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Labour market dynamics in the era of technological advancements: The system-wide impacts of labour augmenting technological change

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ABSTRACT

The employment impact of future technological change is much debated. Some commentators predict devastating job losses, while others are more sanguine, claiming that technological change raises living standards without reducing total employment. Our analysis a use a combination of partial equilibrium and dynamic computable general equilibrium (CGE) analysis with neo-Keynesian characteristics. These models are employed to assess the implications of skill-biased labour-augmenting technological change. They are calibrated on recent German Social Accounting Matrix data and parameterised using the best available empirical results from developed economies. The numerical CGE multi-sectoral model simulates the system-wide impacts of pervasive technical change affecting all sectors of the economy. The model allows investigation of alternative scenarios based around a common economic structure and set of parameter values. The results suggest that labour-augmenting technological change typically stimulates GDP growth and long-run total employment. However, there are negative short- and medium-run employment and real wage implications which might require government policy intervention. The simulations indicate that for open developed economies, improving the efficiency of skilled workers, as opposed to unskilled workers, is the most beneficial. This improvement has positive long-run impacts that are spread across both skill classifications. On the other hand, increasing the efficiency of the unskilled produces negative impacts on skilled employment and real wages. Additionally, the openness of the economy to migration and trade are important in determining the scale of these system-wide effects.

1. Introduction

There is broad agreement that technical change, with the implied increase in factor productivity, is central to economic growth and improved living standards. Further, technologies which impact not only individual, or a small range of, industries but rather apply generally across the whole economy are of especial interest. Examples are electrification, the internal combustion engine and its application to transport, and the adoption of digital technology [1–4]. However, the nature of the economy-wide effects of such waves of innovation are subject to extensive debate, much of which focuses on the labour market and income distributional impacts.

Major concerns are the effects on the shares of national income going to capital and labour and the way labour income is distributed across skill groups within the labour market. One claim, for example, is that in the period 1940–1970 US economic development was beneficial to labour across all skill groups [5]. But since the 1970s, widening income inequality has been at least partly attributed to technological change with unskilled workers benefiting little compared to the increased incomes going to skilled workers and capital [6]. Currently there is a fear of robotic job destruction (so called 'robot angst') and the general impact of the introduction of Artificial Intelligence and large language models such as ChatGPT. One argument suggests that a sudden and simultaneous adoption of technologies across a wide range of sectors might be so disruptive that the economy cannot adapt to these changes, resulting in widespread structural shifts [7–10]. A related viewpoint is that although in general previous waves of technological change have had positive effects, this time it will be different.

General understanding of the potential labour market implications of technological change has improved substantially over time [1–4], though considerable dispute still surrounds its past effects and future impacts. There are several reasons for this. First, it is straightforward to give a basic definition of technical progress – it involves producing more with less. But even a slightly deeper understanding requires a step up in

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conceptualisation. Output is produced with an array of inputs which are, to a degree, substitutable for one another. It is often difficult to identify, either *ex ante* or *ex post,* the underlying nature of the technical change. Does technological change require a reduction in all inputs? In particular, when technical change is said to be labour saving, does this mean a potential or an actual reduction in labour intensity? Where labour saving technical change requires new investment, does this necessarily imply a more capital-intensive technique? And does the interaction of these effects result in an actual reduction in aggregate labour demand?

An additional complication is that the labour market impacts of technical change often vary as the economy adjusts over time to the initial productivity shock. Moreover, the measured outcomes also depend on the focus of the analysis; in particular, whether the labour market is treated as unified or heterogeneous [8,11,12]. The incorporation of general equilibrium influences can also reinforce or modify the impacts observed in single firms or industries that adopt a new technology [1–4,13–17]. For all these reasons, whilst there is agreement about the importance of technical change for labour market outcomes, it is no surprise that there is a lack of conformity concerning the precise nature of these effects.

The central focus of the paper is the change in employment and real wage for skilled and unskilled workers. The primary research hypothesis is that the qualitative character of these changes is sensitive to the skill-augmenting characteristics of the technical change, the time-period over which the impacts are measured and the degree of openness of the labour market. For these principal simulations we employ default parameter values. These are the best estimates given available econometric evidence. Because these are system-wide simulations we also report other important economic variables partly to test the consistency of the model results. We subject these key results to sensitivity analysis through varying the openness of the economy to international trade and investigate in more detail the time path of the labour market outcomes.

For tractability and clarity, the present paper begins with a partial equilibrium investigation applied to a single sector. The analysis is then extended to incorporate all industries through simulation using a dynamic multi-sectoral Computable General Equilibrium (CGE) model parameterised on German data. It should be stressed that the CGE simulations are not predictions but should be regarded as numerical aids to conceptual thought and are most usefully employed in combination with other analytical and empirical approaches.

The strength of the analysis is the unambiguous, generic form of the productivity shock and the theory-consistent nature of the CGE model. Also, whilst the model reflects the structure of the German economy, key parameters can be varied to identify the sensitivity of the results to changes in important economic variables. In this case we are particularly interested in the sensitivity of the impacts to the openness of the labour and product markets. These results can assist policy makers in their pursuit of achieving (economic) policy goals. More widely, however, the analysis presented in this paper supports other modellers, e.g. energy system modellers, in their designs of scenarios and the systematic examination of disruptive drivers [18]. Germany is used as a case study, but our analytical and simulation models can be applied to other countries or regions, where the data allow.[1]

The paper is organised as follows. Section 2 develops a stylised partial equilibrium analysis to identify key parameters governing the impact at the level of the industry. Section 3 outlines key features of the dynamic multi-sectoral CGE model and its calibration on German data. Section 4 identifies the precise nature and scale of the labour efficiency shock. Section 5 reports the simulation results and considers the implications of the openness of the economy to migration and trade. Section 6 provides a summary and conclusions.

[1] The empirical CGE model does need to be appropriately calibrated and parameterised to accurately reflect the specific economy under analysis. This would potentially include modification of the model closures, particularly those relating to the labour market.

2. Partial equilibrium analytical model

We begin by studying the impact of skill-specific labour-augmenting technical change but applied to only one industry.[2] This produces a limited, partial equilibrium, analysis but it allows identification of key relationships operating at the level of the industry which will prove useful in determining system-wide employment impacts. The specification of the analytical model also clarifies what is meant by factor augmenting technical change.

In this approach the labour force is divided into different skill types represented generically by the subscript z. In our case we have skilled and unskilled workers to that $z = s, u$. The classification of workers into these categories is determined by the data used in the empirical model (EXIOBASE 3 Input-Output table [38]) described in Section 3 and are based on the International Standard Classification of Occupations. To model labour-augmenting efficiency improvements it is useful to make a distinction between the labour input in natural and efficiency units. For labour, L, of skill type z, the labour input in efficiency units, L_z^e, is defined as:

$$L_z^e = L_z^n (1 + \gamma_z) \tag{1}$$

where L_z^n is the labour input in natural units (e.g. person hours) and γ_z is the efficiency parameter. Initially, γ_z is set to zero so that the labour input in both natural and efficiency units is calibrated to be equal. A subsequent positive value for γ_z represents a factor-augmenting efficiency improvement in labour skill category z. This is how we will characterise technical change. It implies that, for example, a value of $\gamma_s = 0.5$ means that a given number of skilled person hours can now deliver a 50% more effective labour input. Expressed differently, the same output can be produced with a 33% reduction in skilled labour input, holding the level of all other inputs constant.[3] Labour-skill-augmenting efficiency increases could be brought about through, for example, an improvement in working practices due to the introduction of new technologies.

Labour-augmenting technological change reduces the cost of labour in efficiency units. This is shown in equation (2) where w is the wage, and the subscripts and superscripts are as in equation (1):

$$w_z^e = \frac{w_z^n}{(1 + \gamma_z)} \tag{2}$$

The change in the wage per skill-specific labour efficiency unit generates endogenous substitution, output and income effects which are important for measuring the full impact of any efficiency change.[4] In this basic analytical model, we assume that the labour input, in efficiency units, is a composite of the skilled and unskilled elements, so that:

$$L^e = L(L_s^e, L_u^e) \tag{3}$$

We are primarily interested in identifying the impact on skill-disaggregated employment resulting from an improvement in the efficiency of one of these skill classifications.

The initial partial equilibrium analysis uses results developed in a slightly different context, by Holden and Swales [20]. As outlined in equation (3), the labour composite is made up of two skill types and the supply of both skills is assumed to be perfectly elastic at their existing nominal wages, with the implication that the nominal wage in each skill

[2] Figus et al. [19], apply a similar model in the context of energy efficiency.

[3] If a task requires 100 efficiency units of labour and initial calibration equates one efficiency unit with one physical unit, for a labour efficiency increase of 50%, 100 physical units now provide 150 efficiency units of labour (equation (1)). The physical inputs of labour can therefore be reduced to (100/150) = 2/3 of their initial value, implying a reduction of 1/3, or 33%.

[4] This is especially so in a general equilibrium context.

group is held constant.

The elasticity of substitution between skilled and unskilled labour is labelled as σ. It gives the proportionate change in the ratio of skilled to unskilled workers employed in response to a proportionate change in the relative wage rates. It is a measure of the extent to which the two skill types are substitutes or complements. Where the value is zero, the labour types are pure complements, always used in fixed proportions. Where the value approaches infinity, this would indicate that the two skill types are perfect substitutes. We use the value 1.5 which means that the skill types are substitutes but not perfect substitutes. The share of total wage income going to skill z is q_z.

The price elasticity of demand for the labour composite, η, gives the sensitivity of total labour demand to changes in the aggregate wage. It is the proportionate change in the demand for the labour composite, measured in efficiency units, L^e, in response to a proportionate change in the real aggrege wage rate (again measured in efficiency units). This means that with fixed nominal wage rates for the two skill groups, an increase in labour efficiency will reduce the composite wage, in efficiency units, as given in equation (2). This subsequent increase in the demand for labour, again in efficiency units, depends on the value of η. When the value of the price elasticity of demand for labour is zero, so that labour demand is completely wage inelastic, there is no change in the labour input in efficiency units and employment in physical units (the number of employees) falls by the full amount of the increase in labour efficiency. As long as $\eta < 1$, physical total employment falls in the partial equilibrium model where labour efficiency increases; for values of η above unity it rises.

Equations (4)–(7) below present the results for an analysis of an increase in efficiency relating solely to skilled workers. However, precisely the same formulations operate, with the appropriate changes in notation, where the efficiency improvement only applies to the unskilled. Under the conditions identified in the previous paragraph, we can analytically derive expressions for the partial equilibrium elasticities of skilled and unskilled employment in physical units, with respect to an increase in efficiency applying only to skilled workers. These elasticities are given as $\Gamma^n_{s,s}$ and $\Gamma^n_{s,u}$ respectively. They identify the proportionate change in skilled and unskilled employment for a proportionate change in skilled augmenting technical change:

$$\Gamma^n_{s,s} = \frac{1}{L^n_s}\frac{\partial L^n_s}{\partial \gamma_s} = \sigma(1-q_s) + q_s\eta - 1 \tag{4}$$

$$\Gamma^n_{s,u} = \frac{1}{L^n_u}\frac{\partial L^n_u}{\partial \gamma_u} = (1-q_s)(\eta - \sigma) \tag{5}$$

To reiterate, by adjusting the notation, a corresponding pair of expressions can be generated for the impact of an increase in the efficiency of the unskilled.[5]

It is important to note that for a range of economically meaningful values for the exogenous parameters both equations (4) and (5) can give positive or negative values for the employment elasticities. With the increase in efficiency, the direct impact on skilled employment is negative. However, for both $\Gamma^n_{s,s}$ and $\Gamma^n_{s,u}$, the higher the value of the elasticity of demand for the labour composite, η, the more likely that employment will increase. This is straightforward as an important stimulus to employment in either skill group is the fall in the price of the labour composite following the increase in labour efficiency. On the other hand, the impact of variations in the elasticity of substitution, σ, has opposite effects on employment in the two skill groups. The price of skilled labour falls relative to unskilled, so that there is substitution of s for u, in efficiency units. The higher the elasticity of substitution, the greater is this substitution effect.

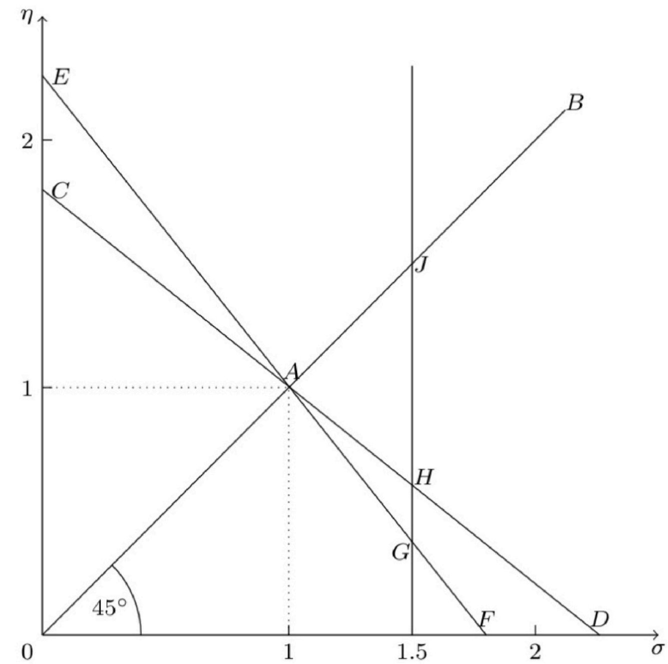

Fig. 1. Zero-employment curves for labour-skill-group-augmenting efficiency improvements.

It is pedagogically useful to use equations (4) and (5) to identify the sets of parameter values where each elasticity takes a zero value. These relationships mark the boundary between the sets of parameter values which give positive or negative changes in employment in different skill-types for the efficiency change under consideration. Setting $\Gamma^n_{s,s}, \Gamma^n_{s,u} = 0$ in equations (4) and (5) respectively gives:

$$\eta = \frac{-(1-q_s)}{q_s}\sigma + \frac{1}{q_s} \tag{6}$$

$$\eta = \sigma \tag{7}$$

These functions are mapped in Fig. 1, where point 0 is the origin and the horizontal and vertical axes show the σ and η values respectively. These zero-employment-change lines both pass through point A, with the co-ordinates (1,1).[6] The 45-degree line 0AB, which is delineated in equation (7), identifies the parameter values for which an increase in the efficiency of skilled workers, s ,leaves employment in the unskilled group, u, unchanged. For parameter combinations on this line the positive output just balances the negative substitution effect. Points lower and to the right of 0AB represent parameter combinations where the employment in skill group u will fall, whereas those above and to the left indicate where it will rise.

Similarly, in Fig. 1 the line CAD, determined by equation (6) is the equivalent zero-employment-change line for skilled workers. In this case, the skilled-augmenting increase in efficiency has a direct negative effect on skilled labour demand. However, this can be offset by high enough levels of either, or both, substitution and labour demand elasticities. Points below and to the left of the line CAD show parameter combinations where skilled employment falls, points above where it rises. The line CAD pivots around A, with the slope depending on the value of q_s, the share of the wages of skilled workers in the labour

[5] For example, equation (4) would be: $\Gamma^n_{u,u} = \frac{1}{L^n_u}\frac{\partial L^n_u}{\partial \gamma_u} = \sigma(1-q_u) + q_u\eta - 1 = \sigma q_s + (1-q_s)\eta - 1$.

[6] With $\eta = 1$, the total expenditure on labour is invariant to changes in its price; adjustments in quantity demanded just counter any change in the price. Similarly, where $= 1$, the share of labour income going to both skill groups is invariant to changes in their relative costs. Given the assumption of constant wage rates, this means that where $\sigma, \eta = 1$, the employment change in both skill groups is zero.

composite. The line cuts the η and σ axes at the values $1/q_s$ and $1/(1-q_s)$ respectively. The lower the value of q_s, the steeper is the negative slope of line CAD.[7]

We also show in Fig. 1 the corresponding functions where the efficiency increase is unskilled augmenting. The zero-employment line for the non-efficiency-augmented skill group, in this case the skilled, is the same: the 45-degree line through the origin OAB. However, the relationship for the unskilled is given by the line EAF. This has the same qualitative characteristics as CAD; it is downward sloping and passes through point A. However, in this case it has intercepts with the η and σ axes equal to $1/q_u$ and $1/(1-q_u)$.[8]

The way that Fig. 1 has been constructed reflects some of the parameter values used in the CGE simulations reported in Section 5. The CGE model is calibrated on German data where, in aggregate, the share of wage income going to the skilled and unskilled is 0.56 and 0.44 respectively (these specific values are obtained from the EXIOBASE 3 Input-Output table [38], ensuring that the model reflects the empirical distribution of wage income). This means that CAD has a shallow negative slope, less than 45°, whereas EAF's negative slope is steeper than 45°. The vertical line GHJ cuts the σ axis at the point 1.5. This is the default, econometrically based elasticity of substitution imposed in the CGE simulations, indicating that skilled and unskilled labour are substitutes in production, rather than complements.

If the elasticity of substitution, σ, is fixed, the employment outcomes then depend solely on the elasticity of labour demand, η. For demand elasticities below G, which here has the value 0.36, employment falls in both skill-types for any efficiency improvement; similarly, for values above J (1.5), employment for both skill-types will rise. For labour demand elasticities between G, H and J combinations of positive and negative skill-specific employment change occurs.[9] From Fig. 1 we can therefore deduce that any combination of skilled or unskilled qualitative employment change can accompany labour efficiency improvements. Note also that an actual productivity shock could be a combination of skilled- and unskilled-augmenting efficiency increases.

The partial equilibrium analysis provides insights concerning the endogenous employment impacts of the labour-augmenting efficiency shock. However, tractability is achieved through making the model extremely basic. There are three important simplifications. The most important is that the labour demand function employed here is essentially a general equilibrium one which incorporates all the accompanying factor substitution, commodity price and income effects that the efficiency improvement generates. As is discussed in greater detail in Section 3, in any sector the composite labour input is only one element of the industry production function and industry output is sensitive to the endogenous own price change and other commodity price and income effects. Therefore, even where the analysis is limited to one sector, the responsiveness of labour demand to changes in the efficiency wage is the result of the general equilibrium interaction in many sectors and markets. A second issue is that in the partial equilibrium analysis the skill-specific wage rates are assumed to be fixed. To fully appreciate the wage and employment impacts of labour augmenting technical change a more fully developed wage-setting/labour supply mechanism needs to be incorporated. Finally, this partial equilibrium approach focuses solely on the employment effects. However, we are also concerned with aggregate and sectoral output and competitiveness impacts. For all these reasons, we extend the analysis through simulation using an empirical CGE model.

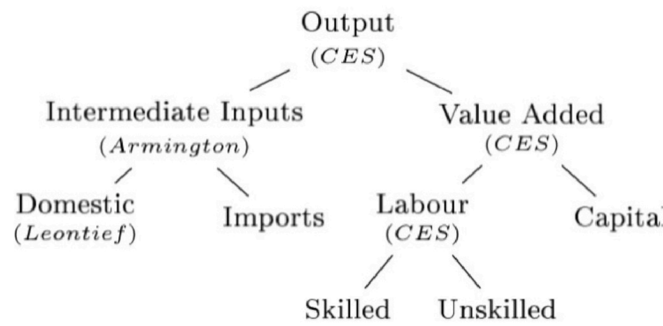

Fig. 2. DEMACRO production structure.

3. DEMACRO: A skill-disaggregated micro-macro model of Germany

We adopt the inter-temporal, dynamic, multi-sectoral CGE DEMACRO model. This is a skill-disaggregated micro-macro model, based around the AMOS [21–24] framework, parameterised on a 2018 Social Accounting Matrix (SAM) for Germany.[10] This section outlines how the labour market options of the AMOS and basic DEMACRO model [26] are extended to incorporate 'skills' in more detail to form the version of the DEMACRO employed in this paper.[11]

The model has three domestic transactors: households, corporations, and government; four major components of final demand: consumption, investment, government expenditure, and exports; and 25 industrial sectors; and two types of labour. Real government expenditure is exogenous and remains fixed (in terms of specific physical quantities).[12] The demand for German exports is determined via conventional export demand functions and imports are obtained through an Armington [29] link with trade substitution elasticities of 2.7 [30,31].[13] Financial flows are not explicitly modelled, with Germany assumed to be a price-taker in financial markets. As the model is parameterised on annual data, in the period-by-period simulations each period is interpreted as a year.

In the model production takes place in perfectly competitive industries using multi-level production functions, as illustrated in Fig. 2. This implies that in every time period all commodity markets clear with price equal to the marginal cost of production [24]. However, the model allows for imperfections in the labour market, generating involuntary unemployment meaning that the equilibria are not necessarily optimal in a conventional welfare sense [32]. Value-added is produced using capital and the skilled-unskilled labour composite, which is discussed in more detail in Section 3.1. In general, constant elasticity of substitution (CES) technology is adopted with substitution elasticities equal to 0.3, so that input substitution occurs in response to changes in the relevant relative factor-prices [33]. In each industry intermediate purchases are modelled as the demand for a composite commodity with fixed (Leontief) coefficients. These are substitutable for imported commodities via

[7] The slope is $-(1-q_s)/q_s$.

[8] Given that $q_s + q_u = 1$ then $q_u = 1 - q_s$ and $q_s = 1$ - qu. The line EAF, which is the elasticity of unskilled employment with respect to an unskilled labour augmenting efficiency change, is therefore symmetric to CAD around the 45-degree line 0AB.

[9] For elasticity values greater than G, unskilled employment will rise for unskilled augmenting technical change and for labour demand elasticities greater than H, 0.61, skilled employment will rise for skill augmenting technical change.

[10] These accounts incorporate the latest skill-disaggregated data available at the time of writing. The 2018 EXIOBASE 3 multi-regional Input-Output table [38] is aggregated to Germany and the rest of world and is augmented with other publicly available information to form the SAM. Emonts-Holley et al. [25], describe the method used to construct and balance the SAM.

[11] Lecca et al. [24], outline the AMOS model more fully. Ross [27] initially developed the labour market skill extensions within the AMOSKI CGE model for Scotland.

[12] There are versions of the model, for example. [21,28], in which this assumption is relaxed.

[13] A mean estimate of the Armington elasticity implied by Bayesian model averaging. The effects of varying the value for this elasticity are shown in Section 5.3.

an Armington link [29].[14]

3.1. The labour market

The model identifies two types of labour, skilled and unskilled, categorised using their International Standard Classification of Occupations. This form of skill disaggregation has been previously adopted in the IO, SAM, and CGE literature (e.g. Refs. [36–38]) and is an aggregate of the skill categories given in the EXIOBASE data set [38].[15] As shown in Fig. 2, in each industry, at the lowest level of the production structure the labour input is a composite of these two skill types. For industry, j, and time, t, value added, Y, is given by a CES combination of the labour composite and capital, given as:

$$Y_{jt} = \left[\alpha_j \left(KD_{jt}\right)^{\rho_j} + \beta_j \left(LD_{jt}\right)^{\rho_j}\right]^{\frac{1}{\rho_j}} \tag{8}$$

where capital and labour inputs are KD and LD, ρ is the elasticity of substitution between capital and labour, and α and β are the calibrated share parameters. Cost minimising demand for the labour composite and the individual skill types are given as equations (9) and (10):

$$LD_{jt} = \left[\beta_j \frac{PY_{jt}}{w^n_{jt}}\right]^{\frac{1}{1-\rho_j}} Y_{jt} \tag{9}$$

$$LD_{sjt} = \left[\gamma_{sjt}{}^{\sigma_j} \frac{w^n_{jt}}{w^n_{sjt}}\right]^{\frac{1}{1-\sigma_j}} LD_{jt},\ LD_{ujt} = \left[\gamma_{ujt}{}^{\sigma_j} \frac{w^n_{jt}}{w^n_{ujt}}\right]^{\frac{1}{1-\sigma_j}} LD_{jt} \tag{10}$$

where γ is the labour augmenting efficiency parameter, PY is the value added price, w is the wage rate in natural units, and σ is the elasticity of substitution between skilled and unskilled labour which, as stated in Section 2, is taken to be 1.5 [39,40]. Although empirical estimates of this substitution elasticity provide a wide range of possible values, few estimate are less than 1 and a consensus has formed around a value of 1.5 [41,42].[16] Skill-differentiated labour efficiency is introduced into the model by the labour augmenting technology efficiency parameters, γ_s and γ_u, in the labour demand function of each skill category given as equation (10). Note that the treatment of the skill decomposition of the labour market in the DEMACRO model exactly matches the approach taken in the partial equilibrium analysis in Section 2.

3.1.1. Wage setting

Although the model offers alternative wage setting options, our preferred labour market closure employs a bargained real wage function (a wage curve [43]) for each skill category [44,45].[17] This is a positive empirical relationship between the real consumption wage and workers bargaining power, which is inversely related to the unemployment rate so that:

$$ln(rw_{zt}) = \varphi_z - \epsilon_z\ ln(un_{zt}) \tag{11}$$

where rw is the after-tax real wage, un is the unemployment rate (set initially to 4% for the skilled and 6% for the unskilled), ϵ is the unemployment rate elasticity which is fixed at 0.16 for the skilled and 0.15 for the unskilled [47–51],[18] and φ is a calibrated parameter so as to replicate base year data.

3.1.2. Labour force and economic migration

In the short run, the labour force of each skill-type, LF_z, is fixed but over this time period for each skill type labour is perfectly mobile across sectors and total employment can vary through changes in the unemployment rate. Over longer time periods we assume that there are no natural demographic labour force changes but there is an option to separately adjust the size of the labour force in each skill-type through flow-equilibrium migration. Adopting this option:

$$LF_{zt+1} = (1 + m_{zt}) \cdot LF_{zt} \tag{12}$$

where m is the net-immigration rate as a proportion of the skill-type labour force. Where the labour force is fixed, migration is set to zero, so that:

$$m_{zt} = 0 \tag{13}$$

If migration is endogenized, it takes a flow-equilibrium form so that the rate of in-migration is positively related to the real wage and negatively to the unemployment rate [44,52,53].[19]

$$m_{zt} = \beta_z - 0.081\left(un_{zt} - un^{ROW}_{zt}\right) + 0.058\left(rw_{zt} - rw^{ROW}_{zt}\right) \tag{14}$$

The superscript ROW identifies the rest of the world, the external sector [24] which, in these simulations we assume to be unchanging. Empirical work suggests that low skilled workers are less geographically mobile than the highly skilled [56–60]. The three migration closures of the model encompass this potential difference in geographical mobility. In the first model closure, there is no migration so that both skilled and unskilled are geographically immobile and equations (12) and (13) apply to both skill categories. In the second, which allows only skilled migration, equations (12) and (14) are adopted for the skilled, and equations (12) and (13) for the unskilled. In the third closure, free migration, labour supply is unconstrained; both skilled and unskilled workers migrate in response to national/ROW differentials in real wages and unemployment rates; equations (12) and (14) apply for both skill categories. The results generated using these closures could also be interpreted as reflecting the impact of skill-differentiated migration restrictions.

Workers are fully mobile between industries, but workers cannot move between skill groups. That is, we do not consider changes in the skilled and unskilled composition of the labour force, due to education and/or training, in this model. Further, existing workers and new immigrants are assumed to be perfect substitutes within each skill group.

3.2. Investment

The capital stock is fixed in the short run, both in total and in its distribution across sectors. Capacity in individual sectors vary through period-by-period flows of net investment, with the capital stocks fully adjusting in the long run.[20] Gross investment at time period t is equal to

[14] Other versions of the model offer a more detailed production structure whereby 'energy' is considered in more detail [21,34,35].

[15] Greater skill disaggregation would require additional labour demand, wage curve, and migration functions, along with empirically plausible elasticities. More importantly, the implicit claim that skill is fixed, at least in the short run, so that movement between skills requires investment in human capital becomes less plausible as the number of skill groups is increased [36].

[16] Ross [27] reports the results from extensive sensitivity analysis around this elasticity value for both demand and supply disturbances with the AMOSKI model.

[17] Standard available alternatives include exogenously fixing, typically at their initial values, either the nominal wage, the real wage or the total employment level. There is also an option which imposes an 'environmental social wage' [21]. We do not currently consider other possibilities, such as sector-specific bargaining between the representative firm and a trade union put forward by Böhringer et al., [46]. This is due to the lack of (plausible) data required to parameterise the model whilst maintaining a high level of sectoral disaggregation.

[18] Again, Ross [27] conducts extensive sensitivity analysis around this elasticity for both demand and supply disturbances using the AMOSKI variant of the AMOS model.

[19] Versions of the model exist in which local amenities also play a role [21,28,54,55].

[20] Note that myopic investment decisions made in period one are unaffected by any possible future migration decisions.

depreciation plus some proportion τ, of the difference between the desired capital stock in the next time period, K^*_{t+1}, and the actual capital stock, K_t, so that:

$$I_t = \tau\left[K^*_{t+1} - K_t\right] + \delta K_t \tag{15}$$

The desired capital stock in period $t+1$ is determined by the expected output price, p, and cost of capital, r, and output in the following period so that:

$$K^*_{t+1} = K_i\left(Q^e_{t+1}, p^e_{t+1}, \tau^e_{t+1}\right) \tag{16}$$

However, the firm takes the existing values for these variables to be the best estimate or the expected next period values, so that:

$$K^*_{t+1} = K_i(Q_t, p_t, \tau_t) \tag{17}$$

Alternative specifications are available. DEMACRO also offers a perfect foresight version, as outlined in detail Lecca et al. [24], and other model version of AMOS offer 'imperfect foresight' specifications [61].

3.3. Model closure

The model closure rules are as follows. Investment is endogenous and determined through equations (15)–(17). Savings is a proportion of household income, calibrated to the base-year data. Government expenditure is fixed in real terms at its base year value, as are tax rates. Exports and imports are endogenous, with foreign prices essentially acting as the model numeraire. The capital, public sector and external accounts are not required to balance individually.

Where the model is run in a period-by-period (dynamic recursive) mode, in each time-period and in each sector, investment operates to partially adjust the capital stock to its optimal (cost-minimising) level given present sectoral prices and outputs. In long-run equilibrium the actual and optimal capital stocks are the same and investment simply covers depreciation. For each sector, the capital stock is updated between periods, so that net investment in period t only affects capacity in period $t+1$.

Labour market options are given by equations (8)–(14). Where migration is allowed, the population, and therefore the labour force, adjusts to variations in the real wage and the unemployment rate, as shown in equation (14). Where migration is allowed, in long-run equilibrium net migration is equal to zero, so that the labour force is stable. As long as the wage curve parameters are unchanged, in the long run the interaction of the wage curve and the zero net migration requirement means that the real wage and unemployment rates, but not total employment, will return to their base year values. Again, where the model is run in dynamic recursive mode, the population is adjusted between periods; net migration driven by labour market outcomes in period t updates the labour force in period $+1$.

4. Simulation strategy

The technology shocks introduced into the model are skilled- and unskilled-augmenting increases in labour efficiency, labelled as ESK and EUN respectively. These correspond to changes in γ_s or γ_u in equation (10). In each case the improvement in efficiency is modelled as a broad-brush, permanent 3.5% stimulus from time-period 1 onward across all the 25 sectors in the DEMACRO model. This translates to a permanent step-change increases in the relevant γ_s or γ_u values across all sectors, j. We are not concerned with niche technologies adopted incrementally in a limited number of sectors, although the system-wide effects of such technical change might still be significant. Rather, the focus is on identifying the likely economy-wide impacts of labour-augmenting technologies that are adopted rapidly and in large scale across all production sectors. A greater increase in labour efficiency would scale up the quantitative results but the qualitative effects would be unchanged. The paper focusses on the aggregate macroeconomic outcomes. It does not report sectoral impacts although these are taken into consideration within the model.

Although we only consider pure skilled- or unskilled-augmenting technical progress, it is likely that labour efficiency improvements are a mixture of both. We could introduce a more nuanced (non-binary) skill augmenting efficiency shock; for example, increasing both skilled and unskilled efficiency by 3.5% would produce a skill-neutral shock which would replicate standard Harrod-neutral technical progress. In practice, the results of a mixed skilled-biased efficiency improvement can be closely approximated by taking a weighted sum of the pure skilled- or unskilled-augmenting simulation results.[21]

The short- and long-run results for a range of aggregate economic and labour market variables are discussed in Section 5.1 whilst the period-by-period employment and wage effects are outlined in Section 5.2. We consider the implications of varying the openness to trade flows in Section 5.3.

5. Simulation results

5.1. Short- and long-run outcomes

The key short- and long-run simulation results are summarised in Table 1. The figures are given as percentage changes from base-year values. There are some common effects that always apply irrespective of the form that the labour efficiency improvement takes. The composite price of labour, measured in efficiency units invariably falls..[22] Production costs are reduced, stimulating exports, gross domestic product (GDP), household consumption and government revenues.[23] Further, the resulting expansion in economic activity is always greater where the efficiency improvement applies to skilled, rather than unskilled, workers. This partly reflects the fact that the larger share of total wage income goes to skilled workers.

Nevertheless, despite these important common outcomes, the detailed economic impacts depend on the skill group that experiences the efficiency increase, the time period, and the labour market closure that is in operation. We are particularly interested in the employment and real-wage effects and, in this respect, the extent to which the general equilibrium simulation results reflect the labour-market-focussed partial equilibrium analysis of Section 2. We begin by detailing the results for the short-run closure. This is where the capital stock is fixed at the level of the individual sector. The labour force is also fixed in total, but the labour supply can vary through changes in the unemployment rate and labour is mobile across sectors. In subsequent simulations we successively relax these supply-side constraints.

The short-run impacts are shown in the first two results columns of Table 1. Note that the increase in skilled efficiency, ESK, generates an increase in economic activity that is around 60% greater than EUN. For example, the changes in GDP and exports are 1.10% and 0.55% for the skilled efficiency improvement, as against 0.68% and 0.34% for the unskilled. But the employment impacts are more nuanced. For both efficiency shocks there is a short-run fall in total employment, which is larger for ESK, where both skilled and unskilled employment decline. This contrasts with the increase in unskilled efficiency (EUN) where

[21] Again, the impact of a skill-neutral 3.5% labour efficiency increase for any of the closures identified in Table 1could be calculated by summing the values in the two corresponding columns. Using the results in columns 1 and 2, the change in short-run GDP would be given as 1.10% + 0.68% = 1.78%. This is extremely close to 1.77%, the result generated from running the corresponding actual skill-neutral simulation.

[22] For example, in the ESK case the short-run unskilled wage, as measured in efficiency units, falls by 5% (1.50% plus the 3.5% change in efficiency).

[23] Depending on the form the labour efficiency improvement takes, the additional government revenues would be between 11 and 18 billion Euro annually in the short run, and 30 and 75 billion Euro annually in the long run.

Table 1
Short- and long-run effects of a 3.5% increase in skill-differentiated labour efficiency. Values are % changes from base year.

	Short run		Long run					
			No migration		Skilled migration		Free migration	
	ESK	EUN	ESK	EUN	ESK	EUN	ESK	EUN
GDP	1.10	0.68	2.55	1.57	4.41	1.32	4.89	1.98
CPI	−0.36	−0.22	−0.83	−0.52	−1.44	−0.43	−1.60	−0.65
Employment	−0.28	−0.16	0.37	0.24	1.80	0.05	2.51	1.01
Skilled	−0.03	−0.45	0.57	−0.08	3.53	−0.48	3.35	−0.73
Unskilled	−0.48	0.08	0.20	0.51	0.35	0.49	1.80	2.47
Nominal gross wage	−0.97	−0.70	0.14	−0.01	−1.02	0.15	−1.59	−0.65
Skilled	−0.44	−1.37	0.63	−0.72	−1.44	−0.43	−1.59	−0.65
Unskilled	−1.50	−0.02	−0.35	0.69	−0.59	0.73	−1.59	−0.65
Real gross wage	−0.61	−0.48	0.98	0.50	0.42	0.58	–	–
Skilled	−0.08	−1.15	1.47	−0.20	–	–	–	–
Unskilled	−1.15	0.20	0.49	1.21	0.85	1.16	–	–
Labour force	–	–	–	–	1.61	−0.22	2.51	1.01
Skilled	–	–	–	–	3.53	−0.48	3.35	−0.73
Unskilled	–	–	–	–	–	–	1.80	2.47
HH consumption	0.06	0.04	0.59	0.37	1.03	0.31	1.14	0.46
Investment	2.68	1.66	2.34	1.45	4.05	1.21	4.50	1.82
Exports	0.55	0.34	2.21	1.37	3.83	1.15	4.25	1.72
Imports	1.91	1.17	0.05	0.03	0.10	0.03	0.11	0.04

Note: ESK = skilled-augmenting and EUN = unskilled-augmenting efficiency increases.

unskilled employment shows a slight increase, of 0.08%, though accompanied by a fall of −0.45% for skilled employment.

The explanation for these differential qualitative impacts is that in the short run the composite labour demand is inelastic as the expansion of output is restricted by the fixed capital in each sector. In terms of the partial equilibrium analysis in Fig. 1, the employment outcomes are consistent with a labour demand elasticity falling between G and H. This would create negative employment changes for the skill type whose efficiency is unchanged but the observed employment changes for the efficiency augmented skill types. In both simulations the real wage falls in aggregate although for the unskilled efficiency increase there is a small, 0.20%, rise for unskilled workers.

In the second set of simulations, whose outcomes are reported in columns 3 and 4, we retain a fixed labour force for each skill whilst relaxing the capital constraint through net investment. These are the long-run equilibrium outcomes where no migration is allowed. This implies that in each sector the capital stock adjusts to its cost-minimising level, given factor prices and the sector's output. Because sectors are no longer restricted by a fixed capital capacity there is a much greater reduction in the consumer price index (CPI). This drives competitiveness and a more substantial expansion in exports. Labour demand is now elastic and total employment increases for both the ESK and EUN simulations. The expansion in employment is accommodated by increases in the aggregate real wage by 0.98% and 0.50% respectively. The aggregate increases in employment and real wages drive increases in household consumption.

Again, it is useful to compare the results with the partial equilibrium analysis represented in Fig. 1. Note that for the skill-augmenting efficiency improvement, ESK, both the skilled and unskilled employment change is now positive, at 0.57% and 0.20% respectively, with 1.47% and 0.49% increases in the real wages. This contrasts with the falling employment and real wages for both skill groups in the corresponding short-run simulation. In terms of Fig. 1, the relevant labour demand elasticity is now above J. For EUN, whilst unskilled employment increases, skilled employment still falls. In this case, the labour demand elasticity lies just below J in Fig. 1. The difference in the elasticity values in the ESK and EUN long-run simulations reflects the sectoral composition of the two employment types with the more price-sensitive exports being more skill-intensive.

Where skilled migration is permitted, in long-run equilibrium the skilled labour force adjusts to reinstate the initial skilled real wage and unemployment rates. The outcomes are given in columns 5 and 6 in Table 1. In the case of the skilled-augmenting technical change, ESK, skill immigration generates an expansion of the skilled labour force in response to the higher skilled wage and lower unemployment rate. This continues until the real skilled wage is brought back to its base-year value, which in this case has a substantial impact on the labour market. With no migration, the long-run real and nominal skilled wages increase by 1.47% and 0.57% respectively. Once skilled migration is allowed these figure transform to a 0% change in the real, and a 1.44% fall in the nominal, wage. This has two important implications; the substitution effect towards the skilled and away from the unskilled is reinforced and the competitiveness of the economy is increased. The CPI now falls by −1.44%, exports increase by 3.83% and GDP by 4.41%. However, whilst allowing skilled migration generates an employment and real wage gain for the unskilled, this is still relatively limited.

The effect of allowing skilled migration is quite different where the efficiency increase applies to the unskilled. Recall that with this simulation, the zero migration long-run equilibrium produced a small fall in skilled employment and real wage. When allowed, this generates skilled out-migration which eliminates the cut in the skilled real wage and reduces the fall in the skilled nominal wage. This has negative competitive effects. As compared to the zero-migration increase in unskilled efficiency, the reduction in CPI is less and the increases in GDP, exports, investment, total employment, and household consumption are smaller. Although there is greater substitution of unskilled workers for skilled, unskilled employment and real wages are slightly lower than with the fixed labour force.

Finally, we consider the long-run equilibrium where flow equilibrium migration occurs for both skill-types, as in equations (12) and (14). Essentially this means that the real wage for both skilled and unskilled workers now remain at their base-year values. As compared to the long-run skilled migration simulation results, for both ESK and EUN aggregate economic activity is boosted. GDP and total employment increase and these are the highest values recorded in any of the simulations reported here. However, note that the change in skilled employment is slightly lower than where only skilled migration occurs because of the greater substitution towards unskilled. For the skilled efficiency shock skilled employment now increases by 3.35% and for the unskilled shock the skilled employment falls by 0.73%, its largest amount.

With labour-augmenting technical progress we observe the substitution of labour, as measured in efficiency units, for capital, measured in natural units. However, in these simulations the elasticity of substitution between capital and labour is low; the two inputs are complements.

Production therefore always becomes more capital intensive in that capital per employee and the share of capital in value-added increase.[24] This illustrates a point made in the introduction; although there has been no change in the efficiency of capital, these labour-augmenting shocks are accompanied by both short- and long-run increases in investment and capital intensity. It is easy to misconstrue causality here and view the increased investment as the cause, rather than the effect, of the improved efficiency.

5.2. The time path of employment and real wage change

When we consider labour-augmenting efficiency improvements the initial aggregate employment effect is always negative. Recall that the skill group whose efficiency has been increased shows a small positive or negative change (0.03%, −0.08%) but employment in the other skill group suffers a much larger fall (−0.48%, −0.45%). In the long run, total employment always increases, independently of our assumptions concerning migration, but it is useful to see in more detail how employment in the different skill groups evolve over time as investment and, in some cases, the size of work force adjusts to reach the long-run equilibrium figures.

Fig. 3a, b and c show the skill-disaggregated time paths for the two efficiency shocks and the three migration options used in Table 1.[25] The dashed and solid lines represent the results for the skill- and unskilled-augmenting efficiency shocks respectively. As stated earlier, given that the relevant relationships are parameterised on annual data each period is interpreted as a year.

For the skilled-augmenting case, ESK, skilled employment increases above the initial level after period 2, but unskilled employment remains below its initial level for between 5 and 12 years, depending on the migration assumption. The adjustment is slowest where there is free migration because there is initially outmigration for the unskilled before the increase in capacity increases the composite demand for labour.

With the increase in efficiency of the unskilled, EUN, the change in unskilled employment is positive in all periods and rises over time. However, skilled employment is negative in period 1 and never get back to the base-year level. With no migration, there is some mitigation of the initial reduction in skilled employment, reflecting the impact of the adjustment to the reduction in the real wage. But in the simulations incorporating skilled migration, skilled employment falls further, until period 5, and then stabilises at this lower level.

In the simulations with no migration, the skill-disaggregated real wage rates simply track the corresponding changes in employment; an increase/fall in employment is accompanied by an increase/fall in the real wage. With migration, the real-wage change is rather more complex, as shown in Fig. 3d which shows the time paths in the full migration results. With the increase in skilled efficiency, ESK, the real wage remains above its initial value for long periods for both skill groups, even though it is restored in the long run. With the EUN this is true for the unskilled, but the skilled real wage stays below its base year value for the whole time, asymptotically approaching the long-run, zero-change value from below.

If instead of a step increase, the efficiency improvement is introduced in a gradual manner, similar long-run results occur but with different adjustment paths. For example, if the efficiency changes are spread across 10 periods, any initial fall in employment is less pronounced but is distributed over a longer time span. Negative effects are thereby prolonged but are less severe as compared to those where labour efficiency is increased abruptly.

[24] This reflects the model assumption that labour and capital are complements with a substitution elasticity equal to 0.3.

[25] The period 1 results are the short-run outcomes shown in the first two columns of Table 1.

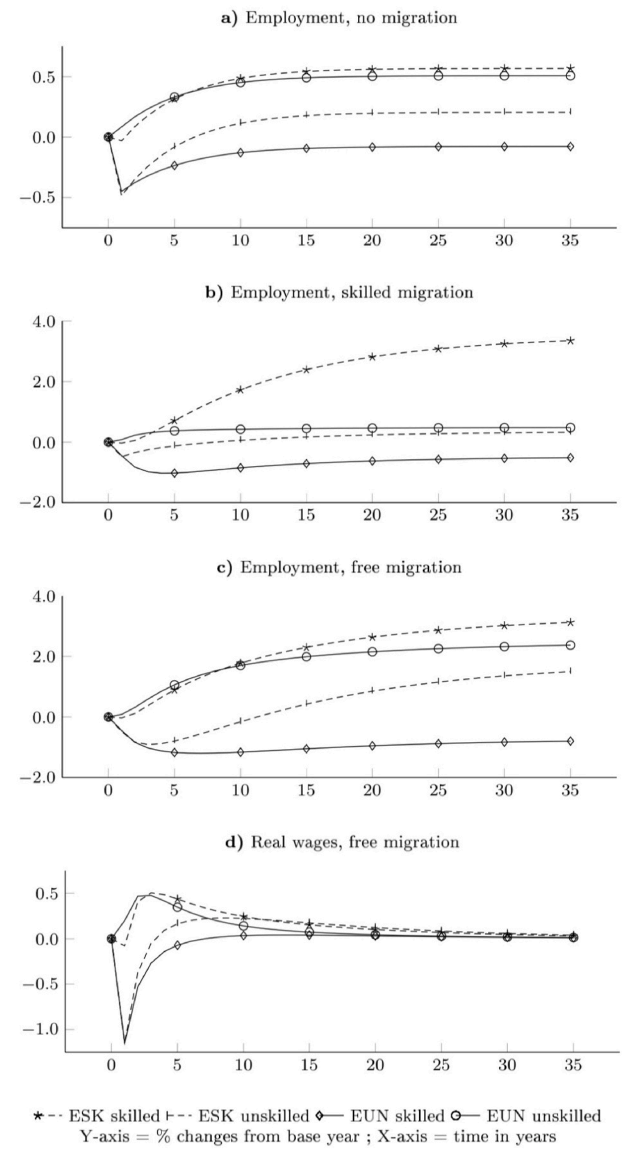

Fig. 3. Aggregate transition paths of employment and real wages of a 3.5% increase in skill-differentiated labour efficiency. Values are % changes from base.

5.3. Openness to trade

The results in Section 5.1 indicate the way in which the efficiency impacts are affected by the openness of the labour market. In this section, we want similarly to quantify the sensitivity of the simulation results to changes in the economy's openness to trade and additionally to see how that interacts with labour market openness.

Fig. 4 summarises the impact of the 3.5% increases in skilled, ESK, and unskilled, EUN, augmenting labour efficiencies on long-run GDP (Fig. 4a), and skilled and unskilled employment outcomes (Fig. 4b and c) for different values of the Armington trade elasticities, θ_V, for imports and exports. The elasticity values used are: 0.7, 1.7, 2.7 and 3.7. The higher the elasticity the more open the economy is to trade with 2.7 the DEMACRO model default value used in generating the results reported in Table 1 and Fig. 3. Figures in the first two columns in Fig. 4 are given for no migration, columns three and four for skilled migration and the final two columns for full migration.

As the trade elasticities increase within this range the system becomes more sensitive to the positive competitiveness changes due to the fall in prices arising from the increased efficiency. This affects both

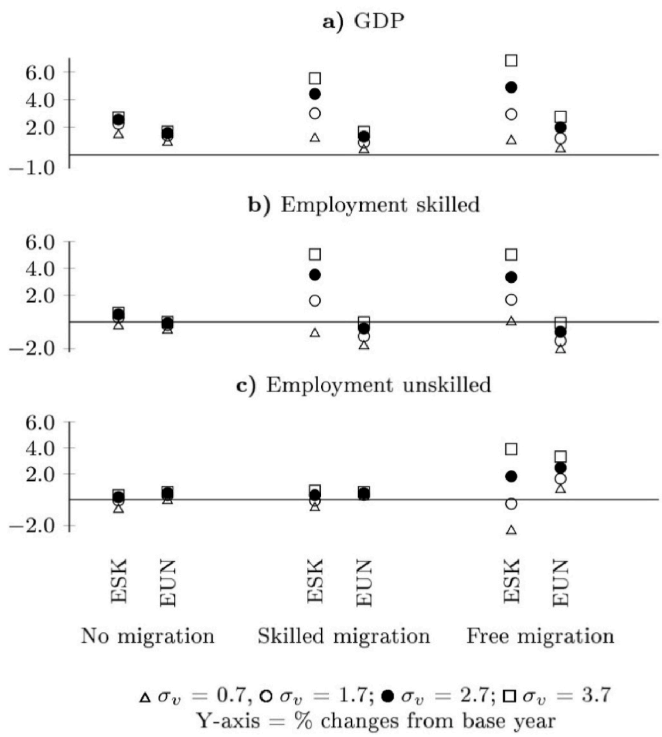

Fig. 4. Long-run effects of a 3.5% increase in skill-neutral and skill-differentiated labour efficiency and changes to the Armington trade elasticity. Values are % changes from base.

export demand and import substitution. For all the variables reported here, in each simulation, the ordering of effects is positively related to the elasticity values, so that the lowest value is where $\theta_V = 0.7$ and the highest where $\theta_V = 3.7$. Also, the range of values generally increases with the degree of migration.

An important issue is the appearance or amplification of negative employment impacts where trade elasticities are reduced. Skilled employment is particularly affected. Where $\theta_V = 0.7$, skilled employment falls for all forms of labour augmenting technical change and with all the labour market options here. The situation with unskilled workers is less extreme but negative impacts are now registered with low trade elasticities and skilled-augmenting technical change. These negative values are increased when migration is introduced. Where economies are small and closely integrated with the neighbours, we would expect these elasticities to be high, which would be appropriate for small European states and regions. However, larger, more self-sufficient economies would be expected to be less open to trade and face lower trade elasticities.

6. Summary and conclusions

It is common to characterise technical change as occurring in waves which affect many sectors of the economy simultaneously, with positive system-wide implications for competitiveness and growth. However, discussion over these technological advances has often exhibited concern over the possible negative labour market effects. In this paper we focus particularly on the skill-specific impacts of different forms of economy-wide labour augmenting technical change. In partial equilibrium analysis, where labour augmenting efficiency improvements apply to one single sector with a passive labour market, we show that any combination of skilled or unskilled employment increase or decrease can occur, depending on the values of key substitution parameters. Our empirical CGE simulations reveal that similar results apply more generally where the labour market is more active and technical change takes place across all sectors. Note that these standard simulations do not give catastrophic outcomes for even widespread adoption of new technology. Rather, clear common principles apply that can underpin both the analysis and subsequent policy prescriptions.

The modelling approach we take has several strengths. Firstly, it is firmly based in standard economic theory, allowing us to provide causal interpretations for the numerical results. This aspect is crucial in ensuring the reliability of our analysis. Secondly, the use of CGE modelling serves as a numerical aid to analytical thought, enabling us to investigate the impact of potential future events and novel government policies.[26] The model framework acts as a test-bed for studying how the economy will respond to changes in specific parameters or exogenous variables while holding all other characteristics constant. This controlled experimentation allows for a comprehensive understanding of the system dynamics. Additionally, conducting sensitivity analysis is particularly straightforward within this modelling framework, enabling us to explore the robustness and sensitivity of our results to changes in key parameters.

However, there are also weaknesses in the model that should be acknowledged. Firstly, the model relies on a large number of parameters, some of which may be difficult to quantify. This implies that the central (default) results presented, such as those in Table 1, should be interpreted more as scenarios rather than precise predictions. Secondly, it is important to note that the default results are derived from a model parameterized on the economic structure of Germany, which is a developed large open European economy with skill-intensive exports. While we would expect the qualitative central system-wide results to be similar for economies with comparable structures, it is likely that economies with less open product and labour markets, lower skill-intensive exports, and a slower speed of adjustment will experience different impacts at the system-wide level.

The simulation results suggest that for an economy open to trade and where skilled and unskilled labour are substitutes, labour augmenting technical change will ultimately increase aggregate employment but not necessarily for all skill groups. In the skill category that receives the efficiency gain, employment is essentially initially unchanged but increases over time as capacity and the labour force adjust. However, for the skill-type whose efficiency remains constant the situation is less clear cut.

In the simulations where skilled, rather than unskilled, labour receives the efficiency improvement the overall employment effects are better. Although unskilled employment initially falls and remains below its initial level for some time, the long-run impacts are positive for both skilled and unskilled and the impact on total employment is always greater. In our simulations, for technical improvements which increase the efficiency of the unskilled, employment for skilled workers falls and never regains its initial value. The decline in skilled employment is particularly strong where skilled workers out-migrate. Moreover, the impact of labour augmenting technical change in general will be less positive where the economy is less open to trade. This might explain the focus in the US literature on possible negative labour market effects.

The model does not allow workers to transfer between skill groups through, for example, education or training. But the possibility of such movement reinforces the asymmetry between skilled and unskilled augmenting technical change. With skilled augmenting technical progress, the expansion of skilled jobs would provide an increased incentive for unskilled workers to retrain, earning a higher, skilled, wage. The fall in the supply of unskilled labour will also improve the wages of those who do not retrain. In this sense, over time there is a widespread benefit across the whole labour market. However, with technical change that solely improves the efficiency of the unskilled, the fall in skilled employment will force some skilled workers to compete with unskilled

[26] The specific framework adopted in this paper has been extensively applied to a wide range of policy-relevant analyses, as noted in the text and reflected in the references.

workers for unskilled jobs. This is a troubling outcome, likely to meet strong worker resistance.[27]

The analysis emphasises the importance of being able to identify the underlying nature of the technical change. However, this is not straightforward, either *ex ante* or *ex post,* because of the interaction of the direct, substitution and output/income effects of generalised technical change. Also note that we have here dealt with separate instances of technical change of one specific skill-augmenting type. However, technical change is likely to augment the efficiency of all inputs to different degrees, so the outcome will be a combination of these. This adds to the difficulty in reaching consensus in the current literature on the system-wide effects of technical change.

Our analysis emphasises that, at least in the short to medium runs, there may be pressure on the Government to counteract negative effects experienced in the labour market. However, the labour augmenting technical change generates additional government revenues. Thus, there is the potential for intertemporal smoothing of effects through policy action by increasing government expenditures to counteract the employment and wage effects.

It would be instructive to develop our work in various ways. To begin, we deal here only with labour-augmenting technical change. There would be value in extending the analysis to other kinds of technical change, though labour-augmenting is the only form compatible with steady-state growth. Second, in the present analysis efficiency improvements are entirely exogenous. These could be partly endogenized, through learning by doing for example. Third, it may be useful to extend the skill disaggregation to three (or more) subgroups to identify the potential hollowing out of the labour market that has been noted in the literature though, as we note in the text, this would require more econometric parameterisation. Fourth, a natural development would be to endogenize training and education as an investment in human capital. Finally, it would be interesting to examine technological change in the context of a complete interregional model of the EU and beyond, so that we could examine the likely impact of potential spatial spill overs.

CRediT authorship contribution statement

Andrew G. Ross: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Peter G. McGregor:** Investigation, Writing – review & editing, Conceptualization, Formal analysis, Methodology, Writing – original draft. **J Kim Swales:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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[27] For example, the classic Luddite rebellion of Nottingham weavers in the early nineteenth century was against technical change with this unskilled-augmenting character, where skilled workers were replaced by the lower-wage unskilled [6,62].

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