using equations (14) and (15) for continuing plants and equations (16) and (17) for exiting plants. It is important to include exiting plants in the estimation as not doing so could induce bias in both the estimated production function and adjustment cost parameters. The estimation is done separately for continuing plants and all plants (continuing and exiting) to assess this potential bias.

4.2 Estimation with adjustment costs for wages and employment

For the case with both employment and wage adjustment cost, the ex-post error for L_t is

$$\begin{aligned} \eta_{t,t+1}(\Phi) \quad = \quad & -\alpha\theta_t L_t^{\alpha-1} q_t^{\gamma} + w_t q_t + \left[J_t^U \nu^U + J_t^D \nu^D\right] \left(\frac{L_t - L_{t-1}}{L_{t-1}}\right) \\ & +\beta \left[I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right] \left(\frac{w_{t+1} q_{t+1} - w_t q_t}{w_t q_t}\right)^2 w_t q_t \\ & -\beta \left[J_{t+1}^U \frac{\nu^U}{2} + J_{t+1}^D \frac{\nu^D}{2}\right] \left(\frac{L_{t+1}^2 - L_t^2}{L_t^2}\right). \end{aligned} \tag{18}$$

The ex-post error for q_t is the same as (14).

For exiting plants, the ex-post error for L_t is

$$\eta_{t,t+1}(\Phi) = -\alpha\theta_t L_t^{\alpha-1} q^{\gamma} + w_t q_t + \left[J_t^U \nu^U + J_t^D \nu^D\right] \left(\frac{L_t - L_{t-1}}{L_{t-1}}\right),$$

and the ex-post error for q_t is the same as (16). The parameters to be estimated are now $\Phi = \{\alpha, \gamma, \lambda^U, \lambda^D, \nu^U, \nu^D\}$.

The estimation involves endogenous variables that are simultaneously determined. These are current revenue, employment, and average wage. The instruments used for endogenous variables are lagged revenue, value added, wage bill, average wage, and their interactions with current-period revenue, employment, average wage and value added, all deflated.[30] Similar estimation procedures apply to the case of adjustment cost with alternative growth rate using the first order conditions in the appendix.

It is important to note that, as in most previous studies, estimation is based on net, not gross, changes in wages and employment. Because the data used here is quinquennial, adjustments associated with gross changes can be important between two consecutive points in time. Gross changes are unfortunately not available in the data used here. In a simulation study based on annual frequency, Hall (2004) finds that adjustment cost is understated when it applies to gross investment instead of net, when there are fixed cost of adjustment and no firm specific shocks – two features not present in the model here.

5 Results

The GMM estimates of parameters using the entire sample of manufacturing plants are reported in Table III. Two measures of revenue are used alternatively: deflated total value of shipments (top panel) and deflated value added (bottom panel). Adjustment costs with both the conventional and the alternative growth rates are considered. The estimates in specifications I and III pertain to continuing plants. For each census year t, continuing plants are the ones that are observed consecutively in census years $t-5$, t, and $t+5$, for $t = 1967, ..., 1997$.[31] The estimates in specifications II and IV include all plants. For each census year t, all plants include continuing plants and the exiting plants – those plants that are observed in census years $t-5$ and t, but not in $t+5$. Both the model with wage adjustment only (specifications I and II), and the model with wage and employment adjustment (specifications III and IV) are estimated.[32]

[30] The results were not significantly different when twice-lagged versions of the variables were also used as instruments.

[31] With the exception that, for $t = 1967$ the previous census year is 1963, corresponding to $t-4$.

[32] In all specifications in Table 3, the top and bottom 1% of the plant level distributions of average wage, wage bill-to-revenue ratio, and labor productivity were trimmed to reduce the influence of some major outliers. The total employment of a plant was also restricted to the range 5 to $10,000$ employees.

5.1 Estimates of production function parameters

In all specifications, the estimates for the production function parameters α and γ are very precise, have the expected signs, and fall in the interval $(0, 1)$. As shown in the top panel, the estimated value of $\alpha + \gamma$ when revenue is measured by the value of shipments range from 0.17 to 0.55. This range also contains the estimated labor share of output, about 0.40, obtained by estimating the specified Cobb-Douglas production on the same sample of plants in a static model with no adjustment costs. When value added is used as the revenue measure in the bottom panel, the estimates of α and γ are much higher, and still highly significant. The estimates of $\alpha + \gamma$ are in the range $0.49 - 0.83$, which also contains the point estimate of labor share, about 0.80, obtained from the static version of the model without adjustment costs based on the same sample of plants. The estimates of γ exceed those of α in most specifications in the top and bottom panels in Table III, pointing to the importance of the labor quality share in the specified production function. However, the higher estimate of labor quality parameter γ may also stem from the omission of some important variables, such as quality of capital measures, especially because higher quality capital may complement skilled labor.

5.2 Estimates of adjustment cost parameters

In most specifications in Table III, the estimates of the adjustment cost parameters have the expected signs, and all are highly significant. In some cases, the estimated upward adjustment cost parameters, λ^U and ν^U, are negative, with relatively small absolute values compared to other adjustment cost parameter estimates. These cases, which also emerge in some of the prior studies (e.g. Hall (2004)), may result from a combination of remaining outliers in the data, measurement error, and sampling errors, although a specification error cannot be ruled out completely. Overall, the estimates reveal significant asymmetry in adjustment costs. Except for one case (specification II with alternative growth rate), downward adjustment costs parameters are much higher than upward adjustment cost parameters, both for wage and employment adjustment. The equality of the upward and downward adjustment costs are easily rejected at high levels of significance across most specifications. Furthermore, downward adjustment cost parameters are generally larger in absolute value when all plants are considered (specifications II and IV), compared to the case of continuing plants only (specifications I and III). This difference suggests that exiting plants face steeper downward adjustment costs than continuing ones. The adjustment cost parameter estimates are generally smaller under alternative growth rates, potentially because the alternative growth rates are bounded and robust to remaining outliers in wage and employment growth.

Table III was obtained from estimating the model without any constraints. An implicit constraint on the model's adjustment cost parameters, however, is that they must be non-negative. Table A.I in the appendix presents the GMM estimates under the non-negativity constraints for adjustment cost parameters. If the model's specification is not largely at odds with the data, moving from the unconstrained to the constrained estimation should not result in drastic sign and significance changes in adjustment cost parameters, such as a shift in a parameter estimate from negative and significant to positive and significant. Estimates of α and γ in Table A.I are generally similar to those in Table III, and they are actually somewhat larger in cases where revenue is measured by value added. Also notable is the fact that almost all of the negative estimates of upward adjustment cost parameters in Table III are now zero – none has become positive and significant. This observation suggests that the upward adjustment cost parameters may indeed be not too far from zero, and the negative estimates in Table III are not likely a result of a gross model misspecification, rather potentially attributable to other factors such as measurement error. The estimates of downward adjustment costs also remain significant and positive in Table A.I. The results in Table A.I overall support the main conclusions from Table III.

5.3 Assessing the magnitude of adjustment costs

Because the percent adjustments in wages and employment apply to different bases in the adjustment cost specifications, it is not appropriate to simply compare the estimated magnitudes of λ^U and ν^U, or λ^D and ν^D, to gauge the relative importance of different adjustment costs. The approach here is to assess the importance of the cost of adjustment for wages versus employment by comparing the shares of the average annual wage and employment adjustment costs in a plant's initial revenue over a 5-year window between two censuses. These static shares, however, do not take into account the dynamic effects of adjustments. In any period, a plant may incur a loss net of adjustment costs to ensure future profitability. The adjustment costs are calculated over a 5-year period between two census years t and $t + 5$, whereas the current revenue is calculated for census year t. The adjustment cost incurred in census year t changes the value of the plant in the future, including the years until census year $t + 5$.

Table IV presents quartiles for the estimated revenue shares of adjustment costs based on the parameter estimates in Table III. Rather than picking a certain specification arbitrarily, for each adjustment cost parameter its maximum estimate across all specifications for the case of total value of shipments in Table III is used to obtain the estimates in Table IV. This approach provides an upper bound on the revenue share of adjustment costs, given our estimation methodology and the sample used. Panel (a) considers estimates from the models using continuing plants only, corresponding to specifications I and III in Table III. For the model with wage adjustment only, at the median adjustment cost, the adjustment cost is 0.8% of revenue when all directions of adjustment are considered together, and around 0.4% and 2% when upward and downward adjustments are considered, respectively. For the model with both wage and employment adjustment, wage adjustment cost is about 1.0% of revenue at the median wage adjustment cost, and upward wage adjustment cost constitutes about 0.6% of revenue, while downward wage adjustment cost makes up about 1.6% of revenue. Employment adjustment cost has a significant share (nearly 4%) of revenue at the median employment adjustment cost when downward employment adjustments are considered. For upward employment adjustments, this share is about 3% at the median employment adjustment cost.

A similar pattern emerges in panel (b) of Table IV, which focuses on the estimated parameters using all plants, corresponding to specifications II and IV in Table III. For the model with wage adjustment only, upward and downward wage adjustment costs make up, respectively, about 0.8% and 3.5% of revenue at the median wage adjustment cost. For the model with both adjustment margins, these shares are about 0.1% and 3.2%, respectively. For employment adjustment, upward adjustment cost is about 5.9% of revenue, but the downward adjustment cost constitutes about 8.2% of revenue, both measured at the median employment adjustment cost.

Adjustment costs constitute a much larger fraction of revenue when only the exiting plants are considered, as panel (c) of Table IV indicates. For almost all model specifications and for both upward and downward adjustment, the shares in panel (c) are much higher compared to panels (a) and (b). In particular, at the 3rd quartile of the adjustment cost distribution, downward wage adjustment cost makes up around 25% of revenue for the model with wage adjustment only, and about 14% of revenue for the model with both adjustment margins. These magnitudes suggest that downward adjustment costs can be a substantial burden for plants, especially for those nearing exit.

How much do adjustment costs in wages change over the life-cycle of a plant? The evolution of adjustment costs along the plant life-cycle is shown in Figure IV. The estimates in Figure IV are for continuing plants only. These estimates are based on the largest adjustment cost parameter estimates from the model with wage adjustment cost only using all plants, corresponding to specifications labelled II in the left panel of Table III, which also generate the left side of panel (b) in Table IV. For plants that are five years from their first census, wage adjustment cost makes up about 2.3% of revenue at the median. This share increases slightly as new plants age and then declines to just below 1.6% by the time a plant is 20 years away from entry. Somewhat reversal of this pattern emerges for plants approaching exit. Wage adjustment cost grows to about 2.2% of a plant's revenue five years before its exit, doubling from about 1.1% when a plant stands twenty years from exit.

5.4 A comparison with previous estimates

While there does not exist a sizeable prior literature on the estimates of wage adjustment costs, several studies have provided estimates of labor adjustment costs. One contribution of this study is that it provides a first set of estimates for labor adjustment costs in the presence of wage adjustment costs. How do the estimates here compare with the existing estimates for labor adjustment costs? Such a comparison is inherently difficult, given the fact that prior studies span a variety of model structures, samples, and aggregations. Nevertheless, most studies find positive labor adjustment costs, based on several adjustment cost function specifications. Quadratic adjustment costs are positive and significant in studies using only a quadratic or higher-order specification with or without interactions among different adjustment margins (e.g. Shapiro (1986), Pfann and Palm (1993), Alonso-Borrego (1998), and Merz and Yashiv (2007)), with the exception of Hall (2004), who finds quadratic costs that are not significantly different from zero using data at high-level industry aggregations. Studies incorporating fixed cost of labor adjustment and partial irreversibilities in addition to quadratic adjustment costs generally find smaller or insignificant quadratic adjustment costs (e.g. Cooper, Haltiwanger, and Willis (2004), and Bloom (2009)). The estimates in this paper are within the range of the estimates found in these previous studies, though there is evidence of asymmetric adjustment costs for both wages and employment. The estimates indicate a small upward adjustment cost, which essentially becomes zero when constrained estimates in Table A.I are considered, but positive downward adjustment costs. When combined, average annual adjustment costs in any direction at the median amount to about 3.2% to 6.7% of revenue, for continuing and all plants, respectively. Note also that labor adjustment costs are smaller when considered next to wage adjustment costs. This finding suggest that not being able to control for labor quality adjustments may introduce some bias in adjustment cost estimates for labor quantity.

In summary, the estimates of production function parameters suggest that the quality of labor is an important input in production when compared to the quantity of labor. In many cases, the quality's share of revenue exceeds that of quantity, as indicated by the relative magnitudes of the estimated α and γ. Both the quality and quantity margins of adjustment matter. Evidence also points to asymmetric adjustment costs both for wages and employment. Upward adjustment costs are smaller compared to downward adjustment costs, both for wages and employment. Plants nearing exit bear a larger burden in terms of downward adjustment in wages and employment. The downward adjustment costs are also considerable even for continuing plants.

6 Conclusion

This paper investigated the dynamics of wages along the life-cycle of manufacturing plants. New plants start with lower wages compared to mature plants. Surviving plants' wages increase and catch up with those of mature plants. Wages in plants approaching exit fall, but not as steeply as they rise in the case of surviving new plants. Wages constitute a lower fraction of young plants' revenue because their labor productivity, as measured by revenue per worker, grows faster than their wages. For plants approaching exit, wages do not fall as fast as labor productivity does, implying that a higher fraction of revenue must be dedicated to wage bill.

A model of plant-level dynamics with asymmetric wage adjustment costs was studied to account for the observed patterns. The model relates wage adjustment to adjustment in labor quality. The contribution of unobserved labor quality both to revenue and adjustment cost is inferred using the restrictions imposed by the dynamic optimization. The estimated parameters of the model reveal evidence of asymmetric adjustment costs in wages. The estimated upper bounds on revenue share of wage adjustment costs indicate economic significance of such costs at the plant level, especially those associated with downward adjustment. The estimates remain economically significant when wage adjustment cost is considered jointly with employment adjustment cost.

The cost of adjusting wages downward may increase the likelihood of exit and speed up the demise of failing plants. Further research can quantify the importance of these costs in exit. The model can be estimated separately for unionized and non-unionized plants to assess the role of unions in wage adjustment. An examination of persistence in plant-level profitability shocks and its implications on wage persistence is also desirable. Higher frequency data, such as annual, can be used to assess how adjustment costs change when shorter periods of adjustment are considered. Adjustments in other components of compensation, such as benefits, can also be introduced. It is also promising to investigate the differences in adjustment costs for wages of production vs. non-production workers. The empirical analysis suggests that the former is likely the main driver of the patterns observed in this paper. It is also important to consider adjustment costs in other key inputs, such as capital, to assess the relative magnitudes of different adjustment costs and to reduce any potential biases due to omission of adjustment costs in capital.[33] Finally, the estimation can also be readily applied to establishments in non-manufacturing industries, for which census data contain only revenue, payroll, and employment.

[33] See Bloom (2009) for estimates of adjustment costs for both labor and capital using firm level data for large, publicly traded firms only.

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Table 1. OLS estimation results for the evolution of average wage, labor productivity, and wages to revenue ratio

Dependent Variable:	**Average Wage ($1,000)**		**Revenue/Employment ($1,000)**		**Wage Bill/Revenue (%)**	
Independent Variables	**I**	**II**	**I**	**II**	**I**	**II**
Exit	-2.031***	-1.846***	-9.852***	-8.962***	0.675***	0.598***
	[0.018]	[0.018]	[0.160]	[0.157]	[0.038]	[0.038]
5 years to exit	-1.010***	-0.897***	-5.220***	-4.939***	0.634***	0.635***
	[0.019]	[0.019]	[0.174]	[0.171]	[0.042]	[0.041]
10 years to exit	-0.695***	-0.613***	-3.920***	-3.914***	0.461***	0.497***
	[0.024]	[0.024]	[0.219]	[0.215]	[0.053]	[0.052]
15 years to exit	-0.447***	-0.412***	-2.566***	-3.010***	0.273***	0.369***
	[0.031]	[0.030]	[0.275]	[0.269]	[0.066]	[0.065]
20 years to exit	-0.159***	-0.179***	-1.240***	-2.281***	0.031	0.211**
	[0.038]	[0.038]	[0.347]	[0.339]	[0.083]	[0.082]
Entry	-2.714***	-2.356***	-5.668***	-1.998***	-1.733***	-2.236***
	[0.017]	[0.017]	[0.156]	[0.155]	[0.037]	[0.038]
5 years from entry	-1.782***	-1.514***	-2.228***	0.282*	-1.247***	-1.580***
	[0.019]	[0.019]	[0.170]	[0.168]	[0.041]	[0.041]
10 years from entry	-1.180***	-0.964***	-1.141***	0.571**	-0.653***	-0.865***
	[0.023]	[0.023]	[0.207]	[0.204]	[0.050]	[0.049]
15 years from entry	-0.628***	-0.469***	-0.151	0.759***	-0.219***	-0.312***
	[0.026]	[0.026]	[0.239]	[0.234]	[0.057]	[0.057]
20 years from entry	-0.229***	-0.120**	1.537***	1.634***	-0.181**	-0.152
	[0.044]	[0.044]	[0.397]	[0.389]	[0.095]	[0.094]
Industry x year fixed effects	Y	Y	Y	Y	Y	Y
Other controls	N	Y	N	Y	N	Y
N	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769
R^2	0.29	0.30	0.38	0.41	0.43	0.44

Notes: Standard errors in brackets. (*),(**),(***) indicate significance at 10%,5%,1%, respectively. Other controls include a cubic spline in plant size (measured by total employment) and an indicator of multi-plant firm. The omitted category is the plants that are more than twenty years away from their entry or exit, and the plants whose entry or exit points do not fall into the sample period.

Table II. OLS estimation results for the evolution of average wage and wages to revenue ratio by worker type

Dependent Variable:	No. of Non-Production Workers/Total Employment		Average Wage ($1,000) Production Workers		Average Wage ($1,000) Non-Production Workers		log(Average Wage) Production Workers		log(Average Wage) Non-Production Workers		Wage Bill/Revenue Production Workers (%)		Wage Bill/Revenue Non-Production Workers (%)	
Independent Variables	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**
Exit	-0.384***	-0.310***	-1.406***	-1.199***	-4.466***	-4.363***	-0.093***	-0.083***	-0.164***	-0.158***	1.112***	1.061***	-0.445***	-0.463***
	[0.041]	[0.042]	[0.019]	[0.019]	[0.054]	[0.157]	[0.0009]	[0.0009]	[0.001]	[0.001]	[0.032]	[0.032]	[0.020]	[0.020]
5 years to exit	-0.232***	-0.181***	-0.664***	-0.538***	-2.345***	-2.279***	-0.043***	-0.037***	-0.081***	-0.077***	0.900***	0.892***	-0.266***	-0.257***
	[0.045]	[0.045]	[0.020]	[0.020]	[0.059]	[0.060]	[0.001]	[0.001]	[0.002]	[0.001]	[0.035]	[0.035]	[0.022]	[0.022]
10 years to exit	-0.153***	-0.112**	-0.458***	-0.368***	-1.611***	-1.562***	-0.029***	-0.025***	-0.054***	-0.051***	0.676***	0.692***	-0.215***	-0.194***
	[0.057]	[0.057]	[0.026]	[0.025]	[0.075]	[0.075]	[0.001]	[0.001]	[0.002]	[0.002]	[0.044]	[0.044]	[0.028]	[0.027]
15 years to exit	0.114	0.141**	-0.280***	-0.242***	-0.976***	-0.950***	-0.019***	-0.018***	-0.033***	-0.032***	0.366***	0.421***	-0.094***	-0.052
	[0.071]	[0.071]	[0.032]	[0.032]	[0.093]	[0.093]	[0.002]	[0.001]	[0.002]	[0.002]	[0.055]	[0.055]	[0.035]	[0.034]
20 years to exit	0.338***	0.348***	-0.128***	-0.152***	-0.094	-0.094	-0.009***	-0.012***	-0.004	-0.005*	-0.077	0.031	0.109**	0.179**
	[0.090]	[0.090]	[0.041]	[0.041]	[0.117]	[0.118]	[0.002]	[0.002]	[0.003]	[0.003]	[0.070]	[0.069]	[0.044]	[0.043]
Entry	-1.689***	-1.575***	-2.222***	-1.818***	-4.319***	-4.135***	-0.138***	-0.115***	-0.151***	-0.138***	-0.445***	-0.771***	-1.289***	-1.465***
	[0.040]	[0.041]	[0.018]	[0.018]	[0.053]	[0.054]	[0.0009]	[0.0009]	[0.001]	[0.001]	[0.031]	[0.032]	[0.020]	[0.020]
5 years from entry	-0.958***	-0.868***	-1.571***	-1.270***	-2.370***	-2.230***	-0.092***	-0.076***	-0.086***	-0.076***	-0.391***	-0.609***	-0.856***	-0.970***
	[0.044]	[0.044]	[0.020]	[0.020]	[0.058]	[0.058]	[0.001]	[0.001]	[0.002]	[0.002]	[0.034]	[0.034]	[0.021]	[0.021]
10 years from entry	-0.743***	-0.664***	-1.098***	-0.855***	-1.308***	-1.193***	-0.061***	-0.048***	-0.049***	-0.042***	-0.133***	-0.275***	-0.520***	-0.590***
	[0.054]	[0.054]	[0.025]	[0.024]	[0.070]	[0.070]	[0.001]	[0.001]	[0.002]	[0.002]	[0.042]	[0.042]	[0.026]	[0.026]
15 years from entry	-0.800***	-0.735***	-0.644***	-0.467***	-0.452***	-0.364***	-0.033***	-0.024***	-0.018***	-0.012***	0.058	-0.008	-0.277***	-0.303***
	[0.062]	[0.062]	[0.028]	[0.028]	[0.239]	[0.080]	[0.001]	[0.001]	[0.002]	[0.002]	[0.048]	[0.048]	[0.030]	[0.030]
20 years from entry	-0.496***	-0.443***	-0.288***	-0.168***	0.028	0.094	-0.011***	-0.006**	0.002	0.005	0.021	-0.033	-0.204***	-0.183***
	[0.103]	[0.102]	[0.047]	[0.046]	[0.133]	[0.133]	[0.002]	[0.002]	[0.003]	[0.003]	[0.080]	[0.080]	[0.050]	[0.050]
Industry x year fixed effects	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Other controls	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
N	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769	1,219,769
R^2	0.39	0.39	0.24	0.25	0.07	0.07	0.29	0.30	0.13	0.14	0.46	0.46	0.06	0.06

Notes: Standard errors in brackets. (*),(**),(***) indicate significance at 10%,5%,1%, respectively. Other controls include a cubic spline in plant size (measured by total employment) and an indicator of multi-plant firm. The omitted category is the plants that are more than twenty years away from their entry or exit, and the plants whose entry or exit points do not fall into the sample period.

Table III. Unconstrained GMM estimates for the model's parameters using all manufacturing plants

	Adjustment costs (conventional growth rate)				Adjustment cost (alternative growth rate)			
	Wage adjustment		Wage and employment		Wage adjustment		Wage and employment	
Parameter	**Continuing plants (I)**	**All plants (II)**	**Continuing plants (III)**	**All plants (IV)**	**Continuing plants (I)**	**All plants (II)**	**Continuing plants (III)**	**All plants (IV)**
Revenue measure: Total value of shipments (deflated)								
α	0.12***	0.11***	0.12***	0.09***	0.12***	0.13***	0.09***	0.14***
	[0.0005]	[0.0006]	[0.002]	[0.0006]	[0.0004]	[0.0004]	[0.0005]	[0.001]
γ	0.19***	0.18***	0.25***	0.24***	0.27***	0.42***	0.08***	0.13***
	[0.0004]	[0.0005]	[0.002]	[0.0007]	[0.0009]	[0.002]	[0.002]	[0.002]
λ^U	2.89***	-2.52***	10.73***	-0.98***	5.94***	14.18***	-1.25***	-2.71***
	[0.05]	[0.04]	[0.41]	[0.01]	[0.11]	[0.15]	[0.03]	[0.08]
λ^D	35.61***	63.10***	20.81***	56.48***	9.55***	6.30***	10.10***	10.46***
	[0.25]	[0.42]	[0.74]	[0.33]	[0.07]	[0.06]	[0.12]	[0.33]
v^U	-	-	8.62***	-0.56***	-	-	1.97***	13.43***
			[0.52]	[0.03]			[0.42]	[0.72]
v^D	-	-	23.17***	42.91***	-	-	8.90***	88.21***
			[4.82]	[1.03]			[0.12]	[1.94]
Revenue measure: Value added (deflated)								
α	0.36***	0.39***	0.25***	0.33***	0.32***	0.37***	0.27**	0.39***
	[0.0005]	[0.0008]	[0.003]	[0.0007]	[0.0002]	[0.001]	[0.001]	[0.003]
γ	0.47***	0.44***	0.37***	0.39***	0.35***	0.27***	0.22***	0.42***
	[0.002]	[0.001]	[0.004]	[0.002]	[0.0002]	[0.001]	[0.002]	[0.002]
λ^U	1.39***	1.00***	3.73***	1.38***	-3.44***	-3.05***	-1.04***	-0.54***
	[0.04]	[0.02]	[0.24]	[0.04]	[0.08]	[0.06]	[0.03]	[0.05]
λ^D	15.63***	13.95***	29.32***	19.25***	10.31***	8.34***	6.82***	1.37***
	[0.17]	[0.20]	[0.47]	[0.21]	[0.06]	[0.06]	[0.08]	[0.22]
v^U	-	-	3.46***	1.13***	-	-	2.03***	17.74***
			[0.28]	[0.04]			[0.32]	[0.79]
v^D	-	-	41.42***	47.60***	-	-	6.69***	58.32***
			[2.70]	[0.72]			[0.09]	[2.20]
N	804,245	986,977	804,245	986,977	804,245	986,977	804,245	986,977

Notes: Standard errors in brackets. (*),(**),(***) indicate significance at 10%,5%,1%, respectively.

Table IV. Adjustment costs as a percentage of revenue

(a) Estimates using continuing plants only

	Adjustment Cost Percentile	Model with wage adjustment only: All	Upward	Downward	Model with wage and employment adjustment: All	Upward (Wages)	Downward (Wages)	Upward (Employment)	Downward (Employment)
Wage Adjustment	25	0.1%	0.1%	0.4%	0.2%	0.1%	0.3%		
	50	0.8%	0.4%	2.0%	1.0%	0.6%	1.6%		
	75	3.7%	1.5%	7.6%	4.2%	2.7%	6.2%		
Employment Adjustment	25				0.6%			0.6%	0.5%
	50				3.2%			2.9%	3.8%
	75				14.3%			12.6%	16.9%

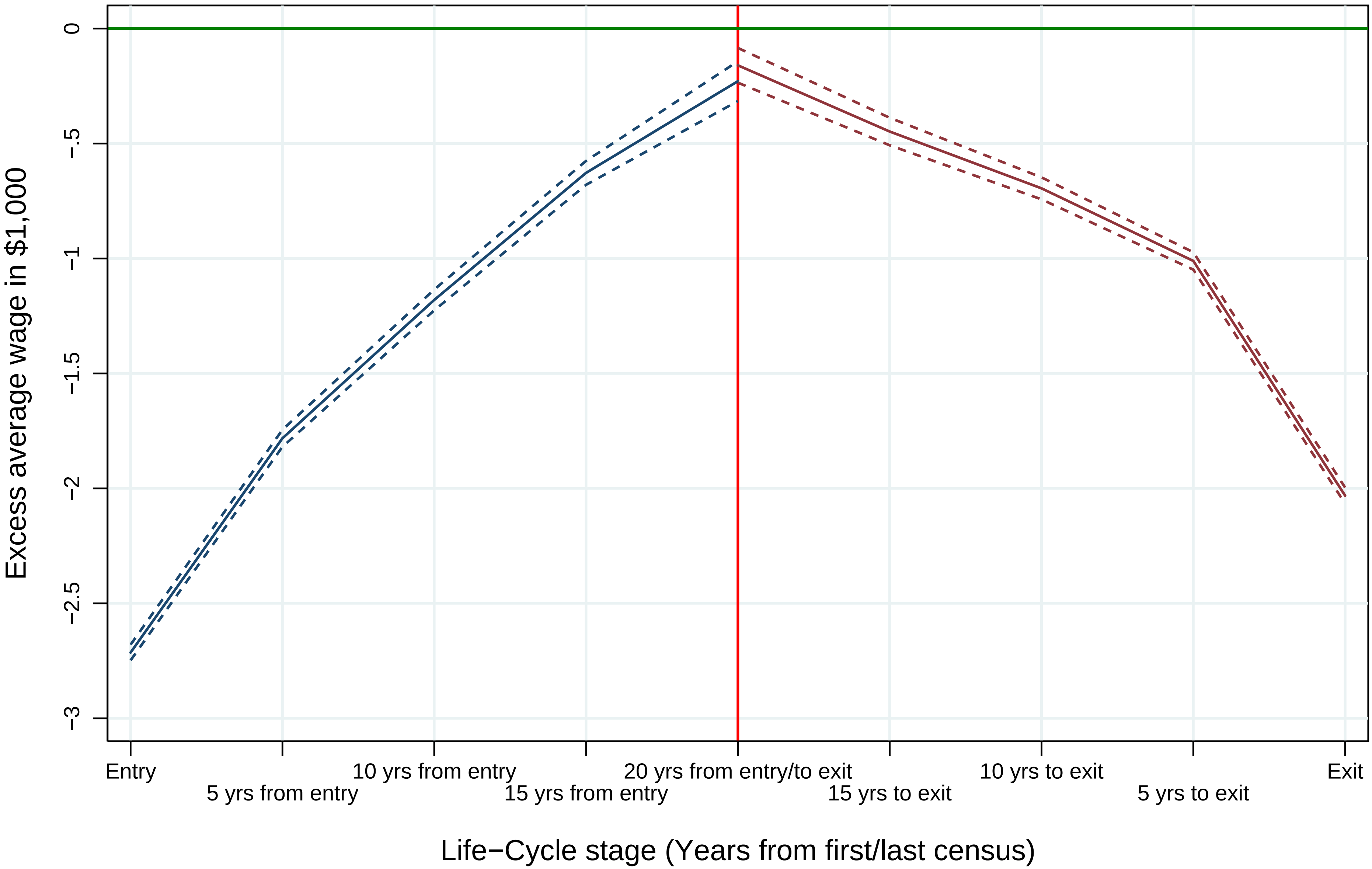
(b) Estimates using all plants: Continuing plants only

	Adjustment Cost Percentile	Model with wage adjustment only: All	Upward	Downward	Model with wage and employment adjustment: All	Upward (Wages)	Downward (Wages)	Upward (Employment)	Downward (Employment)
Wage Adjustment	25	0.3%	0.2%	0.7%	0.0%	0.0%	0.6%		
	50	1.6%	0.8%	3.5%	0.4%	0.1%	3.2%		
	75	7.4%	3.5%	13.4%	3.4%	3.9%	2.9%		
Employment Adjustment	25				1.2%			1.2%	1.1%
	50				6.7%			5.9%	8.2%
	75				29.9%			26.0%	35.9%

(c) Estimates using all plants: Exiting plants only

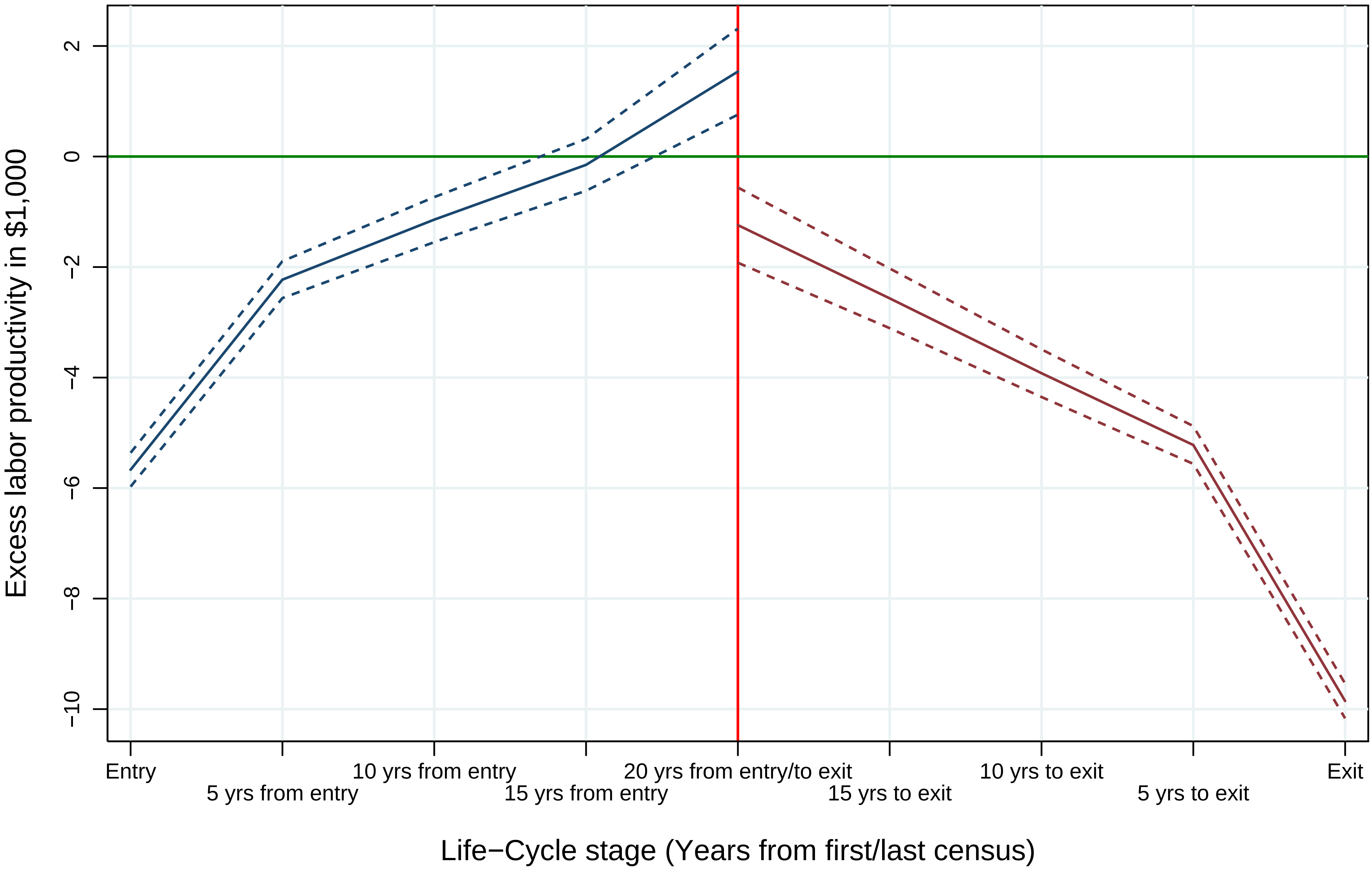
	Adjustment Cost Percentile	Model with wage adjustment only: All	Upward	Downward	Model with wage and employment adjustment: All	Upward (Wages)	Downward (Wages)	Upward (Employment)	Downward (Employment)
Wage Adjustment	25	0.5%	0.2%	1.3%	0.1%	0.0%	1.1%		
	50	3.0%	1.2%	6.7%	0.9%	0.1%	6.0%		
	75	14.2%	5.3%	25.7%	7.9%	0.5%	23.0%		
Employment Adjustment	25				2.4%			1.8%	3.4%
	50				14.8%			10.0%	22.4%
	75				70.6%			48.5%	94.7%

Figure I(a)
Plant Life−Cycle Evolution of Average Wage



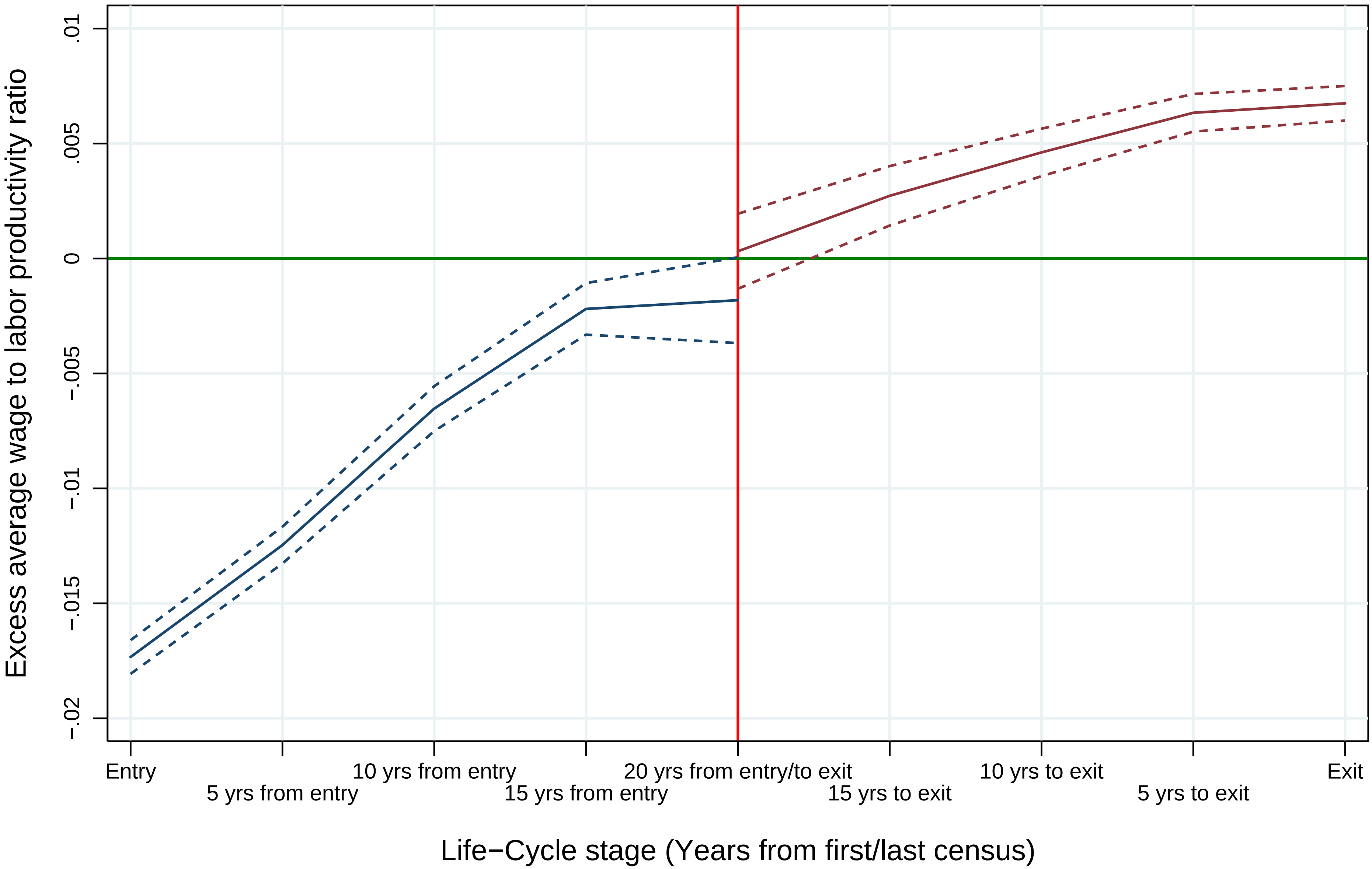
Notes: The horizontal line at zero represents the normalized value for the omitted category. Dashed lines are +/− 2 std. errors.

Figure I(b)
Plant Life−Cycle Evolution of Labor Productivity



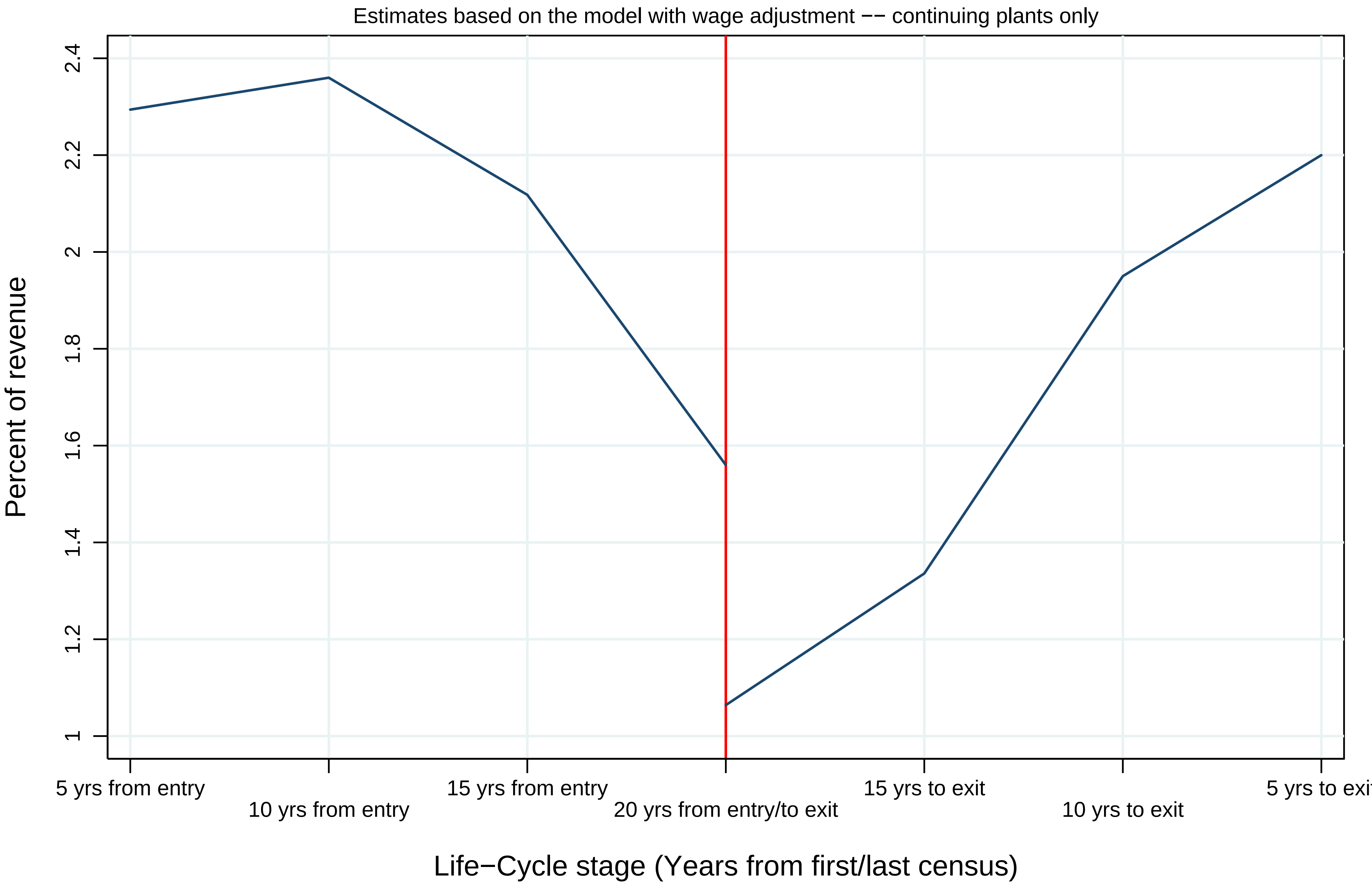
Notes: The horizontal line at zero represents the normalized value for the omitted category. Dashed lines are +/− 2 std. errors.

Figure I(c)
Plant Life−Cycle Evolution of Average Wage to Labor Productivity Ratio



Notes: The horizontal line at zero represents the normalized value for the omitted category. Dashed lines are +/− 2 std. errors.

Figure II
Plant Life−Cycle Evolution of Wage Adjustment Cost as a Share of Revenue



Appendix

A Monotonicity of policy functions

This appendix shows that under certain conditions the policy functions $L(\mathbf{s}_t)$ and $q(\mathbf{s}_t)$ are monotonically increasing in θ_t, i.e. $\frac{dL(\mathbf{s}_t)}{d\theta_t} > 0$ and $\frac{dq(\mathbf{s}_t)}{d\theta_t} > 0$. Consider the case of wage adjustment cost with conventional growth rate. Other cases can be worked out similarly. Let $\lambda_t \equiv \left(I_t^U \frac{\lambda^U}{2} + I_t^D \frac{\lambda^D}{2}\right)$, $K_{t+1} \equiv E\left[\lambda_{t+1}\left(\frac{w_{t+1}q_{t+1}-w_t q_t}{w_t q_t}\right)^2\right]$, and $M_{t+1} \equiv -E\left[\lambda_{t+1}\frac{w_{t+1}^2 q_{t+1}^2 - w_t^2 q_t^2}{w_t^2 q_t^2}\right]$. The first order conditions (4) and (6) can be written as

$$\alpha\theta_t L_t^{\alpha-1} q_t^{\gamma} = (1+\beta K_{t+1}) w_t q_t, \tag{19}$$

$$\gamma\theta_t L_t^{\alpha} q_t^{\gamma-1} = \left(1 + 2\lambda_t\left(\frac{w_t q_t - w_{t-1}q_{t-1}}{w_{t-1}q_{t-1}}\right)\frac{L_{t-1}}{L_t} + \beta M_{t+1}\right) w_t L_t. \tag{20}$$

Total differentiation of (19) and (20) with respect to θ_t results in the system

$$\begin{aligned} A\frac{dL(\mathbf{s}_t)}{d\theta_t} + B\frac{dq(\mathbf{s}_t)}{d\theta_t} &= E \\ C\frac{dL(\mathbf{s}_t)}{d\theta_t} + D\frac{dq(\mathbf{s}_t)}{d\theta_t} &= F \end{aligned} \tag{21}$$

which has the solution

$$\begin{aligned} \frac{dL(\mathbf{s}_t)}{d\theta_t} &= \frac{ED-BF}{AD-BC} \\ \frac{dq(\mathbf{s}_t)}{d\theta_t} &= \frac{AF-EC}{AD-BC} \end{aligned}$$

provided that $AD - BC \neq 0$. The coefficients of the system (21) are given by

$$\begin{aligned} A &= \alpha(1-\alpha)\theta_t L_t^{\alpha-2} q_t^{\gamma-1} + w_t\beta\frac{\partial K_{t+1}}{\partial L_t}, \\ B &= \alpha(1-\gamma)\theta_t L_t^{\alpha-1} q_t^{\gamma-2} + w_t\beta\frac{\partial K_{t+1}}{\partial q_t}, \\ E &= \alpha L_t^{\alpha-1} q_t^{\gamma-1} - w_t\beta\frac{\partial K_{t+1}}{\partial \theta_t}, \end{aligned}$$

$$\begin{aligned} C &= \gamma(1-\alpha)\theta_t L_t^{\alpha-2} q_t^{\gamma-1} + w_t\beta\left(-2\lambda_t\left(\frac{w_t q_t - w_{t-1}q_{t-1}}{w_{t-1}q_{t-1}}\right)\frac{L_{t-1}}{L_t^2} + \frac{\partial M_{t+1}}{\partial L_t}\right), \\ D &= \gamma(1-\gamma)\theta_t L_t^{\alpha-1} q_t^{\gamma-2} + w_t\beta\left(2\lambda_t\frac{w_t}{w_{t-1}q_{t-1}}\frac{L_{t-1}}{L_t} + \frac{\partial M_{t+1}}{\partial q_t}\right), \\ F &= \gamma L_t^{\alpha-1} q_t^{\gamma-1} - w_t\beta\frac{\partial M_{t+1}}{\partial \theta_t}. \end{aligned}$$

For $L(\mathbf{s}_t)$ and $q(\mathbf{s}_t)$ to be strictly increasing in θ_t, one of the following must hold

$$AD - BC > 0,\ AF - EC > 0,\ ED - BF > 0 \tag{22}$$

$$AD - BC < 0,\ AF - EC < 0,\ ED - BF < 0 \tag{23}$$

Thus, any restrictions on the model's parameters that guarantee (22) or (23) would be sufficient. Consider a set of sufficient conditions that leads to (22). Conditions that ensure (23) can also be derived similarly. Assume first that $\frac{\partial K_{t+1}}{\partial L_t} > 0, \frac{\partial K_{t+1}}{\partial q_t} > 0, \frac{\partial M_{t+1}}{\partial L_t} < 0, \frac{\partial M_{t+1}}{\partial q_t} > 0$. This assumption implies that period $t+1$ expected marginal cost of adjustment in average wage is strictly increasing in q_t and L_t, except in the case of M_{t+1} with respect to L_t. Assume also that $\frac{\partial K_{t+1}}{\partial \theta_t} < 0$ and $\frac{\partial M_{t+1}}{\partial \theta_t} < 0$, implying that the partial effect of an increase in θ_t on the expected marginal cost of adjustment in period $t+1$ is negative – this would be the case, for instance, if the stochastic process defined by $H(\theta_{t+1}|\theta_t)$ is such that a higher current period profitability shock θ_t implies a distribution of next period shock θ_{t+1} that assigns higher density to those shocks that render a smaller adjustment cost. In addition, assume that $C < 0$, i.e. the net marginal effect on plant value of an increase in L_t is strictly decreasing as L_t increases.[34] Under these assumptions, the coefficients of the system (21) have the following signs: $A, B, D, E, F > 0$ and $C < 0$. These signs imply that $AD - BC > 0$ and $AF - EC > 0$, ensuring that $\frac{dq(\mathbf{s}_t)}{d\theta_t} > 0$. Finally, $ED - BF > 0$ is needed for $\frac{dL(\mathbf{s}_t)}{d\theta_t} > 0$. One can write

$$ED - BF = w_t\beta\left[\left(2\lambda_t \frac{w_t}{w_{t-1}q_{t-1}}\frac{L_{t-1}}{L_t} + \frac{\partial M_{t+1}}{\partial q_t}\right)E - \frac{\partial K_{t+1}}{\partial q_t}F\right] \tag{24}$$

$$+\alpha(1-\gamma)\theta_t L_t^{\alpha-1} q_t^{\gamma-2} w_t \beta \left(\frac{\partial M_{t+1}}{\partial \theta_t} - \frac{\gamma}{\alpha}\frac{\partial K_{t+1}}{\partial \theta_t}\right) \tag{25}$$

Now consider the terms on the *r.h.s.* of (24). The first term is positive, for instance, if $E > F$ and $\frac{\partial M_{t+1}}{\partial q_t} > \frac{\partial K_{t+1}}{\partial q_t}$. The second term is positive if $\frac{\frac{\partial K_{t+1}}{\partial \theta_t}}{\frac{\partial M_{t+1}}{\partial \theta_t}} > \frac{\alpha}{\gamma}$. Other sufficient conditions can be provided. Similarly, sufficient conditions can be stated for the case with both wage and employment adjustment, and for adjustment costs with alternative growth rates.

[34] Because it was already assumed that $\frac{\partial M_{t+1}}{\partial L_t} < 0$, one obtains $C < 0$ if $\frac{\partial M_{t+1}}{\partial L_t}$ is sufficiently large in absolute value so that it overwhelms the positive terms in C.

B FOCs for adjustment costs with alternative growth rates

B.1 Adjustment cost for wages

First order condition for q_t :

$$\theta\gamma L_t^{\alpha} q_t^{\gamma-1} - w_t L_t - 16\left(I_t^U \frac{\lambda^U}{2} + I_t^D \frac{\lambda^D}{2}\right) \frac{w_t}{(w_t q_t + w_{t-1}q_{t-1})^3}(w_t q_t - w_{t-1}q_{t-1}) w_{t-1}^2 q_{t-1}^2 L_{t-1}$$
$$+4\beta\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right) \frac{L_t w_t}{(w_t q_t + w_{t-1}q_{t-1})^3}(w_{t+1}q_{t+1} - w_t q_t)(w_{t+1}^2 q_{t+1}^2 - w_t^2 q_t^2 - 4 w_t q_t w_{t+1} q_{t+1}) = 0$$

First order condition for L_t :

$$\theta\alpha L_t^{\alpha-1} q_t^{\gamma-1} - w_t q_t - \beta\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right)\left(2\frac{w_{t+1}q_{t+1} - w_t q_t}{w_{t+1}q_{t+1} + w_t q_t}\right)^2 w_t q_t = 0$$

B.2 Adjustment costs for wages and employment

First order condition for q_t :

$$\theta\gamma L_t^{\alpha} q_t^{\gamma-1} - w_t L_t - 16\left(I_t^U \frac{\lambda^U}{2} + I_t^D \frac{\lambda^D}{2}\right) \frac{w_t}{(w_t q_t + w_{t-1}q_{t-1})^3}(w_t q_t - w_{t-1}q_{t-1}) w_{t-1}^2 q_{t-1}^2 L_{t-1}$$
$$+4\beta\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right) \frac{L_t w_t}{(w_t q_t + w_{t-1}q_{t-1})^3}(w_{t+1}q_{t+1} - w_t q_t)(w_{t+1}^2 q_{t+1}^2 - w_t^2 q_t^2 - 4 w_t q_t w_{t+1} q_{t+1}) = 0$$

First order condition for L_t :

$$\theta\alpha L_t^{\alpha-1} q_t^{\gamma-1} - w_t q_t - 16\left(J_t^U \frac{\lambda^U}{2} + J_t^D \frac{\lambda^D}{2}\right) L_{t-1}^2 \frac{L_t - L_{t-1}}{(L_t + L_{t-1})^3}$$
$$-\beta\left[\left(I_{t+1}^U \frac{\lambda^U}{2} + I_{t+1}^D \frac{\lambda^D}{2}\right)\left(2\frac{w_{t+1}q_{t+1} - w_t q_t}{w_{t+1}q_{t+1} + w_t q_t}\right)^2 w_t q_t + \frac{4(L_t - L_{t+1})(4L_t L_{t+1} + L_t^2 - L_{t+1}^2)}{(L_t + L_{t+1})^3}\left(J_{t+1}^U \frac{v^U}{2} + J_{t+1}^D \frac{v^D}{2}\right)\right] = 0$$

Table A.I. Constrained GMM estimates for the model's parameters using all manufacturing plants

	Revenue measure: Total value of shipments (deflated)							
	Adjustment costs (conventional growth rate)				**Adjustment cost (alternative growth rate)**			
	Wage adjustment		**Wage and employment**		**Wage adjustment**		**Wage and employment**	
Parameter	**Continuing plants (I)**	**All plants (II)**	**Continuing plants (III)**	**All plants (IV)**	**Continuing plants (I)**	**All plants (II)**	**Continuing plants (III)**	**All plants (IV)**
α	0.12*** [0.0005]	0.11*** [0.0004]	0.23*** [0.002]	0.16*** [0.001]	0.13*** [0.0004]	0.13*** [0.0004]	0.09*** [0.0005]	0.09*** [0.0004]
γ	0.14*** [0.002]	0.05*** [0.002]	0.22*** [0.002]	0.22*** [0.0003]	0.18*** [0.001]	0.10*** [0.002]	0.12*** [0.001]	0.08*** [0.001]
λ^U	0	0	0.007 [0.02]	0	0	0	0	0
λ^D	45.45*** [0.25]	52.28*** [0.27]	3.06*** [0.02]	2.89*** [0.02]	11.07*** [0.07]	12.12*** [0.08]	8.59*** [0.06]	8.05*** [0.05]
v^U	-	-	0	0.72 [0.93]	-	-	0	0
v^D	-	-	11.21*** [0.05]	87.14*** [2.42]	-	-	8.58*** [0.08]	9.11*** [0.06]
	Revenue measure: Value added (deflated)							
α	0.36*** [0.0008]	0.46*** [0.0004]	0.33*** [0.004]	0.46*** [0.0005]	0.39*** [0.0007]	0.39*** [0.0003]	0.27** [0.001]	0.44*** [0.0006]
γ	0.39*** [0.002]	0.45*** [0.0006]	0.35*** [0.0005]	0.45*** [0.0006]	0.42*** [0.001]	0.35*** [0.0003]	0.32*** [0.002]	0.46*** [0.0007]
λ^U	0	0	0	0	0	0	0	0
λ^D	19.13*** [0.17]	1.93*** [0.06]	2.96*** [0.03]	3.36*** [0.02]	4.15*** [0.04]	1.39*** [0.03]	5.62*** [0.05]	3.56*** [0.03]
v^U	-	-	0	0	-	-	0	0
v^D	-	-	43.56*** [0.35]	8.15*** [0.04]	-	-	6.02*** [0.06]	8.71*** [0.05]
N	804,245	986,977	804,245	986,977	804,245	986,977	804,245	986,977

Notes: Standard errors in brackets. (*),(**),(***) indicate significance at 10%,5%,1%, respectively.