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ABSTRACT

This paper develops a general test of factor price equalization that is robust to unobserved regional productivity differences, unobserved region-industry factor quality differences and variation in production technology across industries. We test relative factor price equalization across regions of the UK. Although the UK is small and densely-populated, we find evidence of statistically significant and economically important departures from relative factor price equalization. Our estimates suggest three distinct relative factor price areas with a clear spatial structure. We explore explanations for these findings, including multiple cones of diversification, region-industry technology differences, agglomeration and increasing returns to scale.

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1. Introduction

Do factor prices vary across regions within a country? This question is of fundamental importance to governments pursuing policies for regional development, firms choosing plant locations, and workers deciding where to live. Economic theory suggests two powerful mechanisms promoting factor price convergence across regions and countries – goods trade and factor mobility. Within a country, goods markets are more highly integrated, and factors of production are more mobile, than they are across countries. As a result, factor price equalization, to the extent it exists anywhere, is more likely to occur within nations than internationally. We develop very general tests of absolute and relative factor price equalization and apply them to regions within the United Kingdom. The UK is a particularly well-suited focus for such tests given its small geographic area and high population density, conditions which promote output and factor market integration.

Absolute factor price equality implies that *identical* factors of production are paid the same wage across regions. Relative factor price equality, on the other hand, allows absolute wages to vary so long as relative wages (i.e. the skill premium) remain constant. An obvious potential explanation for a violation in absolute factor price equality is the existence of regional Hicks-neutral productivity differences: regions with higher Hicks-neutral productivity can offer higher wages to *both* skilled and unskilled workers even while relative wages remain uniform.

Rejection of factor price equality can also arise for more complicated reasons. For example, both absolute and relative factor price equality can fail due to unobserved variation in regional factor quality. Analyzing the effect of such variation on output and wages has a long history in the international trade literature, including the classic paper by Leontief (1953) and the more recent cross-country study by Trefler (1993). A key advantage of the methodology that we develop is its robustness to unobserved differences in factor quality. Indeed, our tests control for factor quality differences across pairs of regions *and* industries.

Our approach is based upon extremely general conditions for producer equilibrium and builds upon techniques developed by Bernard and Schott (2001) to test for factor price equality in the US. We generalize that theoretical framework from the case of the CES production technology to any

constant returns to scale technology, to allow for unobserved factor quality differences that are region-industry specific rather than just region-specific, and to the case of imperfect competition. Our methodology exploits the fact that, although an empirical researcher will not typically observe factor quality or quality-adjusted factor prices, observed factor prices contain information about the quality of observed factors when firms minimize costs. Our approach does not make any assumptions regarding the preferences and costs of living faced by different types of workers. As a result, it is robust to unobserved variation in consumer price indices specific to types of workers or locations. Nonetheless, the analysis has implications for the value of real wages and the degree of factor mobility across locations.

Though our technique is applicable to any number of factors of production, we focus here on the wages of skilled versus unskilled labour. We find strong evidence against both absolute and relative factor price equality in the UK. This rejection exists across both coarsely-aggregated Administrative Regions and much more finely-defined Postcode Areas, which approximate local labour markets. Estimated differences in quality-adjusted factor prices across the UK are highly statistically significant and quantitatively important.

We explore a number of potential explanations for deviations from factor price equality. One subset of explanations provide intuition for the failure of factor price equality. Among these are the existence of multiple Heckscher-Ohlin cones of diversification within the UK and several aspects of the new economic geography. We also consider how data-related issues can induce a rejection of the null hypothesis. In each case, we highlight additional empirical implications which can be pursued.

Existing tests of factor price equality, including Cunat (2001), Debaere and Demiroglu (1997), Repetto and Ventura (1998), and Schott (2001a, 2001b), have focused on the variation of wages across countries or the existence of multiple cones of diversification in international production data. Other studies, including Davis *et al.* (1997), Bernstein and Weinstein (2002) and Hanson and Slaughter (2002), have looked for evidence of factor price equalization across either Japanese prefectures or US states. Further research on the spatial variation of productivity and factor prices in the United States includes Ciccone and Hall (1996), Ciccone (2001), and Hanson (1998). With respect to the UK, recent work by Cameron and

Muellbauer (2000,2001), Duranton and Monastiriotis (2001), Gosling *et al.* (1996), HM Treasury (2001), and Machin (1996) has examined the extent of regional earnings and productivity differences across regions. Haskel and Slaughter (2001) analyze the impact of international trade on wage inequality at the level of the United Kingdom as a whole. Though some of this research has found evidence consistent with a violation of factor price equality, none of the studies has controlled for the sort of variation in factor quality and technology differences that we find so important. Our study is also the first to examine the finely defined UK Postcodes in addition to the coarsely aggregated Administrative Regions.

The paper is structured as follows. Section 2 introduces the general theoretical framework and derives empirical tests for absolute and relative factor price equalization. Section 3 describes the data. Section 4 discusses the econometric specification, and Section 5 presents the empirical results. Section 6 examines a number of potential explanations for violations of absolute and relative factor price equality. Section 7 concludes.

2. Theoretical Framework

2.1. Production

We consider a very general specification of the production environment facing firms that allows for both perfect competition and imperfect competition, as well as variation in goods prices, technology, and factor quality across regions and industries. Regions are denoted by r , industries by j , and time by t . Throughout the exposition, subscripts are used to refer to industries or regions and superscripts to refer to factors of production or pairs of factors.

In each industry-region, firms choose output and employment of factors of production to maximize profits subject to a constant returns to scale production technology,

$$\Pi_{rj} = v_{rj}(Y_{rj})Y_{rj} - w_r^P P_{rj} - w_r^N N_{rj} - w_r^K K_{rj} \quad (1)$$

$$Y_{rj} = A_{rj}F_j(P_{rj}, N_{rj}, K_{rj}) \quad (2)$$

where v is the output price, P is employment of quality-adjusted production workers, N is employment of quality-adjusted non-production workers, and

K is employment of quality-adjusted physical capital. The factor prices w_r^P , w_r^N , and w_r^K are per quality-adjusted unit of a factor of production.

In this specification, firms may either act as price-takers in product markets (perfect competition) or choose prices subject to a downward sloping demand curve (imperfect competition). They behave as price-takers in factor markets. Although the main exposition here assumes constant returns to scale, later sections and an appendix introduce increasing returns to scale and discuss their implications for absolute and relative factor prices.

For clarity, we have concentrated here on the three factors of production for which data are available. However, the analysis makes no assumptions about the relative number of goods and factors of production. We present a general methodology for testing factor price equalization given data on factor prices, employment, and output for arbitrary numbers of goods and arbitrary numbers of factors of production.

2.2. *Quality-adjusted and Observed Factors*

If it were possible to observe quality-adjusted factor prices and quantities in the data, we could test for factor price equalization directly. In practice, factor quality is not observed and we allow it to vary in a completely general way across both regions and industries. Quality-adjusted employments of factors of production will be related to their observed values as follows,

$$P_{rj} = \theta_{rj}^P \tilde{P}_{rj}, \quad N_{rj} = \theta_{rj}^N \tilde{N}_{rj}, \quad K_{rj} = \theta_{rj}^K \tilde{K}_{rj}. \quad (3)$$

where a tilde above a variable indicates that it is an observed value. Observed factor prices will be related to quality-adjusted values according to,

$$\tilde{w}_{rj}^P = \theta_{rj}^P w_r^P, \quad \tilde{w}_{rj}^N = \theta_{rj}^N w_r^N, \quad \tilde{w}_{rj}^K = \theta_{rj}^K w_r^K. \quad (4)$$

2.3. *Cost Minimization*

Our tests for factor price equality are direct implications of firms' cost minimization (hence the property that they hold under both perfect and imperfect competition). The cost function dual associated with the production technology is,

$$B_{rj} = A_{rj}^{-1} \Gamma_j(w_r^P, w_r^N, w_r^K) Y_{rj}. \quad (5)$$

Demands for quality-adjusted factors of production may be obtained using Shepherd's Lemma,

$$P_{rj} = A_{rj}^{-1} Y_{rj} \frac{\partial \Gamma_j(\cdot)}{\partial w_r^P}, \quad N_{rj} = A_{rj}^{-1} Y_{rj} \frac{\partial \Gamma_j(\cdot)}{\partial w_r^N}, \quad K_{rj} = A_{rj}^{-1} Y_{rj} \frac{\partial \Gamma_j(\cdot)}{\partial w_r^K}. \quad (6)$$

Dividing one first-order condition by another, we arrive at an expression for relative demand for any two quality-adjusted factors of production. Thus, for non-production (skilled) and production (unskilled) workers we have,

$$\frac{N_{rj}}{P_{rj}} = \frac{\partial \Gamma_j(\cdot) / \partial w_r^N}{\partial \Gamma_j(\cdot) / \partial w_r^P}. \quad (7)$$

Using the relationship between quality-adjusted and observed values in (3), this implies the following relative demand for observed factors of production,

$$\frac{\tilde{N}_{rj}}{\tilde{P}_{rj}} = \frac{\theta_{rj}^P \partial \Gamma_j(\cdot) / \partial w_r^N}{\theta_{rj}^N \partial \Gamma_j(\cdot) / \partial w_r^P}. \quad (8)$$

2.4. Regional Factor Price Differences

In principle, the price of each quality-adjusted factor of production may vary across regions. To capture this variation, we make use of the fact that any factor price difference between a region r and another reference region s can be decomposed into a component common to all factors of production (λ_{rs}) and a factor-specific component (γ_{rs}^z , $z \in \{P, N, K\}$). For example,

$$\begin{aligned} w_r^N &= \delta_{rs}^N w_s^N = \lambda_{rs} \gamma_{rs}^N w_s^N \\ w_r^P &= \delta_{rs}^P w_s^P = \lambda_{rs} \gamma_{rs}^P w_s^P \\ w_r^K &= \delta_{rs}^K w_s^K = \lambda_{rs} w_s^K \end{aligned} \quad (9)$$

where, in the example above, we have normalized the common component using capital price differences across regions ($\lambda_{rs} = \delta_{rs}^K$ and $\gamma_{rs}^N = \delta_{rs}^N / \delta_{rs}^K$). Other normalizations are clearly possible and the analysis is invariant to which is chosen.

Since it is hard to accurately measure the real user cost of capital at the regional level, we focus in our empirical work on the absolute and relative

wages of non-production and production workers. Under the null hypothesis of factor price equalization, *all* factor prices are equalized. A rejection of relative factor price equalization for any pair of factors will therefore be sufficient for a rejection of the null hypothesis. In principle, the analysis here may be undertaken for all combinations of factors of production.

2.5. *Relative Factor Price Equalization (RFPE)*

2.5.1. *Null Hypothesis*

Our most general test of factor price equalization is concerned with *relative* factor prices, and allows for both unobserved variation in factor quality across region-industry pairs and neutral technology differences. The null hypothesis of Relative Factor Price Equalization (RFPE) may be formalized as:

$$(H_0 : \text{RFPE}), \quad \gamma_{rs}^z = 1 \quad \forall \quad z, \quad \frac{w_r^N}{w_r^P} = \frac{w_s^N}{w_s^P}. \quad (10)$$

The potential existence of unobserved factor quality differences across regions within an industry ($\theta_{rj}^N \neq \theta_{sj}^N$ and/or $\theta_{rj}^P \neq \theta_{sj}^P$ in equation 4) means that we cannot test this hypothesis directly using observed relative wages. However, we show below that RFPE implies the equalization of observed relative wage bills across regions and that this prediction is robust to unobserved factor quality differences. Without loss of generality, we choose region s as the reference region for measuring factor quality differences so that,

$$\theta_{sj}^N = 1, \quad \theta_{sj}^P = 1, \quad \forall \quad j. \quad (11)$$

Under the null hypothesis of RFPE, the values of observed relative wages in the two regions are given by,

$$\frac{\tilde{w}_r^N}{\tilde{w}_r^P} = \frac{\theta_{rj}^N \tilde{w}_s^N}{\theta_{rj}^P \tilde{w}_s^P}. \quad (12)$$

Observed values of relative employment in the two regions may be obtained using equation (8). Under RFPE, quality-adjusted factor prices differ across regions by a component λ_{rs} that is common across all factor prices. Homogeneity of degree 1 of the cost function implies that the derivatives $\partial \Gamma_j / \partial w_r^z$

are homogenous of degree 0 in factor prices. Thus,

$$\frac{\partial \Gamma_j(w_r^P, w_r^N, w_r^K)}{\partial w_r^z} = \frac{\partial \Gamma_j(\lambda_{rs} w_s^P, \lambda_{rs} w_s^N, \lambda_{rs} w_s^K)}{\partial (\lambda_{rs} w_s^z)} = \frac{\partial \Gamma_j(w_s^P, w_s^N, w_s^K)}{\partial w_s^z}, \quad \forall z.$$

It follows immediately from equation (7) that, with identical quality-adjusted relative factor prices, regions will employ quality-adjusted factors of production in the same proportions. Using the relationship between observed and quality-adjusted values, observed relative employment will vary across regions in direct proportion to factor quality differences (from equation (8)),

$$\frac{\tilde{N}_{rj}}{\tilde{P}_{rj}} = \frac{\theta_{rj}^P \tilde{N}_{sj}}{\theta_{rj}^N \tilde{P}_{sj}}. \quad (13)$$

Multiplying the expressions for observed relative factor prices and observed relative employments, the terms in unobserved factor quality cancel. We obtain the empirical prediction that, under the null hypothesis of RFPE, *the ratio of the observed wage bills (wbill) of non-production to production workers is equalized across regions:*

$$(H_0 : \text{RFPE}), \quad \frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P}. \quad (14)$$

2.5.2. Alternative Hypothesis

The alternative hypothesis is that relative quality-adjusted wages vary across regions. This variation is reflected in the factor-specific component of factor price differences (γ_{rs}^z):

$$(H_1 : \text{non-RFPE}) \quad \gamma_{rs}^z \neq 1, \quad \frac{w_r^N}{w_r^P} = \frac{\gamma_{rs}^N w_s^N}{\gamma_{rs}^P w_s^P} = \gamma_{rs}^{NP} \frac{w_s^N}{w_s^P}. \quad (15)$$

Observed values of relative wages in the two regions are thus,

$$\frac{\tilde{w}_r^N}{\tilde{w}_r^P} = \gamma_{rs}^{NP} \frac{\theta_{rj}^N \tilde{w}_s^N}{\theta_{rj}^P \tilde{w}_s^P}. \quad (16)$$

Observed values of relative employment in the two regions may again be obtained from equation (8),

$$\frac{\tilde{N}_{rj}}{\tilde{P}_{rj}} = \frac{\theta_{rj}^P}{\theta_{rj}^N} \left(\frac{\partial \Gamma_j(\cdot) / \partial w_r^N}{\partial \Gamma_j(\cdot) / \partial w_r^P} \right) \left(\frac{\partial \Gamma_j(\cdot) / \partial w_s^P}{\partial \Gamma_j(\cdot) / \partial w_s^N} \right) \frac{\tilde{N}_{sj}}{\tilde{P}_{sj}}. \quad (17)$$

Multiplying the expressions for observed relative factor prices and observed relative employments, the terms in unobserved factor quality again cancel. The ratio of the observed wage bills of non-production to production workers under the alternative of non-relative factor price equalization is thus:

$$\frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = \gamma_{rs}^{NP} \left(\frac{\partial \Gamma_j(\cdot) / \partial w_r^N}{\partial \Gamma_j(\cdot) / \partial w_r^P} \right) \left(\frac{\partial \Gamma_j(\cdot) / \partial w_s^P}{\partial \Gamma_j(\cdot) / \partial w_s^N} \right) \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P}. \quad (18)$$

$$(H_1 : \text{non-RFPE}), \quad \frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = \eta_{rsj}^{NP} \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P}. \quad (19)$$

Appendix A shows that with a CES production technology, which is itself a fairly flexible functional form, the expression in equation (18) simplifies to,

$$\frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = (\gamma_{rs}^{NP})^{\rho_j / (\rho_j - 1)} \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P}. \quad (20)$$

Together equations (14) and (19) provide the basis for a test of the null hypothesis of RFPE that is robust to unobserved region-industry variation in factor quality. RFPE implies a testable parameter restriction in equation (19), namely $\eta_{rsj}^{NP} = 1$, which we exploit in our empirical work below.

Note that $\eta_{rsj}^{NP} \neq 1$ is *sufficient* to reject RFPE, but not necessary. This is seen most clearly from equation (20), where even if $\gamma_{rs}^{NP} \neq 1$ (so that quality-adjusted relative wages are not equalized), the parameter $\eta_{rsj}^{NP} = (\gamma_{rs}^{NP})^{\rho_j / (\rho_j - 1)}$ will still equal 1 for the special case of a Cobb-Douglas production technology ($\rho_j = 0$). This is consistent with our empirical approach. We test the null hypothesis $\eta_{rsj}^{NP} = 1$ and, in so far as this hypothesis is rejected, this is *sufficient* for us to reject RFPE. Indeed, the fact that $(\gamma_{rs}^{NP})^{\rho_j / (\rho_j - 1)}$ is close to 1 for ρ_j close to 0 actually makes it *harder* for us to reject the null hypothesis and strengthens any finding of a rejection of RFPE.

2.6. *Absolute Factor Price Equalization (AFPE)*

Also of potential interest is the question whether the absolute level of factor prices is equalized across locations. In order to control for unobserved factor quality, we once more make use of the result demonstrated above that, multiplying observed wages by observed employment levels, terms in factor quality cancel.

To test absolute factor price equalization (AFPE) we analyze variation across regions in the share of total payments to a factor of production in output. We demonstrate this for non-production workers; the analysis for other factors of production is analogous. Observed employment of non-production workers may be obtained from equations (6) and (3). Multiplying observed employment by observed wages and dividing by output, we obtain,

$$\frac{\tilde{w}_{rj}^N \tilde{N}_{rj}}{Y_{rj}} = \frac{w_r^N N_{rj}}{Y_{rj}} = (\theta_{rj}^N w_r^N) \frac{1}{\theta_{rj}^N} A_{rj}^{-1} \frac{\partial \Gamma_j(\cdot)}{\partial w_r^N}. \quad (21)$$

Under the null hypothesis of AFPE, quality-adjusted wages are equalized across regions ($w_r^N = w_s^N$) and observed wages vary in direct proportion to unobserved factor quality ($\tilde{w}_{rj}^N = \theta_{rj}^N w_s^N$), where we again choose region s as a reference region so that $\theta_{sj} = 1 \forall j$. The equalization of the absolute level of factor prices requires identical production technologies across regions and industries ($A_{rj} = A_{sj}$). Using this in equation (21), it follows that, under the null hypothesis of AFPE, factor shares are equalized across regions:

$$(H_0 : \text{AFPE}), \quad \frac{w_r^N N_{rj}}{Y_{rj}} = \frac{w_s^N N_{sj}}{Y_{sj}}. \quad (22)$$

Under the alternative hypothesis of non-AFPE, technical efficiency may vary across region-industry pairs and regions may be characterized by different equilibrium factor prices. In this case, from equation (22), factor shares in the two regions are related as follows:

$$(H_1 : \text{non-AFPE}), \quad \frac{w_r^N N_{rj}}{Y_{rj}} = \gamma_{rs}^N \left(\frac{A_{sj}}{A_{rj}} \right) \left(\frac{\partial \Gamma_j(\cdot) / \partial w_r^N}{\partial \Gamma_j(\cdot) / \partial w_s^N} \right) \left(\frac{w_s^N N_{sj}}{Y_{sj}} \right). \quad (23)$$

Together, equations (22) and (23) provide the basis for a test of the null hypothesis of AFPE, with AFPE implying a testable parameter restriction

in equation (23). In the rest of the paper, we focus on the test for relative factor price equalization derived above.

2.7. Diagrammatic Representation of Producer Equilibrium

To provide some further economic intuition for the tests, this section complements the formal analysis above with a graphical representation of producer equilibrium using a Lerner (1952) diagram. There are two regions A and B , each of which is endowed with skilled labour (N) and unskilled labour (P) in quantities indicated by the endowment points E_A and E_B . Figure 1 considers an example with three goods: skilled labour-intensive Computers, unskilled labour-intensive Textiles, and intermediate skill-intensity Machinery. The production technology is characterized by the unit value isoquants for the three sectors and, for simplicity and without loss of generality, the figures are drawn for the case of Leontief or fixed unit input requirement technologies. The analysis is directly analogous for technologies with unit input requirements that vary with relative factor prices.

Even if the regions face common commodity prices and have identical technologies, sufficiently large differences in endowments will induce them to specialize in different mixes of goods with different equilibrium relative factor prices. The skilled abundant region (A) produces skilled-labour intensive Computers and Machinery, while the unskilled abundant region (B) specializes in Machinery and unskilled-intensive Textiles. Each region lies within a different cone of diversification, where the word ‘cone’ refers to the set of endowment vectors that select the same set of goods of produced.

The relative wage of skilled workers is *lower* in the skilled labour abundant region so that, as one looks across regions in different cones of diversification, the relative wage of skilled workers *falls* with their relative factor abundance. Production structure overlaps in the good with intermediate factor intensity (Machinery). And, with technologies characterized by variable unit input requirements (not shown in the figure), this overlapping good will be produced using different factor intensities in the two regions.

Other potential explanations for violations of relative factor price equalization include non-neutral technology differences across regions, regional variation in goods prices due to transport costs that differ systematically

across industries, increasing returns to scale, as well as non-traded goods and variation in the amenities provided by different regions. All of these explanations are encompassed by the theoretical framework of the previous section and can be shown diagrammatically using analogues of Figure 1. We return to consider these explanations in detail in the empirical discussion below.

3. Data Description

Our data source is the United Kingdom’s Annual Respondents Database (ARD). Basic information on the population of establishments in the production sector is available during 1980-98, including employment, location, ownership, and industry. More detailed information is available for a sample of these establishments, including output, investment, intermediate inputs, employment, and wages.¹ This sample includes around 13000 establishments per year, and is comprised of the population of establishments with 100 or more employees together with a sample of smaller establishments.² As our methodology requires information on wages and employment, we work with the sampled data. In the robustness section, we demonstrate that the results are not driven by any resulting sample selection bias.

In the empirical analysis, we focus on the manufacturing sector for which data are available. Under the null hypothesis of RFPE, relative wage bills should be equalized in all sectors of the economy. A rejection of the null hypothesis for manufacturing is thus sufficient for a violation of RFPE. For skilled workers we use data on Administrative, Technical, and

¹ARD establishments correspond roughly to a ‘line of business’. Establishments are potentially more disaggregate than firms, i.e. some firms are single establishments while others consist of several establishments. Establishments are more aggregate than plants, i.e. some establishments consist of a single plant, while others include several. As a result, an establishment’s plants may be located in more than one region. Such overlap reduces spatial variation in wages, employment, and wage bills in our data, making it more difficult to reject the null hypothesis of RFPE. As a check on the empirical results, we perform several robustness tests in section 5.2..

²For the years that we consider (1992 and 1986), the sampling threshold is 100 employees. The ARD only contains information on production activity. Other non-production activities such as headquarter services and research and development (R&D) are excluded. For further discussion of the ARD data, see Devereux *et al.* (1999), Disney *et al.* (2000), Duranton and Overman (2002), and Griffith (1999).

Clerical Workers (non-production workers), and for unskilled workers we use information on Operatives (production workers). These are widely-used measures of skills in the existing trade and labour market literatures (see for example Berman *et al.* 1998 and Lawrence and Slaughter 1993) and the only measures available in the ARD data. The existing literature typically finds a high correlation between these occupation-based measures of skills and those based on educational attainment (see in particular Machin and Van Reenen 1998). Furthermore, a key advantage of our methodology is that it explicitly controls for any unobserved variation in the quality of non-production and production workers across both regions and industries.

The United Kingdom's Labour Force Survey (LFS) does report some information on the wages and employment by region according to an educational attainment-based definition of skills. A central advantage of the ARD over this alternative data source is the detailed level of industrial disaggregation. The LFS reports information only for 2 and 3-digit industries compared with 4-digit industries in the ARD. Furthermore, because the LFS is survey-based, cell sizes for even 2 and 3-digit industries in the highly disaggregated geographical regions considered here may be very small.³ The ARD yields consistent information on the wages and employment of skilled and unskilled workers across regions of the United Kingdom within highly disaggregated industries.

These aspects of the data are important because our empirical approach focuses on variation in relative wages *within industries*. One potential explanation for relative wage differences across regions within an industry is that the analysis is undertaken at too high a level of aggregation. The composition of an industry may vary across regions (for example, a 2-digit sector may consist of different 4-digit sub-sectors across regions). In general, tests of relative factor price equality should employ the most disaggregate industry data available.

We examine spatial variation in relative wages, employment, and wage bill levels at two levels of geographical disaggregation. First, we consider 10 Administrative Regions of the United Kingdom.⁴ This enables us to

³An additional problem with the LFS is that the information is reported on a place of residence rather than place of work basis.

⁴Northern Ireland is excluded from the analysis because the data are collected separately and there is only one Postcode Area for the entire of Northern Ireland.

analyze the broad pattern of spatial variation and allows the results of our methodology to be compared with existing studies which have focused on Administrative Regions. Second, we examine variation across the 100+ Postcode Areas listed in Table 1. These regions are based around towns and correspond approximately to commuting patterns and local labour market areas. Examples include Aberdeen, Birmingham, and Manchester. We aggregate the 8 postcode areas in Central London to form a single geographical region, as is consistent with commuting patterns. These data provide a rich source of information on spatial variation in factor prices within the United Kingdom, and enable us to examine whether factor price variation is greater within or across Administrative Regions.

Information on Postcode Areas is only available in the ARD from 1985 onwards; separate data on non-production and production workers ceases to be collected after 1995; and there is a change in the United Kingdom's Industrial Classification after 1992. In our main specification, we examine spatial variation in relative wages, employment, and wage bills for 1992. As a robustness test, we also report results for 1986. To the extent that we find persistent differences in quality-adjusted relative wages across UK regions for years that are at such different stages of the UK business cycle, we have evidence of systematic departures from RFPE that are not driven by idiosyncratic shocks to regions or business cycle fluctuations. In practice it may take time for firms to adjust some factors of production such as physical capital, and analyzing two separate points in time also provides evidence that the results are not driven by out of equilibrium physical capital stocks in any one year.

Establishments themselves will be subject to idiosyncratic shocks and there is likely to be measurement error in establishment-level data that may be large in any one year. Therefore, in our empirical analysis we aggregate establishments in each region to the level of approximately 200 4-digit manufacturing industries. We exclude all industries classified as 'other manufacturing' since these are heterogeneous categories and may include different sub-industries in different regions. The null hypothesis of RFPE predicts the equalization of relative wage bills across regions within each 4-digit industry. This yields approximately 1400 region-industry observations for Administrative Regions and over 5000 region-industry observations for Postcode Areas.

4. Econometric Specification

In Section 2, we showed that, under the null of RFPE, the ratio of the non-production workers' wage bill to the production workers' wage bill will be the same across regions within an industry. This implies that, for an industry j , each region's relative wage bill should equal the value for the United Kingdom as a whole,

$$\frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P} = \frac{\widetilde{\text{wbill}}_{UKj}^N}{\widetilde{\text{wbill}}_{UKj}^P} \quad (24)$$

The simplest test of the null hypothesis is therefore to regress the ratio of wage bills for region r relative to the ratio for the UK as a whole on set of region dummies,

$$\ln \left(\frac{RWB_{rj}^{NP}}{RWB_{UKj}^{NP}} \right) = \sum_r \alpha_r^{NP} d_r + \varepsilon_{rj}^{NP} \quad (25)$$

where RWB_{rj}^{NP} denotes the relative wage bill in industry j and region r for non-production workers and production workers ($RWB_{rj}^{NP} = \text{wage bill}_{rj}^N / \text{wage bill}_{rj}^P$); RWB_{UKj}^{NP} is the corresponding relative wage bill for the UK as a whole; and the α_r^{NP} correspond to the coefficients on the regional dummies d_r . When defining the relative wage bill for the UK as a whole, we exclude the own region r . Under the null hypothesis of RFPE, $\alpha_r^{NP} = 0$ for all regions and factor pairs, and a test of whether the α_r^{NP} are jointly equal to zero therefore provides a test of RFPE.

The regression in equation (25) corresponds to a differences in means test. We choose the UK as a whole as a base region and test RFPE by comparing the relative wage bill for an industry j across all regions r to the value for the UK as a whole in the same industry. We also test RFPE by estimating equation (19) for all industry and region-pair combinations. That is, we begin by choosing a region s to be the base ($\gamma_s^{NP} = 1$) and run an analogous regression to equation (25),

$$\ln \left(\frac{RWB_{rj}^{NP}}{RWB_{sj}^{NP}} \right) = \sum_r \alpha_{rs}^{NP} d_r + \varepsilon_{rsj}^{NP} \quad (26)$$

A test of whether the α_{rs}^{NP} are jointly equal to zero provides a test of the null hypothesis of RFPE. Rejecting $\alpha_{rs}^{NP} = 0$ is sufficient to reject the null hypothesis of RFPE, and any pair of regions r and r' face the same relative factor prices if $\alpha_{rs}^{NP} = \alpha_{r's}^{NP}$. Equation (26) is then estimated for all possible choices of base region s .

Although regions have the same relative wage bills under the null hypothesis of RFPE (hence $\alpha_{rs}^{NP} = 0$), the theoretical analysis of Section 2 suggests that, under the alternative hypothesis, the coefficient on the regional dummies (η_{rs}^{NP} in equation 19 and α_{rs}^{NP} in equations 25 and 26) may vary across industries. With a constant elasticity of substitution (CES) production technology, this cross-industry variation is associated with different elasticities of substitution between skilled and unskilled workers (equation 20).

We have no strong priors on how the elasticity of substitution between different types of labour (ρ_j) or other features of the operator Γ_j in the cost function (B_{rj}) vary across industries, and therefore we pool observations across industries. Since under the null hypothesis $\alpha_{rsj}^{NP} = 0$ for all industries j , a finding of statistically significant coefficients on the regional dummies when pooling observations is sufficient to reject RFPE.

Under the assumption of a CES production technology and choosing a value for the elasticity of substitution σ and hence $\rho = 1 - 1/\sigma$, the estimated coefficients on the regional dummies may be used to derive implied quality-adjusted relative wage differences across regions (equation 20). Comparing these estimates of quality-adjusted wage differences with actual values for relative wages, we can also derive implied differences in the relative quality of skilled and unskilled workers across regions and industries ($\theta_{rj}^N/\theta_{rj}^P$ in equation 16).

For a given value of the elasticity of substitution between skilled and unskilled workers, we are thus able to obtain estimates of the extent to which actual relative wage differences across regions correspond to true differences in quality-adjusted relative wages or are instead explained by unobserved variation in factor quality.

Note that equations (25) and (26) compare the relative wage bill for non-production and production workers in region r to the value in a base region within each industry j . This is a ‘*difference in differences*’ specification with a number of attractive statistical properties. Any industry-

specific determinant of relative wage bills that is common across regions is ‘differenced-out’ when we normalize relative to the base region on the left-hand side of the equations (for example, features of the production technology, compensating differentials across industries, other inter-industry wage differentials, and industry-specific labour market institutions such as the degree of unionization). The analysis thus explicitly controls for observed and unobserved heterogeneity in the determinants of relative wage bills across industries.

Similarly, in both region r and the base region we analyze the wage bill of non-production workers *relative* to production workers. Therefore, any region-specific determinant of wage bills that is common to both non-production and production workers is ‘differenced-out’ when we construct a region’s relative wage bill ($RWB_{rj}^{NP} = \text{wage bill}_{rj}^N / \text{wage bill}_{rj}^P$). Here potential examples include neutral regional technology differences and compensating differentials across regions.

5. Empirical Results

5.1. Baseline Specification

We begin by presenting the estimation results using the UK as a whole as the base region. We first report the results for Administrative Regions, followed by those for Postcode Areas. Table 2 reports the estimated differences in log relative wage bill ratios for Administrative Regions in 1992 and 1986. In 1992 at the 5% significance level, we find one rejection above zero (for the South-East of England) and 5 rejections below zero (for the East Midlands, Yorkshire & Humberside, Northern, Wales, and Scotland). The results for 1986 display a similar pattern. At the 5% significance level, we again find a rejection above zero for the South-East of England, and there are again 5 rejections below zero, with the West Midlands replacing the East Midlands.

Whether a positive estimated value of the dummies corresponds to a higher or lower quality-adjusted relative wage of skilled workers depends on the operator Γ_j in the cost function (equation 18). With a CES production technology, a positive coefficient corresponds to a lower quality-adjusted relative skilled wage under a CES production technology if $0 < \rho < 1$ (see equation 20). These values of ρ imply an elasticity of substitution between

skilled and unskilled workers greater than unity (i.e. $\sigma > 1$), which is consistent with typical empirical estimates in the labour literature (see in particular Katz and Autor 1999 and Katz and Murphy 1992).

Table 3 reports implied quality-adjusted relative skilled wages for $\sigma = 2$. We find that the skilled-abundant region (here the South-East) is characterized by a lower equilibrium value of the relative wage of skilled workers. The actual wage of non-production workers relative to production workers in the South-East was 97% of the UK value in 1992 and 99% in 1986. In both years, this is higher than the estimated quality-adjusted relative wage for $\sigma = 2$. This therefore suggests that the relative quality of non-production workers in the South-East is higher than in the UK as a whole, as is consistent with economic priors.

Results for Postcode Areas in 1992 and 1986 are presented in Tables 4 and 5. As indicated in the tables, 32 of 111 regions reject factor price equality at the 10% level in 1992. Of these, 9 reject above zero and 23 reject below zero. Table 4 reports the estimated dummies for those Postcode Areas that reject above zero. These are concentrated exclusively in the South-East of England close to the M25, M4 corridor, and the area around Cambridge; they include Cambridge, St. Albans, Reading, and Slough (see Figure 3).

Results for 1986 display a similar pattern: 34 regions reject factor price equality at the 10% level of significance, with 7 rejecting above zero and 27 rejecting below zero. Four of the rejections above zero are the same Postcode Areas as in 1992: Hemel Hempstead, Reading, Slough, and Sutton. The emergence of Cambridge and St. Albans as high relative wage bill regions is specific to 1992 and is consistent with the recent development of a cluster of skill intensive information technology and biotechnology industries in this area.

Tables 4 and 5 also report implied quality adjusted relative wages for $\sigma = 2$. Figures 2 and 3 display the geographical distribution of the estimated coefficients for Administrative Regions and Postcode Areas respectively in 1992. The figures separate three groups of regions - those with positive and statistically estimated values of the dummies (indicated by the dark shading); those with negative and statistically significant estimated values of the dummies (corresponding to the intermediate shading); and those with statistically insignificant estimated values of the dummies (light

or no shading). Both figures show a clear concentration of regions with positive estimated values of the dummies in the South-East of England, where, for $\sigma > 1$, the (quality-adjusted) skill premium is relatively low.

We also allow each Administrative Region and each Postcode Area to serve as the base and then run the bilateral regression specified in equation (23). Given the large number of coefficients the bilateral regressions generate, we report a summary of rejections by region definition in Table 6.⁵ For all choices of the base, for both Administrative Regions and Postcode Areas, and in both 1992 and 1986, the null hypothesis that the estimated coefficients on the regional dummies are equal to zero is easily rejected at the 1% level with a F-test. For Postcode Areas in 1992, 17% of the region-pairs reject relative factor price equality at the 10% level, while 11% reject at the 5% level. Every region rejects with at least 6 other regions. In 1986, 19% of the region pairs reject relative factor price equality at the 10% level, and 12% reject at the 5% level. Every region rejects with at least 5 other regions at the 10% level. For Administrative Regions, we find that 57% of region-pairs reject at the 10% level in 1992 and 40% in 1986. This corresponds to an average number of rejections against 5 and 4 Administrative Regions respectively, making clear that the rejection of RFPE is not simply driven by the South-East of England. Every region rejects with at least 2 other regions at the 10% level in both years.

Taken together, the UK base and the bilateral regression results emphatically reject the null hypothesis of relative factor price equality in the UK.

5.2. Robustness

These results are robust across a variety of econometric specifications and to a number of dataset refinements, reported in Table 7. To conserve space, we highlight robustness with respect to the 1992 Administrative Region results. However, similar checks for 1986 Administrative Regions and for Postcode Areas display the same robustness.

The first column of Table 7 reports the baseline results for factor price equality across Administrative Regions in 1992. The baseline sample for

⁵Overall, there are 90 and 12,210 possible bilateral rejections for Administrative Regions and Postcode Areas respectively. Any single base region can reject up to 9 or 110 other regions for Administrative Regions and Postcode Areas, respectively.

these results includes all establishments, some of which may report on plants in more than one Administrative Region or Postcode Area. We therefore undertake the following two robustness tests. First, in column (2) we report coefficient estimates for the sub-sample of single plant establishments where overlap does not occur and where we find a very similar pattern of results. Second, in column (3), we allocate establishment-level data to plants on the basis of their shares of establishment employment. All plants associated with an establishment are given the same relative wages and relative wage bills. This robustness test introduces a bias against rejecting RFPE. However, even with this bias, we continue to find a rejection, with the South-East coefficient positive and statistically significant and the Northern, Wales, and Scotland coefficients negative and statistically significant.

The baseline sample includes the population of establishments with more than 100 employees and a sample of establishments with fewer than 100 employees. In order to ensure that our results are not being driven by the presence of a non-random sample of smaller establishments, column (4) also reports results separately for the population of establishments with more than 100 employees. Finally, our coefficient estimates are means across all 4-digit industries in each region. Although each region has a large number of establishments across all industries, some individual industries within a region may contain few establishments. Since measurement error at the establishment level is a potential concern, column (5) also reports estimation results dropping all 4-digit region-industries that contain fewer than 5 establishments. Once again RFPE is rejected and we find a similar pattern of estimated coefficients.

The rejection of relative factor price equality in the UK is an extremely robust empirical finding. In the next Section we explore a number of potential explanations for these results.

6. Explanations

6.1. *Multiple Heckscher-Ohlin Cones*

The existence of multiple Heckscher-Ohlin cones of diversification within the UK provides a potential true rejection of relative factor price equality. This rejection is based the immobility of at least one factor, which prevents

regional factor prices (and endowments) from converging towards a common value across the country.⁶ As noted above, a central prediction of the Heckscher-Ohlin model is that the skill premium is inversely proportional to regional skill endowments across cones (see for example Leamer 1995). Graphically, this relationship is apparent in Figure 1, where the slope of the isocost line anchoring unit value isoquants is steeper in the relatively skill abundant cone.

Our estimates of quality-adjusted relative wages in Table 3 exhibit just such a violation of factor price equality: for reasonable estimates of the elasticity of substitution between production and non-production workers, we find the skill premium to be lower in the regions around London, where skilled labour is relatively abundant, and higher in outlying areas, where skilled labour is relatively scarce.

The potential existence of multiple cones of diversification within the UK is quite important for formulating public policy, in that it implies asymmetric sensitivity of regions to external shocks. A decline in the price of unskilled labour intensive products on world markets (associated with decreases in tariffs and transport costs, or economic growth of labour abundant economics like China) affects workers differently depending upon their region. Such price declines drive down the return to unskilled workers in low-skill regions while unskilled workers in high-skill regions benefit unambiguously from cheaper imports.

A key empirical prediction of multiple Heckscher-Ohlin cones is that regions will exhibit systematic differences in production structure, with skilled abundant regions producing a set of goods that is more skilled intensive than that in unskilled abundant regions.

6.2. Region-Industry Productivity Differences, Transport Costs and Increasing Returns

Region-industry variation in total factor productivity (TFP) can also lead to a true rejection of relative factor price equality. If technology is not common across regions and varies differentially across industries, relative factor prices will vary so long as workers cannot re-locate to arbitrage

⁶Cameron and Muellbauer (1998) and Hugues and McCormick (1994) provide empirical evidence on limited labour mobility within the United Kingdom.

away wage differences. Thus, this explanation, though having a different cause than the multiple cone Heckscher-Ohlin explanation, nevertheless relies upon a similar assumption of factor immobility.

To explain our empirical finding of a lower quality-adjusted skill premium in relatively skill abundant regions, it would have to be the case that technical efficiency is systematically relatively higher in *low-skill* intensive industries within *high-skill* abundant regions. This is because an increase in technical efficiency of low-skill industries acts like an increase in the relative price of the low-skill goods. Within the simple two factor, two good Heckscher-Ohlin framework, this increase in the price of the low-skill good reduces the quality-adjusted skill premium (via a clockwise rotation of the isocost line), inducing a switch toward more skill intensive techniques in both sectors.

Though this explanation yields an additional empirical prediction, it seems implausible that technical efficiency is higher in skill scarce industries within skill abundant regions. If anything, considerations of knowledge spillovers and external economies of scale appear to suggest that technical efficiency is higher in skill intensive industries disproportionately located in skilled abundant regions.

A conceptually similar violation of relative factor price equality is possible via industry-region variation in transport costs. Indeed, lower transport costs for low-skill industries within skill-abundant regions can lead to the pattern of relative wages observed above.

Geography can also play a role in a true rejection of relative factor price equality via the existence of increasing returns to scale (see Appendix A). To match the skill premia we observe, increasing returns to scale can be either internal or external, but must reduce relative (average) costs of production of low-skill industries in high-skill regions. This region variation in scale economies raises the relative demand for low-skill workers (in the skill-abundant regions) and reduces the skill premium. Here, too, however, we find the existence of this pattern of increasing returns to be implausible. This hypothesis is testable empirically, either indirectly using measured TFP or directly by examining the relative wages of skilled workers and the scale of production in a region.

6.3. Spatial Variation in Nominal But Not Real Wages

Relative wage bills can vary systematically across regions even with perfect labour mobility. If real consumption wages are equal in each region for both types of workers, then workers have no incentive to relocate. Nominal wages may still vary due to differences in the regional cost of living associated with non-traded goods or variation in amenities. For relative wage bills to differ, the cost of living must vary differentially for skilled and unskilled workers across regions. In particular, to explain our finding of a lower relative skilled wage in the South-East, the relative cost of living must be lower there for skilled workers.

This hypothesis also involves a true rejection of RFPE. It implies differential variation in the cost of living for skilled and unskilled workers and empirically testable. The hypothesis predicts the same variation in production structure as in the multiple cone Heckscher-Ohlin model. Industries that are intensive in skilled workers should locate in the region with the lower nominal relative wage for skilled workers, as firms care only about their production costs and not the consumption wage of different types of workers.

6.4. Heterogeneous products

The existence of heterogeneous products within industries can lead to a spurious rejection of RFPE. Suppose that relative factor prices are equal across all regions, but there are products with different skill requirements within each industry. If a region systematically produces products that are intensive in skilled labour (in every industry) then its relative wage bill will be larger than the average for the country even without differences in relative (or absolute) factor prices. Thus product heterogeneity can generate a rejection of RFPE but it has to exhibit a particular systematic pattern. Our analysis, by examining wage variation at the four-digit industry level, is a substantial improvement over existing inter- and intra-national studies based upon a coarser aggregation of products and exploits the most disaggregated data currently available data. Furthermore, when restricting the sample to establishments with similar characteristics (e.g. single versus multi-plant or small versus large establishments), we continue to find a similar pattern of results.

6.5. *Misclassified workers*

Finally, we note that while our analysis can account for unobserved differences in the quality of non-production and production workers within region-industry pairs, it is susceptible to systematic errors in assigning workers to these job categories. Random misclassification across industry-region pairs and systematic misreporting within an industry is accounted for in our methodology. However, systematic misclassification across regions (e.g. all industries in region r report non-production workers as production workers) can induce spurious rejection of relative factor price equality. While job misclassification may occur, we think it unlikely that all industries in a region will systematically misclassify workers in the same way.

7. Conclusions

We examine the extent of relative wage variation across geographic areas of the United Kingdom using a methodology that is robust to unobserved region-industry differences in factor quality, variations in production functions across industries and Hicks-neutral regional technology differences. Despite the United Kingdom being a small, densely-populated country with highly integrated goods markets and the potential for factor mobility, there is strong evidence against absolute and relative wage equality. We find statistically significant and quantitatively important differences in quality-adjusted absolute and relative wages across both broadly defined Administrative Regions as well as more narrowly defined Postcode Areas.

We find that skill abundant regions in the South-East have a lower skill premium than skill scarce regions for plausible values of the elasticity of substitution between skilled and unskilled workers. We examine a number of potential explanations for this finding and highlight additional, empirically verifiable implications of each. Multiple Heckscher-Ohlin cones of diversification and spatial variation in workers' relative cost of living provide natural explanations for the observed variation in skill premia and have the same implications for production structure across regions of the UK. Other explanations based on TFP differences, increasing returns to scale, and transport costs require implausible assumptions to be made. More formal testing of the relative importance of each explanation is an interesting area for further research but lies beyond the scope of this paper.

Taken together, our findings suggest that variation in relative factor prices plays an important role in shaping firms' location decisions within the UK. The results contribute to our understanding of regional variation in economic outcomes within the UK, an issue of increasing policy-interest in the context of the ongoing process of political devolution.

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A Appendix A

A1. Imperfect Competition

This section discusses in more detail the case of imperfect competition. Each of the tests of absolute and relative factor price equality is robust to allowing firms to choose prices subject to a downward sloping demand curve under conditions of imperfect competition. All the tests require is that firms minimize costs. To see this, note that firms' profit maximization problem (1) may be re-written as follows,

$$\max_{Y_{rj}} \quad \pi_{rj} = v_{rj}(Y_{rj})Y_{rj} - A_{rj}^{-1}\Gamma_j(w_r^P, w_r^N, w_r^K)Y_{rj}. \quad (27)$$

where $B_{rj} = A_{rj}^{-1}\Gamma_j(w_r^P, w_r^N, w_r^K)Y_{rj}$ is the total cost function. The first-order condition for profit-maximization is,

$$\frac{dv_{rj}(Y_{rj})}{dY_{rj}}Y_{rj} + v_{rj}(Y_{rj}) - \frac{\Gamma_j(\cdot)}{A_{rj}} = 0. \quad (28)$$

assuming that the demand function $v_{rj}(Y_{rj})$ is invertible and noting that the elasticity of demand is $\varepsilon_{rj}(Y_{rj}) \equiv -(dY_{rj}/dv_{rj})v_{rj}/Y_{rj}$, we obtain the standard result that equilibrium price is a constant mark-up over marginal cost,

$$v_{rj}(Y_{rj}) = \left(\frac{\varepsilon_{rj}(Y_{rj})}{\varepsilon_{rj}(Y_{rj}) - 1} \right) \frac{\Gamma_j(\cdot)}{A_{rj}}. \quad (29)$$

By Shepherd's Lemma, equilibrium demand for each quality-adjusted factor of production continues to be given by the derivative of the total cost function with respect to the price of a factor of production as specified in equation (6). Our tests for both relative and absolute factor price equalization may derived in exactly the same way as in the main text.

A2. External Economies of Scale

It is straightforward to introduce external economies of scale into the framework above in either perfectly or imperfectly competitive market structures. External economies of scale correspond to the assumption that technical efficiency in a region-industry is a function of scale. In the most general case, we have,

$$A_{rj} = A_{rj}(Y_{rj}, Y_{r,-j}, Y_{-r,j}, Y_{-r,-j}) \quad (30)$$

where $Y_{r,-j}$ is the vector of outputs in all other industries in a region, $Y_{-r,j}$ is the vector of all other regions outputs in the industry, and $Y_{-r,-j}$ is the vector of all other regions outputs in all other industries.

External economies of scale provide an explanation for variation in technical efficiency across countries and industries. In order for all production in an industry not to concentrate in a single region, we require either that external economies of scale operate across regions or there to be transport costs. The derivation of the tests for both relative and absolute factor price equality remains exactly as in the main text. The region-industry variation in technical efficiency induced by external economies of scale supplies a potential explanation for violations of absolute and relative factor price equality as discussed in the main text.

A3. Internal Economies of Scale

Internal economies must clearly be combined with imperfect competition and modify the discussion above in so far as the cost function is no longer linearly homogenous of degree 1 in output. An individual firm i 's profit maximization problem takes the form,

$$\max_{Y_i} \quad v_i(Y_i)Y_i - A_{rj}^{-1}\Gamma_j(w_r^P, w_r^N, w_r^K, Y_i) \quad (31)$$

where $B_i = A_{rj}^{-1}\Gamma_j(w_r^P, w_r^N, w_r^K, Y_i)$ is the total cost function. The firm's equilibrium price continues to be a constant mark-up over marginal cost,

$$v_i(Y_i) = \left(\frac{\varepsilon_i(Y_i)}{\varepsilon_i(Y_i) - 1} \right) \frac{1}{A_{rj}} \frac{\partial \Gamma_j(w_r^P, w_r^N, w_r^K, Y_i)}{\partial Y_i} \quad (32)$$

Equilibrium demands for quality-adjusted factors of production may again be obtained using Shepherd's Lemma. Using the relationship between quality-adjusted and non-quality adjusted values, a firm's relative demand for observed production and non-production workers will be given by,

$$\frac{\tilde{N}_i}{\tilde{P}_i} = \frac{\theta_{rj}^P \partial \Gamma_j(w_r^P, w_r^N, w_r^K, Y_i) / \partial w_r^N}{\theta_{rj}^N \partial \Gamma_j(w_r^P, w_r^N, w_r^K, Y_i) / \partial w_r^P} \quad (33)$$

Multiplying the expressions for observed relative factor prices and observed relative employments, the terms in unobserved factor quality will again cancel. The expression for relative wage bills now becomes,

$$\frac{\widetilde{\text{wbill}}_{irj}^N}{\widetilde{\text{wbill}}_{irj}^P} = \gamma_{rs}^{NP} \left(\frac{\partial \Gamma_j(\cdot) / \partial w_r^N}{\partial \Gamma_j(\cdot) / \partial w_r^P} \right) \left(\frac{\partial \Gamma_j(\cdot) / \partial w_s^P}{\partial \Gamma_j(\cdot) / \partial w_s^N} \right) \frac{\widetilde{\text{wbill}}_{hsj}^N}{\widetilde{\text{wbill}}_{hsj}^P} \quad (34)$$

In the standard benchmark case in the theoretical literature on trade under internal economies of scale, firms within an industry face the same constant elasticity of substitution ε_j , cost functions are identical and homothetic within industries, and there is free entry so that price equals average cost. Combining free entry with the pricing relationship in (32), the equilibrium ratio of average to marginal cost will equal a constant $\varepsilon_j / (\varepsilon_j - 1)$, which with homothetic cost functions defines a unique equilibrium value of output for all firms in the industry $Y_i = \bar{Y}_j$.

Under the null hypothesis of factor price equalization, $\gamma_{rs}^{NP} = 1$ and with all firms in the industry facing the same factor prices and producing the same output the terms in parentheses in (34) will cancel, so that we again obtain the prediction that relative wage bills are equalized under the null.

More generally in the presence of internal economies of scale, variation in firm size across regions and industries provides an additional explanation for violations of relative and absolute factor price equality. For the relative price of skilled workers to be lower in skilled abundant regions, we require firm size to be relatively larger in unskilled intensive industries in skilled abundant regions.

A4. CES Technology

In this section of the appendix, we consider the special case of a CES production technology. In this case, relative wage bill ratios under the alternative of non-RFPE depend only on relative quality-adjusted wages and the elasticity of substitution between factors of production. In the empirical analysis, this enables us to extract from the estimated coefficients implied differences in quality-adjusted wages across regions.

A4.1. Profit Maximization

With a CES production technology, it proves tractable to work directly with the firm's profit maximization problem,

$$\begin{aligned} \max_{P,N,K} \quad \Pi_{rj} = v_{rj} A_{rj} \left[a_j^P P_{rj}^{\rho_j} + a_j^N N_{rj}^{\rho_j} + a_j^K K_{rj}^{\rho_j} \right]^{\frac{1}{\rho_j}} \\ - w_r^P P_{rj} - w_r^N N_{rj} - w_r^K K_{rj} \end{aligned} \quad (35)$$

where for simplicity we consider the case where firms are price-takers in product markets. The first-order conditions to this maximization problem are,

$$w_r^P = v_{rj} A_{rj} \rho_j a_j^P P_{rj}^{\rho_j - 1} Y_{rj}^{1 - \rho_j} \quad (36)$$

$$w_r^N = v_{rj} A_{rj} \rho_j a_j^N N_{rj}^{\rho_j - 1} Y_{rj}^{1 - \rho_j} \quad (37)$$

$$w_r^K = v_{rj} A_{rj} \rho_j a_j^K K_{rj}^{\rho_j - 1} Y_{rj}^{1 - \rho_j} \quad (38)$$

where $P_{rj} = \theta_{rj}^P \tilde{P}_{rj}$, $N_{rj} = \theta_{rj}^N \tilde{N}_{rj}$, and $K_{rj} = \theta_{rj}^K \tilde{K}_{rj}$. From the first-order conditions, observed (non quality-adjusted) relative employment levels of non-production and production workers must satisfy,

$$\frac{\tilde{N}_{rj}}{\tilde{P}_{rj}} = \frac{\theta_{rj}^P}{\theta_{rj}^N} \left(\frac{a_j^N}{a_j^P} \right)^{1/(1-\rho_j)} \left(\frac{w_r^N}{w_r^P} \right)^{-1/(1-\rho_j)} \quad (39)$$

A4.2. Null Hypothesis

Under the null hypothesis of RFPE, we again obtain the prediction that the ratio of the observed wage bills of non-production to production workers is equalized across regions (this follows immediately from combining equation 12 with equation 39, noting that under RFPE $w_r^N/w_r^P = w_s^N/w_s^P$):

$$(H_0 : \text{RFPE}), \quad \frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P} \quad (40)$$

A4.3. Alternative Hypothesis

Under the alternative hypothesis of non-RFPE, the observed (non-quality adjusted) relative wages of non-production and production workers in regions r and s are again related according to,

$$\frac{\tilde{w}_r^N}{\tilde{w}_r^P} = \gamma_{rs}^{NP} \frac{\theta_{rj}^N \tilde{w}_s^N}{\theta_{rj}^P \tilde{w}_s^P} \quad (41)$$

Using equation (15) with equation (39), relative employment levels in regions r and s under the alternative of non-RFPE are given by,

$$\frac{\tilde{N}_{rj}}{\tilde{P}_{rj}} = (\gamma_{rs}^{NP})^{1/(\rho_j-1)} \frac{\theta_{rj}^P \tilde{N}_{sj}}{\theta_{rj}^N \tilde{P}_{sj}}, \quad (42)$$

Combining equations (41) and (42), we obtain the following prediction for the ratio of the observed wage bills of non-production to production workers:

$$(H_1 : \text{non-RFPE}) \quad \frac{\widetilde{\text{wbill}}_{rj}^N}{\widetilde{\text{wbill}}_{rj}^P} = (\gamma_{rs}^{NP})^{\rho_j/(\rho_j-1)} \frac{\widetilde{\text{wbill}}_{sj}^N}{\widetilde{\text{wbill}}_{sj}^P} \quad (43)$$

Given estimates of $(\gamma_{rs}^{NP})^{\rho_j/(\rho_j-1)}$ for r, s , if one makes an assumption about the elasticity of substitution between non-production and production workers ($\sigma_j = 1/(1 - \rho_j)$), one can evaluate the relative wage differences across regions implied by the estimates.

Postcode	Post Town	Postcode	Post Town	Postcode	Post Town	Postcode	Post Town
AB	Aberdeen	E	London (East)	LE	Leicester	SK	Stockport
AL	St Albans	EC	London (East Central)	LL	Llandudno	SL	Slough
B	Birmingham	EH	Edinburgh	LN	Lincoln	SM	Sutton
BA	Bath	EN	Enfield	LS	Leeds	SN	Swindon
BB	Blackburn	EX	Exeter	LU	Luton	SO	Southampton
BD	Bradford	FK	Falkirk	M	Manchester	SP	Salisbury
BH	Bournemouth	FY	Fylde (Blackpool)	ME	Medway (Rochester)	SR	Sunderland
BL	Bolton	G	Glasgow	MK	Milton Keynes	SS	Southend on Sea
BN	Brighton	GL	Gloucester	ML	Motherwell	ST	Stoke on Trent
BR	Bromley	GU	Guildford	N	London (North)	SW	London (South West)
BS	Bristol	GY	Guernsey & Alderney	NE	Newcastle on Tyne	SY	Shrewsbury
BT	Belfast	HA	Harrow	NG	Nottingham	TA	Taunton
CA	Carlisle	HD	Huddersfield	NN	Northampton	TD	Tweed (Galashiels)
CB	Cambridge	HG	Harrogate	NP	Newport	TF	Telford
CF	Cardiff	HP	Hemel Hempstead	NR	Norwich	TN	Tunbridge Wells
CH	Chester	HR	Hereford	NW	London (North West)	TQ	Torquay
CM	Chelmsford	HS	Western Isles (Harris)	OL	Oldham	TR	Truro
CO	Colchester	HU	Hull	OX	Oxford	TS	Teesside (Middlesbrough)
CR	Croydon	HX	Halifax	PA	Paisley	TW	Twickenham
CT	Canterbury	IG	Ilford	PE	Peterborough	UB	Uxbridge
CV	Coventry	IM	Isle of Man	PH	Perth	W	London (West)
CW	Crewe	IP	Ipswich	PL	Plymouth	WA	Warrington
DA	Dartford	IV	Inverness	PO	Portsmouth	WC	London (West Central)
DD	Dundee	JE	Jersey	PR	Preston	WD	Watford
DE	Derby	KA	Kilmarnock	RG	Reading	WF	Wakefield
DG	Dumfries & Galloway	KT	Kingston upon Thames	RH	Redhill	WN	Wigan
DH	Durham	KW	Orkney Isles (Kirkwall)	RM	Romford	WR	Worcester
DL	Darlington	KY	Kirkcaldy	S	Sheffield	WS	Walsall
DN	Doncaster	L	Liverpool	SA	Swansea	WV	Wolverhampton
DT	Dorchester	LA	Lancaster	SE	London (South East)	YO	York
DY	Dudley	LD	Llandrindod Wells	SG	Stevenage	ZE	Shetland Isles (Lerwick)

Table 1: Postcode Regions in the UK

1992			1986		
Administrative Region	Coeff	p-value	Administrative Region	Coeff	p-value
South-East	0.263	0.000	South-East	0.226	0.000
South-West	0.067	0.171	South-West	-0.072	0.123
East Anglia	-0.044	0.415	East Anglia	-0.047	0.343
North-West	-0.086	0.056	North-West	-0.044	0.290
East Midlands	-0.091	0.049	East Midlands	-0.067	0.121
West Midlands	-0.069	0.134	West Midlands	-0.086	0.048
Yorkshire	-0.098	0.033	Yorkshire	-0.109	0.011
Northern	-0.172	0.001	Northern	-0.309	0.000
Wales	-0.187	0.000	Wales	-0.120	0.010
Scotland	-0.182	0.000	Scotland	-0.145	0.001
F-stat. (p-value)		0.000	F-stat. (p-value)		0.000
Observations		1440	Observations		1413

Notes: Estimates based on pooling 4 digit industries and regions, taking the UK as a whole as the base region.

Table 2: Estimation Results, Administrative Regions, UK Base

1992		1986	
Administrative Region	$\sigma = 2$ $\rho = 0.5$	Administrative Region	$\sigma = 2$ $\rho = 0.5$
South-East	0.77	South-East	0.80
South-West	0.94	South-West	1.05
East Anglia	1.05	East Anglia	1.07
North-West	1.09	North-West	1.12
East Midlands	1.10	East Midlands	1.07
West Midlands	1.07	West Midlands	1.04
Yorkshire	1.10	Yorkshire	1.09
Northern	1.19	Northern	1.36
Wales	1.21	Wales	1.13
Scotland	1.20	Scotland	1.16

Notes: Coefficients used to evaluate relative wage differences are from Table 1, based on pooling 4 digit industries and regions, taking the UK as a whole as the base region.

Table 3: Implied Quality-Adjusted Relative Wage Differences (CES Technology)

Positive and Significant Region Coefficients at the 10% Level					
1992			1986		
Postcode Region	Coeff	$\sigma = 2$ $\rho = 0.5$	Postcode Region	Coeff	$\sigma = 2$ $\rho = 0.5$
Slough	0.195	0.82	Reading	0.187	0.83
Twickenham	0.236	0.79	Enfield	0.201	0.82
Swindon	0.237	0.79	Guildford	0.208	0.81
Hemel Hempstead	0.244	0.78	Swindon	0.283	0.75
Kingston	0.247	0.78	Slough	0.303	0.74
Redhill	0.271	0.76	Hemel Hempstead	0.311	0.73
Cambridge	0.298	0.74	Sutton	0.623	0.54
St Albans	0.364	0.69			
Sutton	0.559	0.57			
F-stat. (p-value)		0.00	F-stat. (p-value)		0.00
Observations		5044	Observations		5027

Notes: Coefficients based on pooling 4 digit industries and postcode areas, taking the UK as a whole as the base region. Listed regions have statistically significant positive coefficients at the 10% level.

Table 4: Postcode Areas With Positive and Significant Coefficients, UK Base

Negative and Significant Region Coefficients at the 10% Level					
1992			1986		
Postcode Region	Coeff	$\sigma = 2$ $\rho = 0.5$	Postcode Region	Coeff	$\sigma = 2$ $\rho = 0.5$
Llandrindod Wells	-0.669	1.95	Dumfries	-0.504	1.66
Dumfries	-0.530	1.70	Aberdeen	-0.433	1.54
Chester	-0.432	1.54	Cleveland	-0.366	1.44
Galashiels	-0.392	1.48	Sunderland	-0.364	1.44
Watford	-0.364	1.44	Plymouth	-0.330	1.39
Sunderland	-0.357	1.43	Blackpool	-0.327	1.39
Exeter	-0.350	1.42	Cardiff	-0.322	1.38
Llandudno	-0.344	1.41	Kilmarnock	-0.319	1.38
Aberdeen	-0.322	1.38	Truro	-0.306	1.36
Peterborough	-0.285	1.33	Newcastle	-0.296	1.34
Plymouth	-0.282	1.33	Llandudno	-0.293	1.34
Durham	-0.260	1.30	Canterbury	-0.276	1.32
Doncaster	-0.249	1.28	Darlington	-0.273	1.31
Cleveland	-0.239	1.27	Wolverhampton	-0.252	1.29
Sheffield	-0.236	1.27	Wakefield	-0.251	1.29
Kilmarnock	-0.234	1.26	Halifax	-0.245	1.28
Cardiff	-0.221	1.25	Bradford	-0.231	1.26
Crewe	-0.218	1.24	Bath	-0.220	1.25
Walsall	-0.197	1.22	Sheffield	-0.210	1.23
Dudley	-0.190	1.21	Wigan	-0.208	1.23
Manchester	-0.171	1.19	Motherwell	-0.207	1.23
Wolverhampton	-0.167	1.18	Oldham	-0.200	1.22
Newport	-0.152	1.16	Nottingham	-0.188	1.21
			Carlisle	-0.185	1.20
			Walsall	-0.185	1.20
			Hull	-0.181	1.20
			Dudley	-0.174	1.19
F-stat. (p-value)		0.00	F-stat. (p-value)		0.00
Observations		5044	Observations		5027

Notes: Coefficients based on pooling 4 digit industries and postcode areas, taking the UK as a whole as the base region. Listed regions have statistically significant negative coefficients at the 10% level.

Table 5: Postcode Areas With Positive and Significant Coefficients, UK Base

Region Definition	Fraction of All Region-Pairs Rejecting FPE		Distribution of Rejections Across All Base Regions at the 10% Level of Significance		
	5% Level of Significance	10% Level of Significance	Minimum	Mean	Maximum
Administrative Regions					
1992	0.46	0.57	2	5	9
1986	0.37	0.40	2	4	9
Postcode Areas					
1992	0.11	0.17	6	19	50
1986	0.12	0.19	5	22	74

Notes: Bilateral regressions use each region, in turn, as a base region in testing for factor price equality. These regressions analyze wage bills across 4 digit industries in 10 Administrative Regions and 111 Postcode Areas. The first two columns report the share of rejections out of the total number of possible rejections. Total possible bilateral rejections are 90 and 12,210 for Administrative Regions and Postcode Areas, respectively. The final three columns given the minimum, mean and maximum number of rejections for each base region. Total possible rejections for each base region are 9 and 110 for Administrative Regions and Postcode Areas, respectively.

Table 6: Bilateral Region-Pair Rejections

	(1)	(2)	(3)	(4)	(5)
Administrative Region	Base Results	Single Plant Establishments	Plant-level Estimation Results	Establishments with >100 employees	At Least 5 Establishments Per Region-Industry Pair
South-East	0.263 *	0.200 *	0.232 *	0.280 *	0.256 *
South-West	0.067	0.115 *	0.005	-0.013	0.015
East Anglia	-0.044	0.049	0.055	0.062	-0.053
North-West	-0.086	-0.049	-0.015	-0.076	-0.072
East Midlands	-0.091 *	-0.043	-0.035	-0.086	-0.030
West Midlands	-0.069	-0.060	-0.063	-0.120 *	-0.056
Yorkshire	-0.098 *	-0.059	-0.037	-0.094 *	-0.074
Northern	-0.172 *	-0.129 *	-0.101 *	-0.214 *	-0.347 *
Wales	-0.187 *	-0.133 *	-0.103 *	-0.227 *	-0.196 *
Scotland	-0.182 *	-0.214 *	-0.129 *	-0.161 *	-0.151 *
F-stat. (p-value)	0.000	0.000	0.000	0.000	0.000
Observations	1440	1317	1551	1309	593

Notes: * denotes statistical significance at the 5% level. Column (1) reports results from Table 1. Column (2) reports results based upon a sample of single plant establishments. Column (3) reports results where establishment-level data are allocated to plants on the basis of their shares of establishment employment. Column (4) reports results for the population of establishments with more than 100 employees. Column (5) reports results where region-industry pairs are excluded if they have fewer than five establishments.

Table 7: 1992 Administrative Region Coefficients For Various Specifications

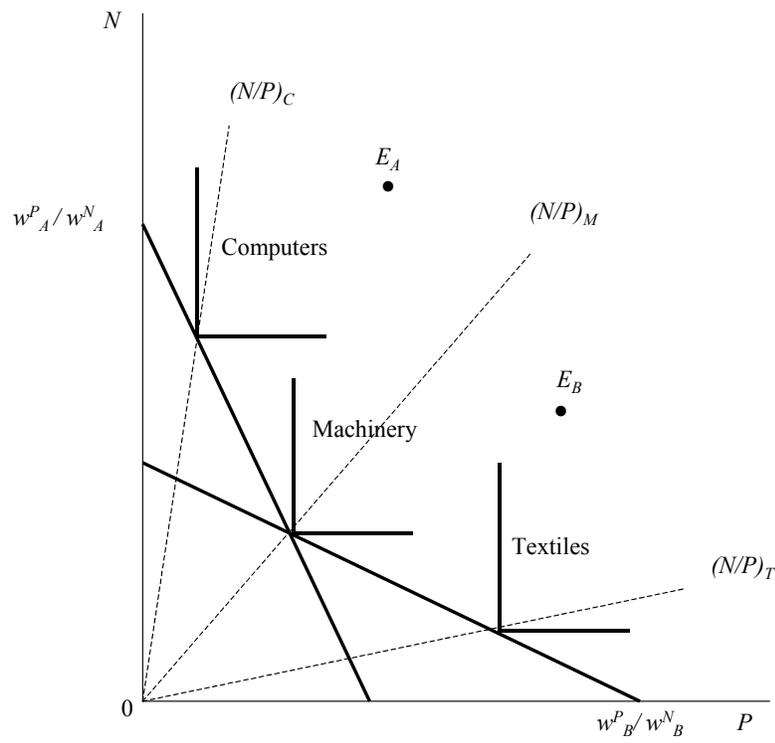


Figure 1: Multiple Cones of Diversification

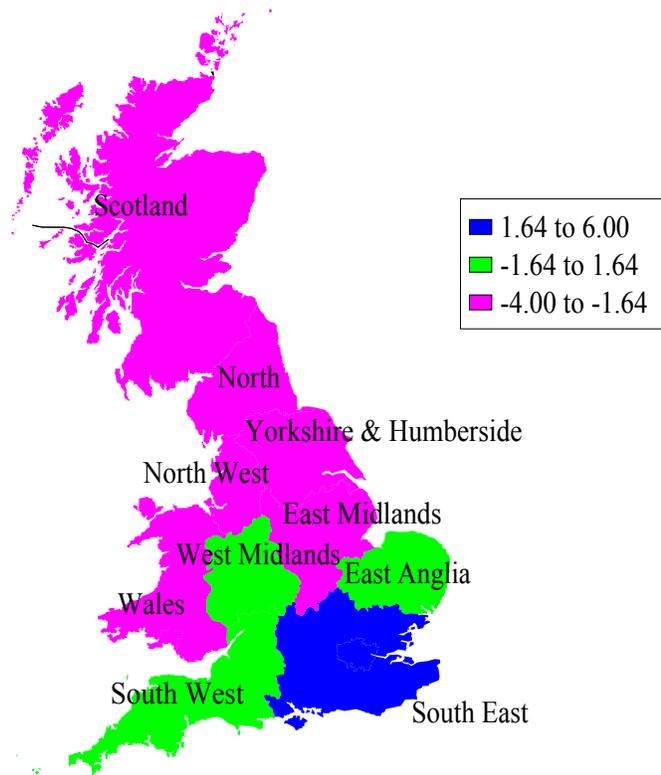


Figure 2: Administrative Region Estimates, 1992

1992 10%

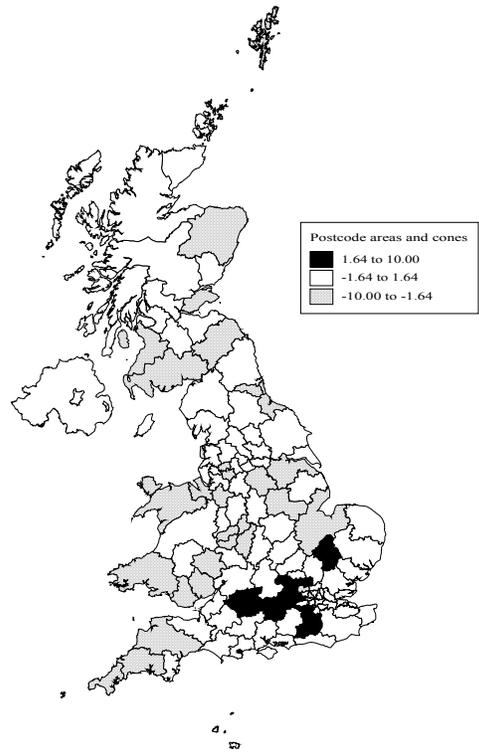


Figure 3: Postcode Area Estimates, 1992