Decomposing Structural Change*

Jaime Alonso-Carrera [a]
Departamento de Fundamentos del Análisis Económico
Universidade de Vigo

María Jesús Freire-Serén [b]
Departamento de Fundamentos del Análisis Económico and GRiEE
Universidade de Vigo

Xavier Raurich [c]
Departament d'Economia
Universitat de Barcelona

May 3, 2024

*Financial support from the Government of Spain and FEDER through grants PID2021-126549NB-I00 and PID2021-124015NB-I00 is gratefully acknowledged. This paper has benefited from comments by the participants in the Workshop on Structural Change and Economic Growth at University of Barcelona, III Navarre-Basque Country Macroeconomic Workshop, Annual Meeting of the Association for Public Economic Theory, DEGIT XXII, XI Workshop on Public Policy Design at University of Girona, SAEe 2018 and seminar at ESADE, Universitat Autònoma de Barcelona, Universidad de Santiago de Compostela, Universitat de les Illes Balears and Católica Lisbon Economic and Bussines.

[a] Postal address: Universidade de Vigo, Facultad de Ciencias Económicas y Empresariales, Campus As Lagoas-Marcosende, 36310 Vigo (Spain). Phone: (34)986813516. E-mail: jalonso@uvigo.es

[b] Postal address: Universidade de Vigo, Facultad de Ciencias Económicas y Empresariales, Campus As Lagoas-Marcosende, 36310 Vigo (Spain). Phone: (34)986812524. E-mail: mjfreire@uvigo.es

[c] Postal address: Universitat de Barcelona, Facultat d'Economia i Empresa, Avinguda Diagonal 696, 08034 Barcelona (Spain). Phone: (34)934024333. E-mail: xavier.raurich@ub.edu

Abstract

We identify the mechanisms governing the propagation of technological shocks to the sectoral allocation of labor in a non-parameterized growth model. These propagation mechanisms are: (i) the change in aggregate income; whose effect on sectoral composition depends on the income elasticities of consumption demand; (ii) the change in the relative prices of consumption goods, which alters the sectoral composition depending on the Allen-Uzawa elasticities of substitution between goods; (iii) the change in the rental rates, whose effect on sectoral composition is determined by the sectoral elasticities of substitution between capital and labor; and, (iv) the direct effect of the sector and factor bias of the technological change. From this analysis, we derive an accounting method to measure the contribution of these propagation mechanisms to structural change in parameterized growth models. By using some well-known parameterizations, we account for the contribution of each mechanism to the U.S. structural change in the period 1948-2010.

JEL classification codes: O11, O41, O47.

Keywords: structural change; non-homothetic preferences; sectoral productivity.

1. Introduction

The process of economic development exhibits structural change as one of the most clear-cut features. Developed countries have experienced a secular shift in their allocation of economic activity across sectors. Figure 1 shows evidence of this long-run trend in the U.S. economy. We observe that the production valued added, employment and expenditure on consumption valued added have continuously shifted from agriculture and manufactures to services from 1948 to 2010.

Figure 2 shows the dynamic path followed by total factor productivity (henceforth, TFP) indexes, relative prices, and the ratio between rental rates of labor and capital in these three sectors. We easily observe that the relative price of agriculture in terms of manufactures has decreased substantially, whereas the relative price of services has increased during the sample period. Furthermore, the dynamic behavior of the other two magnitudes also clearly differs across the three sectors. Especially, we must emphasize that the accumulated growth rate of TFP, computed as the Solow residual from KLEMS 2013 data, has been much larger in agriculture than in manufacturing and services. The changes in the variables displayed in Figure 2 together with the growth of income are the mechanisms that, according to the literature, drive the patterns of structural change shown in Figure 1.[1] Our objective is to provide a method to measure the contribution of these mechanisms to the process of structural change.

[Insert Figures 1 and 2]

The literature has identified four propagation mechanisms in a closed economy. A first mechanism, which we denote as the income mechanism, is the reallocation of consumption expenditure from goods with low income-elasticity of demand towards those with high income-elasticity driven by rising income. Second, any variation in the relative prices of goods also alters the sectoral composition of consumption demand in a manner that depends on the consumer's substitution elasticities between goods. We denote this mechanism the demand substitution mechanism. Third, there is a technological substitution mechanism driven by changes in the rental rates of inputs that affect the sectoral composition depending on the sectoral differences in capital intensities and in the substitution elasticities between capital and labor. Finally, apart from the indirect effect through income and prices, the sectoral processes of technological change also directly drives structural change by altering: (a) the relative productivity of each sector; and, (b) the optimal capital to labor ratio.[2] We denote this direct effect as the technological change mechanism.

Accounting for the contribution of these mechanisms in explaining the observed structural change is a necessary step to build empirically plausible multisector growth models. As is explained below, some applied studies have separately assessed the relevance of the aforementioned mechanisms by calibrating and simulating parameterized models that incorporate an incomplete set of these mechanisms. We contribute to this literature by providing an accounting method of the propagation

[1] See, for example, Herrendorf et al. (2014) for an extensive review of the literature on sectoral structural change.

[2] Technological change causes income growth and modifies prices. Therefore, it also affects structural change indirectly through the other mechanisms.

mechanisms in a closed economy. In contrast with previous studies, in this paper, we use a generic framework, i.e., a model with the minimum set of assumptions and where preferences and technologies are not parameterized, which allows for a complete characterization of the propagation mechanisms. We show that the contribution of these mechanisms to structural change depends on the following variables describing preferences and technologies: (i) the income elasticities of the demand for consumption goods; (ii) the Allen-Uzawa elasticities of substitution between consumption goods; (iii) the capital income shares in sectoral outputs; (iv) the elasticity of substitution between capital and labor in each sector; (v) the sectoral bias of the neutral component of technological change; and (vi) the degree of factor-bias in the sectoral technological change.

As an empirical illustration of our accounting approach, we consider Stone-Geary preferences and sectoral CES production functions to account for the contribution of the different mechanisms in explaining U.S. structural change. The use of these particular functional forms for preferences and technologies has two advantages. On the one hand, they are largely used in the literature on structural change because they are quite flexible. On the other hand, Herrendorf et al. (2013) and Herrendorf et al. (2015) have, respectively, estimated the parameters of these preferences and technologies for the US economy. We use these estimations to compute the associated elasticities of consumption demand, the sectoral elasticities of substitution between labor and capital, and the rates of capital and labor-augmenting technological change. We then measure the contribution of the propagation mechanisms to the observed growth of sectoral employment shares in the US economy from 1948 to 2010.

We show that the four propagation mechanisms have substantially contributed to the dynamics of sectoral employment shares in the US economy. However, they have worked in different directions, that is, in each sector, some mechanisms had an attractive effect on employment and others contribute to drive away employment. Obviously, the observed structural change in employment is the result of the balance between these opposite effects. We conclude that the dynamics of employment out of agriculture is mainly driven by the two aforementioned technological mechanisms, whereas the reallocation of employment from manufacturing to services is channeled mainly through the income mechanism.

In the accounting exercise, we obtain income, prices and rental rates directly from the data. As a result, we only consider the direct effect of technological progress on structural change, which we denote as the technological change mechanism. However, technological progress increases income and changes both prices and rental rates. As a result, technological progress affects indirectly structural change through the other three mechanisms. In the last part of the paper, we simulate the competitive equilibrium path to disentangle the contribution of the different mechanisms to structural change under different technological processes when income, prices and rental rates are determined in equilibrium. In particular, we compare three economies that exhibit the same sectoral composition but different technological progress: with and without sectoral and factor bias. We obtain that the contribution of the propagation mechanisms to sectoral composition is very different in each economy even when they exhibit the same process of structural change. This result is the consequence of the fact that the paths of income, prices and rental rates substantially differ across these economies because of the differences in the technological progress.

This paper is related to three different strands of the literature on structural change. First, it is related to those papers that propose alternative mechanisms through which structural shocks may alter the sectoral composition of the economy. Within this literature, we distinguish those papers that consider sectoral differences in income elasticities of the consumption demand as a driver of structural change. This mechanism has been studied by, among others, Echevarria (1997), Laitner (2000), Kongsamut et al. (2001), Caselli and Coleman (2001), Foellmi and Zweimüller (2008), Boppart (2014), Comin et al. (2021) or Alder et al. (2021). Alternatively, Ngai and Pissarides (2007) formalize the original idea of Baumol (1967) to explain structural change as a consequence of a sectoral-biased process of technological change that changes relative prices of goods. Another group of papers demonstrates that the substitution effects associated to changes in rental rates may drive structural change if sectors differ in their technological features. Acemoglu and Guerrieri (2008) prove that the process of capital deepening associated to economic growth may also generate structural change if the sectoral production functions exhibit different capital intensities. In addition, Alvarez-Cuadrado et al. (2017) point out that the sectoral differences in the capital-labor substitution may also be a mechanism of structural change. All these theoretical studies in this first strand of the literature highlight how a single propagation mechanism of structural change operates. Our general expression for structural change nests all these mechanisms and, as a result, we can account for their relative contribution to the observed structural change.[3]

A second strand of the literature estimates preferences and technologies that exhibit the features making the previous mechanisms operative. Herrendorf et al. (2013) estimates the preferences parameters from the expression of expenditure shares resulting from considering Stone-Geary preferences. Comin et al. (2021) and Alder et al. (2020) estimate the parameters of two classes of preferences that, contrary to the Stone-Geary preferences, allow for sustained differences between income elasticities of different consumption goods even when income is growing. Regarding sectoral technologies, Herrendorf et al. (2015) estimate the sectoral elasticities of substitution between capital and labor, and the sectoral rates of capital-augmenting and labor-augmenting process of technological change, associated to a CES production function. Finally, Valentinyi and Herrendorf (2008) measure the sectoral income shares of capital and labor for the US economy, and they find significant differences across sectors. We use these estimations to perform the accounting exercise in this paper.

A final strand of the literature studies the contribution of the aforementioned mechanisms in explaining the observed structural change. Examples of this literature are Dennis and Iscan (2009), Buera and Kaboski (2009), Moro et al. (2017), Swiecki (2017), Humber (2021), García-Santana et al. (2021), and Comin et al. (2021). These papers obtain very different conclusions on the contribution of the different mechanisms.

[3] Recently, Garcia-Santana et al. (2021) proposed another novel mechanism of structural change. They argue that the dynamics of the investment rate may alter the sectoral configuration if consumption and investment differ in their sectoral composition. Our theoretical framework does not actually consider final consumption and investment as two differentiate composite goods. However, this framework can be modified to account for structural change driven by the dynamics of the investment rate.

These different results are due to the fact that these studies only consider a subset of the mechanisms driving structural change. Our general framework overcomes this limitation. More importantly, this literature studies the contribution of a particular mechanism by analyzing the changes in the sectoral composition that result from eliminating it from the set of mechanisms considered in the model. This elimination of a mechanism is achieved by modifying preferences or technologies. However, this procedure is not an accounting exercise that measures the contribution of each mechanism, since it is based on the comparison between models that differ in preferences or technologies and, therefore, the equilibrium of these models presents different trajectories of prices, rental rates and incomes. Instead, in this paper we introduce an accounting procedure that allows us to account for the relative contribution of all mechanisms in the propagation to structural change of different shocks.

The rest of the paper is organized as follows. Section 2 presents the theoretical framework used in the analysis. Section 3 derives the growth rates of the sectoral employment shares, and it characterizes the mechanisms driving structural change in this general setting. Section 4 quantifies the contribution of these mechanisms to the structural change observed in the US data. Section 5 simulates the general equilibrium response of income, prices and rental rates to variations in the rates of technological change to disentangle the different mechanisms trough which technological progress affects the sectoral composition. Section 6 includes some concluding remarks.

2. Theoretical framework

We consider a continuous time, closed economy composed of m productive sectors. We interpret sectoral production functions in value-added form. We identify the m sector as the one producing manufactures that can be devoted to either consumption or investment, whereas the other $m-1$ sectors produce pure consumption goods. We denote by p_i the price of goods produced by sector i.

Firms in each sector i operate under perfect competition by using the following sector-dependent production function:[4]

$$Y_i = A_i F^i \left(B_i z_i K, u_i L \right), \tag{2.1}$$

where Y_i is the output produced in sector i; z_i is the share of total capital, K, employed in sector i; u_i is the share of total employment, L, in sector i; and A_i and B_i are the processes of neutral and capital-augmenting technological change in sector i, respectively. Observe that B_i then stands for the factor imbalance of technological change. We denote by γ_i^a and γ_i^b the sectoral-specific growth rates of A_i and B_i. These growth rates can be time-varying and different across sectors.

We assume that the sectoral production functions are increasing in both capital and labor, they exhibit decreasing returns in each of these two arguments, and they are linearly homogenous in both private inputs. We can then express sectoral production in units of labor as

$$y_i = A_i f_i \left(B_i k_i \right), \tag{2.2}$$

[4]For the sake of simplicity, time subindexes are only introduced when necessary to clarify the exposition.

where $y_i = Y_i/u_iL$ is the output per unit of labor in sector i, and $k_i = z_iK/u_iL$ measures capital intensity in sector i. Given the properties of the sectoral production functions, we deduce that $f_i' > 0$ and $f_i'' < 0$.

Finally, the assumptions of competitive factor markets and full input utilization imply that each production factor is paid according to its marginal productivity. Hence, the following conditions hold:

$$r_i = p_iA_iB_if_i'(B_ik_i), \tag{2.3}$$

and

$$w_i = p_iA_i\left[f_i(B_ik_i) - f_i'(B_ik_i)B_ik_i\right], \tag{2.4}$$

where r_i and w_i are the rental rates of capital and labor in sector i, respectively. These rental rates can differ across sectors. This may be the case, for instance, if there exist some costs of moving production factors across sectors or intersectoral distortions and frictions (see, e.g., Caselli and Colleman, 2001; Buera and Kaboski, 2009; Sweicki, 2013; or Alonso-Carrera and Raurich, 2018).[5] We denote by $\omega_i = w_i/r_i$ the rental rate ratio in sector i. By combining (2.3) and (2.4), we conclude that the capital-labor ratio k_i is an implicit function of the rental rate ratio ω_i and of the factor imbalance B_i of technological progress, with

$$\frac{\partial k_i}{\partial \omega_i} = -\frac{[f_i'(B_ik_i)]^2}{f_i(B_ik_i)f_i''(B_ik_i)} > 0,$$

and

$$\frac{\partial k_i}{\partial B_i} = \frac{B_ik_i[f_i'(B_ik_i)]^2 - f_i(B_ik_i)\left[f_i'(B_ik_i) + B_ik_if_i''(B_ik_i)\right]}{B_i^2f_i(B_ik_i)f_i''(B_ik_i)},$$

which follows from the properties of sectoral production functions.

For our analysis, it will also be useful to introduce the following variables describing the features of sectoral technologies and, therefore, of capital and labor demands: (i) the share of capital income in output from sector i, that we denote by α_i; (ii) the elasticity of marginal productivity of labor with respect to capital, that we denote by β_i; (iii) the elasticity of substitution between capital and labor in sector i, that we denote by π_i; and (iv) the elasticities of capital-labor ratio with respect to the factor imbalance of technological progress B_i in sector i, that we denote by λ_i. By using (2.2), (2.3) and (2.4), we obtain, after some simple algebra, that

$$\alpha_i \equiv \frac{r_ik_i}{p_iy_i} = \frac{B_ik_if_i'(B_ik_i)}{f_i(B_ik_i)}, \tag{2.5}$$

$$\beta_i \equiv \left(\frac{\partial w_i}{\partial k_i}\right)\left(\frac{k_i}{w_i}\right) = -\frac{(B_ik_i)^2f_i''(B_ik_i)}{f_i(B_ik_i) - B_ik_if_i'(B_ik_i)}, \tag{2.6}$$

$$\pi_i \equiv \left(\frac{\partial k_i}{\partial \omega_i}\right)\left(\frac{\omega_i}{k_i}\right) = \frac{\alpha_i}{\beta_i}, \tag{2.7}$$

[5] Differences in rental rates across sectors could also arise if the production factors are heterogenous, in the sense that sectors use different types of capital and labor (see, e.g., Caselli and Coleman, 2001; Herrendorf and Schoellman, 2018; or Herrendorf et al., 2019).

and

$$\lambda_i \equiv \left(\frac{\partial k_i}{\partial B_i}\right)\left(\frac{B_i}{k_i}\right) = \pi_i - 1. \tag{2.8}$$

Observe that the elasticity λ_i determines the factor bias of the technological change in sector i, i.e., it informs about the effects of this change on capital deepening. In particular, the factor bias of technological progress is given by $\lambda_i \gamma_i^b$, so that this progress is capital biased if $\lambda_i \gamma_i^b > 0$.

This economy is populated by N identical individuals. Population grows at the (possibly time-varying) rate n. In each period, each individual is endowed with l hours of time that inelastically supplies in the labor market, so that the total household's labor supply is $L = lN$.[6] Each individual derives utility from the consumption of m goods. To be consistent with the value-added approach followed in the production-side, we interpret the commodities in the utility function as the value-added components of final consumption. We consider time-additively separable preferences, where the utility function at any period t depends on the consumption levels of the m goods at this period. We denote this instantaneous utility function by $v(c_1, ..., c_m)$, which is increasing in each of its arguments and quasiconcave. Given per capita consumption expenditure, e, each individual maximizes the utility v subject to

$$e_t = \sum\nolimits_{i=1}^{m} p_{it} c_{it} \tag{2.9}$$

and a non-negativity constraint on the choice variables.

The solution of this problem characterizes the demands of consumption goods as a function of per capita expenditure e and the vector of prices $p = (p_1, ..., p_m)$. We denote by $c_i = C^i(p, e)$ the Marshallian consumption demand for the good produced in sector i. Since we are only interested in the sectoral composition of consumption expenditure, we only need to characterize the properties of the temporal functions of consumption demand $c_i = C^i(p, e)$. Therefore, we abstract from the intertemporal decisions by just focusing on a sequence of static problems for any path of expenditure and prices. This implies that our analysis is consistent with any model of intertemporal decisions.

The features of the demand functions are summarized by the price and income elasticities of those demand functions. Let μ_i and η_{ij} denote the income elasticity of demand of good i and the elasticity of this demand with respect to the price of good j, respectively. In an online appendix, we state the properties that these elasticities satisfy.

3. Sectoral composition of employment

We next characterize the dynamics of the sectoral employment shares u_i. To this end, we use the clearing condition in the markets of the pure consumption goods, which is given by

$$c_i \equiv C^i(p, e) = \frac{u_i A_i L f^i(B_i k_i)}{N}, \tag{3.1}$$

[6] In the present analysis we consider that labor supply is exogenous and the goods can only be adquired through markets. However, our analysis is easily extended to incorporate both endogenous labor supply and home production.

for $i \neq m$. Log-differentiating with respect to time this condition, taking into account that capital-labor ratio k_i is a function of rental rate ratio ω_i and of capital-augmenting technological progress B_i, and using the definitions of η_{ij}, μ_i, α_i, λ_i and π_i given in the previous section, we obtain, after some algebra, that

$$\frac{\dot{u}_i}{u_i} = \mu_i \left(\frac{\dot{e}}{e}\right) + \sum_{j=1}^{m} \eta_{ij} \left(\frac{\dot{p}_j}{p_j}\right) - \alpha_i \pi_i \left(\frac{\dot{\omega}_i}{\omega_i}\right) - \left(\gamma_i^a + \alpha_i \pi_i \gamma_i^b\right) - \frac{\dot{l}}{l}, \tag{3.2}$$

for $i \neq m$. Given the clearing condition for the labor market $\sum_{j=1}^{m} u_j = 1$, we also obtain the growth rate of the employment share in the manufacturing sector as

$$\frac{\dot{u}_m}{u_m} = -\sum\nolimits_{i \neq m} \left(\frac{u_i}{u_m}\right) \left(\frac{\dot{u}_i}{u_i}\right). \tag{3.3}$$

A shock altering prices affects employment shares by changing the terms of trade between sectors and the purchasing power of income. We next proceed to decompose the price effect into the substitution effect and the income effect. To this end, in the online appendix we use the Slutsky equation to show that the price-elasticities of the Marshallian demand are given by

$$\eta_{ij} = x_j \left(\sigma_{ij} - \mu_i\right), \tag{3.4}$$

where x_j is the expenditure share of the good produced in sector i, i.e., $x_j = p_j c_j / e$; and σ_{ij} is the Allen-Uzawa partial elasticity of substitution, which measures the net substitutability between consumption goods i and j. Therefore, we can rewrite the growth rate of the sectoral employment share u_i for $i \neq m$, given by (3.2), as follows:

$$\frac{\dot{u}_i}{u_i} = \left\{ \begin{array}{l} \mu_i \left[\frac{\dot{e}}{e} - \sum_{j=1}^{m} x_j \left(\frac{\dot{p}_j}{p_j}\right)\right] + \sum_{j=1}^{m} \sigma_{ij} x_j \left(\frac{\dot{p}_j}{p_j}\right) \\ \\ -\alpha_i \pi_i \left(\frac{\dot{\omega}_i}{\omega_i}\right) - \left(\gamma_i^a + \alpha_i \pi_i \gamma_i^b\right) - \frac{\dot{l}}{l} \end{array} \right\}. \tag{3.5}$$

By using this growth rate, we can also directly obtain the change in the composition of employment between any two sectors i and j other than sector m as

$$\Delta_{ij} \equiv \frac{\dot{u}_i}{u_i} - \frac{\dot{u}_j}{u_j} = \left\{ \begin{array}{l} \left(\mu_i - \mu_j\right) \left[\frac{\dot{e}}{e} - \sum_{l=1}^{m} x_l \left(\frac{\dot{p}_l}{p_l}\right)\right] \\ \\ + \sum_{l=1}^{m} \left(\sigma_{il} - \sigma_{jl}\right) x_l \left(\frac{\dot{p}_l}{p_l}\right) \\ \\ - \left[\alpha_i \pi_i \left(\frac{\dot{\omega}_i}{\omega_i}\right) - \alpha_j \pi_j \left(\frac{\dot{\omega}_j}{\omega_j}\right)\right] \\ \\ - \left(\gamma_i^a - \gamma_j^a + \alpha_i \pi_i \gamma_i^b - \alpha_j \pi_j \gamma_j^b\right) \end{array} \right\}. \tag{3.6}$$

From (3.5) and (3.6), we distinguish the following four mechanisms that propagate the effects of any exogenous shock to the sectoral composition of employment:

1. *Income mechanism.* It measures the variation in the sectoral composition of employment derived from the dynamics of real expenditure. It is given by the following term of (3.5):

$$E_i^I = \mu_i \left[\frac{\dot{e}}{e} - \sum_{j=1}^{m} x_j \left(\frac{\dot{p}_j}{p_j} \right) \right]. \tag{3.7}$$

   This income mechanism decomposes into the effect from changes in the nominal expenditure (i.e., the *Marshallian's income effect*), and the effect from the variation in prices (i.e., the *Hicks' income effect*). Note that the magnitude of the income mechanism clearly depends on the income elasticity of the demand of good i. Hence, as shown in (3.6), this mechanism will modify the sectoral composition if and only if the income-elasticities of demand differ across sectors. Therefore, this mechanism requires preferences to be non-homothetic to generate the necessary gaps between the sectoral income elasticities.

2. *Demand Substitution mechanism.* It measures the variation in the sectoral composition of employment derived from variations in relative prices. This mechanism is given by the following term of (3.5):

$$E_i^{DS} = \sum_{j=1}^{m} \sigma_{ij} x_j \left(\frac{\dot{p}_j}{p_j} \right). \tag{3.8}$$

   The contribution of this mechanism to the change in the employment share of sector i depends on: (a) the Allen-Uzawa elasticities of demand of good i with respect to the vector of sectoral prices; and (b) the expenditure share of the good whose price is being considered. As follows from (3.6), this mechanism will generate changes in the sectoral composition of employment between two sectors i and j if and only if they exhibit different Allen-Uzawa elasticities of substitution with the other goods, i.e., $\sigma_{il} \neq \sigma_{jl}$ for $l \neq \{i, j\}$.

3. *Technological Substitution mechanism.* It measures the variation in the sectoral composition of employment due to changes in the sectoral capital intensities, k_i, caused by the change in the sectoral rental rate ratios. This mechanism is given by the following term of (3.5):

$$E_i^{TS} = -\alpha_i \pi_i \left(\frac{\dot{\omega}_i}{\omega_i} \right). \tag{3.9}$$

   The magnitude of this third mechanism depends on both the share of capital income in output and on the elasticity of substitution between capital and labor in sector i. Therefore, the change in the sectoral composition of employment across sectors driven by this mechanism will derive from the difference between the variation in the rental rate ratios across sectors weighted by the share of capital income in output and by the elasticity of substitution between capital and labor.

4. *Technological Change mechanism.* It measures the contribution to structural change of the sector-specific technological progress. This mechanism is given by the following term of (3.5):

$$E_i^{TC} = -\frac{\dot{T}_i}{T_i} \equiv -\gamma_i^a - \alpha_i \pi_i \gamma_i^b, \tag{3.10}$$

which represents the rate of the technological progress in sector i. Obviously, this mechanism only accounts for the direct effect of technological change. Technological progress also alters the sectoral composition indirectly by altering income, prices and rental rates. These indirect effects of technological progress are accounted by the other aforementioned drivers of structural change.

We distinguish two components operating in this mechanism. On the one hand, we have the neutral component of the technological change, which is given by the first term, γ_i^a. Structural change is partially driven by the sectoral biases of the neutral technological change given by $\gamma_i^a - \gamma_j^a$. On the other hand, we also have the effect on sectoral composition of capital deepening driven by technological change, which is given by the second term $\alpha_i \pi_i \gamma_i^b$. Observe that the magnitude of this mechanism also depends on: (a) the sectoral differences in the factor bias of technological change, i.e., the differences $\gamma_i^b - \gamma_j^b$; (b) the share of capital income in output; and (c) the elasticity of substitution between inputs in sector i. Therefore, this technological mechanism does not require technological change to be sectoral or factor biased. It also arises if $\gamma_i^s = \gamma_j^s$, with $s = \{a, b\}$, provided that $\alpha_i \pi_i \neq \alpha_j \pi_j$.

Summarizing, structural change might be driven by several alternative mechanisms. As was suggested by Buera and Kaboski (2009), none of these mechanisms alone can provide a good explanation for the observed structural change. Hence, we should consider all of them together as potential explanations of the observed structural change. This requires quantifying their relative contributions to the observed structural change. We will deal with this empirical analysis in the next sections.

Before closing this section, we clarify that our contribution to related literature is to identify the mechanisms of propagation of any structural shock on the sectoral composition. To see this, consider, for instance, how an exogenous technological advance spreads out to the sectoral structure. Since in equilibrium relative prices and relative rental rates depend on technological parameters, this advance affects the sectoral structure through the aforementioned four mechanisms:

- It increases aggregate income, which has an impact on sectoral composition when sectoral income elasticities of demand are different across sectors. This income mechanism was theoretically studied by Kongsamut et al. (2001).
- The sectoral bias of technological progress alters the relative prices, which modifies sectoral composition when there are differences in the Allen-Uzawa elasticities. Ngai and Pissarides (2007) propose a model that illustrates how this demand substitution mechanism works.

- The sectoral bias of technological progress also alters the relative rental rates, changing the sectoral composition when either capital income shares are different across sectors (see, Acemoglu and Guerrieri, 2008) or elasticities of substitution between capital and labor are different across sectors (see, Alvarez-Cuadrado et al., 2017). This effect on sectoral composition corresponds to the technological substitution mechanism.

- The technological change mechanism groups the direct effects of technological progress on structural change. On the one hand, the sectoral bias of technological progress modifies total factor productivity differently in each sector. Ngai and Pissarides (2007) also incorporate this driver in their model. On the other hand, intersectoral differences in the capital-bias of technological progress generate sectoral differences in the marginal rate of technical substitution between capital and labor. This effect is reinforced when there are also sectoral differences in capital income shares or in the elasticities of substitution between capital and labor. To our knowledge, although the literature has already considered the role of this propagation mechanism (see, e.g., Acemoglu and Guerrieri, 2008, Alvarez-Cuadrado et al., 2018, Barany and Siegle, 2020; or Buera et al., 2022), it has not been quantified. In the following sections, we outline that it has a sizeable effect on sectoral composition.

Therefore, Condition (3.5) for structural change is quite general and nests the mechanisms commonly used by the literature to account for observed structural change. In the online appendix, we show how our condition (3.5) particularizes when one considers the functional forms of preferences and technologies considered in the literature. In particular, we consider: (a) the Stone-Geary preferences considered by Kongsamut et al. (2001); (b) the sectorally biased technological progress considered by Ngai and Pissarides (2007); (c) the capital deepening proposed by Acemoglu and Guerrieri (2008); (d) the sectoral differences in capital-labor substitution considered by Alvarez-Cuadrado et al. (2017); and (e) the long-run income and price effects introduced by Comin et al. (2021).

4. Empirical analysis

As an illustration of our decomposition method, we now quantify the contribution of the four propagation mechanisms to the structural change of the US economy over the period 1948-2010. This first requires to obtain the income elasticities μ_i, the Allen-Uzawa elasticities σ_{ij}, the sectoral elasticities of substitution between capital and labor π_i, and the rates of technological change γ_i^a and γ_i^b. We obtain them using the estimations that the literature on structural change has made of the parameters of Stone-Geary preferences and of constant elasticity of substitution (CES) sectoral technologies. These functions are extensively used in the empirical analysis of the process of structural change. We obtain the rates of technological change and the elasticities of substitution between capital and labor from the estimations of Herrendorf et al. (2015) of sectoral CES technologies, and we derive the elasticities of consumption demands from the estimation of Stone-Geary preferences by Herrendorf et al. (2013).[7]

We consider three aggregate sectors: agriculture, manufacturing and services.[8] Furthermore, we use annual US data for the period 1948-2010, with 2005 as the base year of the price, rental rates and quantity indexes. More precisely, we retrieve the data on consumption expenditure in valued added and on relative prices from Herrendorf et al. (2013), whereas the sectoral data on rental rates, capital income shares and employment (people and hours) directly come from Herrendorf et al. (2015). Both studies build the time series of these variables with the information from the US Bureau of Economic Analysis (BEA). We proceed to derive the expression of the elasticities that appear in (3.5) for the particular specifications of preferences and technologies considered in the empirical analysis.

4.1. Sectoral CES production functions

We now consider that each sector uses the following CES production function:

$$Y_i = A_i \left[\varphi_i \left(B_i z_i K \right)^{\frac{\pi_i - 1}{\pi_i}} + \left(1 - \varphi_i \right) \left(u_i L \right)^{\frac{\pi_i - 1}{\pi_i}} \right]^{\frac{\pi_i}{\pi_i - 1}}, \tag{4.1}$$

with $\varphi_i \in (0, 1)$, and where π_i is the constant elasticity of substitution. Herrendorf et al. (2015) estimate these sectoral production functions for agriculture, manufacturing and services on the same period we consider. This estimation yields the following results:

- The estimated elasticities of substitution between capital and labor π_i for agriculture, manufacturing and services are 1.58, 0.80 and 0.75, respectively.
- The estimated growth rate γ_i^a of the neutral technological progress A_i for agriculture, manufacturing and services are 0.050, 0.044 and 0.016, respectively.
- The estimated growth rate γ_i^b of the capital-augmenting technological progress B_i for agriculture, manufacturing and services are -0.027, -0.089 and -0.016, respectively.[9]

[7] These two papers estimate separately technologies and preferences. Herrendorf et al (2013) obtain the values of the parameters of the Stone-Geary utility function by estimating the implied system of sectoral expenditure shares. Herrendorf et al. (2015) obtain the values of the parameters of the CES production functions by estimating the system of first order conditions obtained from minimizing the sectoral cost functions.

[8] Other sectoral configuration may be more appropriate for the post-1947 period considered. On the one hand, agriculture is steadely declining from already very low employment shares. On the other hand, the evidence suggests that services is a largely heterogenous sector (see, e.g., Bárány and Siegel, 2020; Duarte and Restuccia, 2020; Duernecker et al., 2021; or Buera et al., 2022). However, we use the standard three sector configuration to compare with the previous literature and to make use of the estimations of the specifications of Stone-Geary preferences and of CES technologies.

[9] Observe that B_i is the net effect between capital-augmenting and labor-augmenting technical progresses, which are separately estimated by Herrendorf et al. (2015). Therefore, a negative value of γ_i^b means that the labor-augmenting progress dominates in sector i. In any case, the aforementioned study estimates that the rate of the gross capital-augmenting progress is not significantly different to zero in services, whereas it is negative in manufacturing. They find difficult to explaining the later result. We will come back to this issue in the sensitivity analysis below.

As shown in (2.8), the values of γ_i^b and π_i determine the factor bias of technological progress, which is measured by $\gamma_i^b(\pi_i - 1)$. Since the elasticity of substitution is smaller than one in manufacturing and services, then these two sectors exhibit capital-biased technological progress, whereas agriculture experimented a labor-biased technological change since $\pi_a > 1$.

4.2. Stone-Geary preferences

Consider now the following preferences:

$$v(c_a, c_m, c_s) = \left[\sum_{i=a,m,s} \phi_i^{\frac{1}{\varepsilon}} (c_i - \overline{c}_i)^{\frac{\varepsilon}{\varepsilon-1}}\right]^{\frac{\varepsilon-1}{\varepsilon}}, \tag{4.2}$$

where $\phi_i > 0$ are nonnegative weights that add up to one, $\overline{c}_i$ are constants, and $\varepsilon \geq 0$ is the elasticity of substitution between effective consumptions $c_i - \overline{c}_i$.[10] By deriving the consumption demands, and after some simple algebra, we obtain in the online appendix that the income elasticity is given by

$$\mu_i = \left(\frac{e}{e - \overline{e}}\right)\left(1 - \frac{\overline{c}_i}{c_i}\right), \tag{4.3}$$

for all i, and where

$$\overline{e} = \sum_{i=a,m,s} p_i \overline{c}_i.$$

Similarly, we obtain that the Allen-Uzawa elasticities are:

$$\sigma_{ij} = \varepsilon \mu_i \mu_j \left(1 - \frac{\overline{e}}{e}\right), \tag{4.4}$$

for all $i \neq j$, and

$$\sigma_{ii} = \left(\frac{\varepsilon \mu_i}{x_i}\right)\left(1 - \frac{\overline{e}}{e}\right)(x_i \mu_i - 1), \tag{4.5}$$

for all i.[11]

Herrendorf et al. (2013) estimates the parameters of the utility function (4.2) by imposing that the minimum consumption on manufacturing is $\overline{c}_m = 0$. The results of this restricted estimation are: $\varepsilon = 0.002$ (although no significantly different from zero), $\overline{c}_a = 138.68$, $\overline{c}_m = 0$, $\overline{c}_s = -4,261.82$, $\phi_a = 0.002$, $\phi_m = 0.15$ and $\phi_s = 0.85$. With this parameterization, we obtain the elasticities of consumption demand from (4.3), (4.4) and (4.5). They are time-variant because of the minimum consumptions $\overline{c}_i$. Figure 3 shows the time-path of these elasticities and Table 1 displays their cross-time average values.

[10] The elasticity of substitution between gross consumption goods c_i should be computed because it is not only determined by ε but also by the minimum consumptions $\overline{c}_i$. In any case, we assert that this elastiticity is not relevant for structural change.

[11] Observe that the income-elasticity of demand c_i is different from unity even when $\overline{c}_i = 0$ provided $\overline{c} \neq 0$.

[Insert Figure 3 and Table 1]

Several properties of the consumption demand must be pointed out from the computed elasticities. With respect to income elasticities, we obtain that the three consumption goods are normal goods, with the exception of agriculture that exhibits negative income elasticity during the 1970s.[12] We also observe that the demands of agriculture and manufactures exhibit income elasticities smaller than one, whereas the demand of services has an income elasticity larger than one. Finally, as the literature explaining structural change based on demand factors assumes, we obtain that income elasticities satisfies the ranking $\mu_a < \mu_m < \mu_s$ in the whole sample and they converge to one as income grows, which is a well known property of the Stone-Geary preferences.

With respect to Allen-Uzawa elasticities, we first observe that their values are very small as a consequence of the fact that the estimated value of the elasticity of substitution ε is almost zero. In any case, we obtain that $\sigma_{as} \neq \sigma_{am} \neq \sigma_{ms}$, and consumption goods are Hicks substitutes as σ_{am}, σ_{as} and σ_{ms} are positive, with the exception of the last two elasticities that are negative during the 1970s. Once again, the non-homotheticity leads these elasticities to vary along time in the US economy. This variation is relatively large, since the variation coefficients are 79.25%, 73.48% and 5.06% for σ_{am}, σ_{as} and σ_{ms}, respectively.

4.3. Accounting for the contribution of the mechanisms

The purpose of this subsection is to measure the importance of each mechanism in driving the observed structural change. To this end, we first simulate sectoral employment shares to test how well the proposed parameterization fit the observed employment shares. In particular, we simulate the structural change equation (3.5) with the estimated elasticities, and using annual data on aggregate expenditure e, sectoral prices p_i, sectoral rental rates ω_i, sectoral expenditure shares x_i and sectoral shares of capital income α_i, which we obtain from Herrendorf et al. (2013) and Herrendorf et al. (2015). Therefore, we consider these variables as exogenous in this first simulation and accounting exercises.

More precisely, we simulate employment shares $\widehat{u}_{it}$ for agricultural and services sectors from 1948 to 2010 by setting the value of $\widehat{u}_{i0}$ to the actual value of the US employment share in 1948 for sector i, and using the estimated growth rate $\widehat{G}_{it} \equiv \dot{u}_i/u_i$ in (3.5), which is defined as the sum of the following partial growth rates corresponding to the different mechanisms of structural change:

$$\widehat{G}^I_{it} = \widehat{\mu}_i \left[\dot{e}/e - \sum_{j=a,m,s} x_j \left(\dot{p}_j/p_j \right) \right],$$

[12]The price of agricultural products increase very rapidly in 1970s because of a strong expansion in the world demand of grain, particularly from socially planned economies, and some adverse weather conditions that reduce the yields of main world producers of grain (see, e.g., Peters et al., 2009). This increase in prices may explain the reduction in agricultural income elasticities and even negative values of these elasticities if the price increase reduces the consumption of agricultural products.

for the income mechanism;

$$\widehat{G}_{it}^{DS} = \sum_{j=a,m,s} \widehat{\sigma}_{ij} x_j \left(\dot{p}_j / p_j\right),$$

for the demand substitution mechanism; $\widehat{G}_{it}^{TS} = -\alpha_i \widehat{\pi}_i \left(\dot{\omega}_i/\omega_i\right)$ for the technological substitution mechanism; $\widehat{G}_{it}^{TC} = -\widehat{\gamma}_i^a - \alpha_i \widehat{\pi}_i \left(\widehat{\gamma}_i^b - \widehat{\gamma}_i^a\right)$ for the technological change mechanism; and the growth rate of hours worked, $\widehat{G}_{it}^{HW} = -\dot{l}/l$. Finally, the simulated employment shares in manufacturing are directly obtained by using the market clearing condition in the labor marked $\widehat{u}_{mt} = 1 - \widehat{u}_{at} - \widehat{u}_{st}$.

Figure 4 compares the path of the simulated employment shares $\{\widehat{u}_{it}\}_{t=1948}^{2010}$ with the path followed by actual shares $\{u_{it}\}_{t=1948}^{2010}$. First, we observe that the fit of the simulated shares to the actual shares is very good. This is confirmed in Table 2, which provides the Pearson's correlation coefficient (R) and the root mean-square error ($RMSE$) of the regression of the actual employment shares with respect to the simulated shares.

[Insert Figure 4 and Table 2]

We now measure the contribution of each mechanism of structural change to the predicted average growth rate of the sectoral employment shares between 1948 and 2010, which we denote by $\widehat{G}_i$. We face this question by accounting for the contribution of the partial growth rates $\widehat{G}_i^I$, $\widehat{G}_i^{DS}$, $\widehat{G}_i^{TS}$ and $\widehat{G}_i^{TC}$ to the average predicted growth rate $\widehat{G}_i$ of the employment shares.[13] Table 3 and Figure 5 provide the results from these decomposition and accounting exercises. We conclude that all propagation mechanisms, with the exception of the demand substitution mechanism, have played a significant role in explaining the structural change observed throughout the sample period. These mechanisms were then relevant channels for the transmission of structural shocks to the aggregate economy.

[Insert Table 3 Figure 5]

The insignificant role of the demand substitution mechanism means that the changes in the relative prices of consumption goods have only affected sectoral composition of employment through the income mechanism. Table 3 also decomposes the income mechanism into the Marshallian component, which captures the effect of changes in nominal expenditure, and the Hicksian component, which covers the change in the purchasing power of income driven by changes in relative prices. We observe that the two components are largely significant, although they work in the opposite direction. We must remember at this point that the substitution mechanism obtained by the previous literature accounts for the sum of the demand substitution and Hicksian

[13] The growth rate decomposition of employment shares in agriculture and services follows the structural change equation (3.5). The decomposition in manufactures is done by using (3.3) and the decomposition of the other sectors. In particular, the growth rate decomposition in manufacturing is computed as

$$\widehat{G}_{mt}^{E} = -\left[\left(\frac{u_{at}}{u_{mt}}\right)\widehat{G}_{at}^{E} + \left(\frac{u_{st}}{u_{mt}}\right)\widehat{G}_{st}^{E}\right],$$

where $E = \{I, DS, TS, TC, HW\}$.

income mechanisms, since this literature does not consider the Slutsky decomposition of the price elasticities of consumption demand. Our results then indicate that this substitution mechanism in the literature would be fully attributable to the Hicksian income mechanism under our preference parameterization with a near-zero estimated elasticity of substitution between goods.

From Table 3, we observe that the propagation mechanisms have driven the sectoral employment shares in opposite directions. We first observe that the technological substitution and the technological change mechanisms pushed labor out of agriculture, whereas the income mechanism has slowed down this decrease in the employment share in agriculture. By the contrary, the income mechanism was the responsible of the increase and the decrease of the employment shares in services and manufacturing, respectively. In these two sectors, the technological mechanisms worked in the opposite direction and, in particular, the technological change mechanism was the largest counterbalance force of the income mechanism in both sectors.

We outline that only the technological change mechanism is crucial in driving structural change in the three sectors. This technological change effect is the sum of two different effects: the neutral component of the technological change, measured by $\gamma_i^a - \gamma_j^a$, and the technological change-driven capital deepening that results from factor-biased technological changes, measured by $\alpha_i \pi_i \gamma_i^b - \alpha_j \pi_j \gamma_j^b$. This second component is sizable. To see this, we also compute the contribution of each component of the technological change mechanism to the predicted growth rate of the employment shares. Table 3 shows that the capital deepening component reduced the impact of the neutral component.

4.4. Sensitivity analysis

We now carry out some robustness exercises to determine how the previous accounting results depend on some controversial assumptions of the parameterization used in this section. We next present the main conclusions from this sensitivity analysis, whose details and results are included in the online appendix.

A. Sectoral elasticities of substitution between capital and labor. Herrendorf et al. (2015, pp. 106-107) claim that "Cobb-Douglas sectoral production functions with different technological progress capture the main technological forces behind the postwar US structural change". We check here this claim by using our accounting exercise. We consider a Cobb-Douglas specification for the sectoral production functions, where the capital income shares are given by the across-time arithmetic average in data. Furthermore, the elasticity of substitution π_i is in this case equal to one, so that the technological progress does not exhibit now factor bias, which modifies the technological substitution and the technological change mechanisms. We show in the online appendix that the fit of the simulated shares to the data in this case is significantly worse than in the simulations with the estimated CES production functions.

B. The factor-bias of the sectoral technological progress. We should point out that Herrendorf et al. (2015) obtain a negative capital-augmenting progress in manufacturing, which they find challenging to interpret. The literature finds the estimation of factor-biased technological change troubling because it is mainly attributed to measurement errors (see, e.g., Antras, 2004). In the online appendix, we approximate the magnitude of these errors by computing our net capital-augmenting technological progress as the across-time average residual of our structural change equation (3.5). In this way, we obtain that the growth rate γ_i^b of the net capital-augmenting technological progress B_i for agriculture, manufacturing and services is -0.033, 0.041 and -0.014, respectively. While these rates in agriculture and services are close to the benchmark values, observe that the rate in manufacturing is largely different. In particular, the rate of the gross capital-augmenting progress in manufacturing, which is given by $\gamma_m^b + \gamma_m^a$, is now positive.

In the online appendix, we simulate the sectoral employment shares with these new values of γ_i^b. We first obtain that the fit of these new simulations to the data on employment shares is slightly worse than the one in the benchmark simulations. We also show that the new simulation implies remarkable changes in the contribution of the propagation mechanisms. The technological change mechanism maintains the direction of its force but reduces its importance in the three sectors. The lower contribution of the latter effect is compensated by the increase in the importance of the income and the technological substitution mechanisms. Furthermore, the decomposition of the technological change mechanism shows that the capital-deepening technological change is now larger in agriculture and smaller in services and in manufacturing.

C. The long-run income and price effects. One feature of the Stone-Geary preferences is that the income effects driving structural change vanish in the long-run as the economy grows because $\bar{c}_i / c_i$ tends to zero, so that the income elasticities converge to one for all i (see Figure 3). Therefore, the contribution of the income mechanism as a driver of structural change vanishes in the long run. Comin et al. (2021) overcome this feature by considering a class of utility functions that generates non-homothetic sectoral demands for all levels of income. They consider constant relative elasticities of income and substitution (CREIS) preferences, which is characterized by the utility function $v\left(c_a, c_m, c_s\right)$ implicitly defined through the following constraint:

$$\sum_{i=a,m,s} \theta_i v^{\frac{\varepsilon_i - \eta}{\eta}} c_i^{\frac{\eta-1}{\eta}} = 1. \tag{4.6}$$

By using cross-country data for the OECD countries, Comin et al. (2021) estimates the parameters of the utility function (4.6). In the online appendix, we derive the income and the Allen-Uzawa elasticities associated to this utility function. We obtain that the variability of these elasticities is now quite small and, more important, the income elasticities do not converge to one. In particular, the income elasticity of agriculture remains very small along the entire period, so that its cross-time average value is in this case much smaller than in the benchmark case with Stone-Geary preferences.

We simulate the sectoral employment shares by using the estimated elasticities of the consumption demand based on CREIS preferences. In the online appendix, we show that the fit of these new simulations to the data on employment shares is also very good. In fact, the fit with the CREIS preferences is in overall similar to the one with the Stone-Geary preferences. However, regarding the decomposition of the drivers of structural change, we show that the importance of each of the mechanisms significantly changes with this alternative specification of preferences. The contribution of the demand substitution mechanism in the three sectors now is not negligible, which is explained by the fact that the Allen-Uzawa elasticities differs now significantly from zero. In particular, this mechanism slows down the reallocation of employment across sectors. Furthermore, the increase in the importance of this mechanism is mainly balanced with a reduction in the contribution of the income mechanism. Finally, we also show that this slightly better fit of the simulation based on CREIS preferences to employment share data is at the cost of a worse fit of the simulation to the expenditure share data. While the fit of the simulation of the expenditure share in agriculture under both specifications is quite similar, the fit of the simulation of the expenditure shares in services and manufacturing with the Stone-Geary preferences is much better than with the CREIS preferences.

5. Structural change and technological progress

Technological progress affects structural change through the different propagation mechanisms considered in the previous sections, since it increases income and changes prices and rental rates. In this section, we use the accounting method discussed in the previous sections to study the direct and indirect effects of technological progress on structural change. This exercise requires first solving the dynamic general equilibrium to determine how income, prices and rental rates respond to technological progress. We next simulate the equilibrium employment shares and the contribution to structural change of the different mechanisms when we consider the technological progress estimated by Herrendorf (2015). We also consider alternative processes of technological progress that are calibrated to generate the same path of sectoral compositions. We then compare the contribution of the different mechanisms under these different processes of technological progress.

We parameterize our model with the production functions (4.1) and the utility function (4.2), and we use the values of parameters $\{\pi_i, \gamma_i^a, \gamma_i^b, \bar{c}_i, \phi_i, \varepsilon\}$ for $i = \{a, m, s\}$ that we considered in the previous section and that we obtained from the estimations of Herrendorf et al. (2013) and Herrendorf et al. (2015). The firm's and intratemporal household problem are described in Section 2 and a detailed derivation of the equilibrium is in the online appendix. Therefore, we only need to define and intertemporal framework to determine capital accumulation and to clarify some additional aspects of the calibration. These additional assumptions are:

- To simplify the equilibrium computation, we consider a Solow type model and we set the path of the investment rate exogenously from the data. We obtain this exogenous path of investment rate from the perpetual inventory method commonly used in building the aggregate capital stock observed in the data. More precisely, we consider the following law of motion for capital in efficient units of labor:

$$(1+n)\, k_{t+1} = s_t Q_t + (1-\delta)\, k_t,$$

  where s_t is the investment rate; Q_t is the aggregate GDP in efficient units of labor, i.e., $Q = \sum_{i=\{a,m,s\}} p_i y_i$; and δ is the depreciation rate. We set the depreciation rate at 0.045, which is obtained by imposing that the law of motion of capital stock is asymptotically consistent with the following empirical facts taken from the Penn World Table 1950-2010: (i) the average investment-capital ratio is 0.076; (ii) the average population growth rate is equal to $n = 0.011$; and, (iii) the average value of the aggregate growth rate is 0.02.

- Herrendorf et al. (2015) normalizes the initial values of neutral and capital-augmenting technological progress, $A_i(0)$ and $B_i(0)$, to one. While we maintain these values for $B_i(0)$, we instead calibrate the values of $A_i(0)$ to match the observed data on sectoral composition of labor, u_i, and the aggregate GDP at 1948. We obtain $A_a(0) = 0.7005$, $A_m(0) = 2.0383$ and $A_s(0) = 0.8769$.

- We consider exogenous gaps in the rental rates across sectors and exogenous wedges between production and consumer prices. These gaps and wedges cover the existence of any distortion like, for instance, fiscal policy or mark-ups. We define $\upsilon_i = \omega_i/\omega_m$ and $\kappa_i = r_i/r_m$ for $i = \{a, s\}$; and $\tau_i = \widehat{p}_i/p_i$; where $\widehat{p}_i$ and p_i are the prices faced in sector i by consumers and producers, respectively. We assume that these gaps follow a linear trend and we set the value of the trend to match the linear trend of these gaps observed in the data during the period 1948-2010.

- Finally, since we consider exogenous labor supply, we plug in out model the hours worked per capita observed in the data.

We simulate the equilibrium path over the next 60 years using as initial capital the aggregate capital stock observed in the data in 1948. Figure 6 compares the simulated employment shares with the shares observed in the data. The fit of the simulated benchmark shares to the actual shares is very good. In particular, we obtain that the $RMSE$ are 0.0093, 0.0186 and 0.0200 for agriculture, manufacturing and services, respectively.

[Insert Figure 6]

We now use the model to compare the effects on sectoral composition of different processes of technological change. To that purpose, we consider two counterfactual economies that are identical to the benchmark economy except that in one there is no factor bias of technological progress and in the other one there is no sectoral bias in the neutral component. These new technological progresses are calibrated to generate the same sectoral allocation of employment than the benchmark economy during the period 1948-1968.[14] In particular, we consider the following two counterfactual economies:

1. *Economy A*. An economy with sectoral bias in the neutral component and without factor-bias of technological progress. In particular, we consider that the levels of B_i remains constant at its initial values $B_i(0) = 1$. Furthermore, we consider that A_m follows the same path as in the benchmark economy, whereas the paths $\{A_a(t), A_s(t)\}_{t=1}^{20}$ are calibrated, so that this counterfactual economy replicates

[14] We consider only 20 periods because the counterfactual technological progress drive prices to extreme values, which makes difficult to match the sectoral employment allocation of the benchmark economy in longer periods.

the same path of sectoral employment shares u_i generated by the benchmark economy. The average annual growth rate of the calibrated processes $A_a(t)$ and $A_s(t)$ are -0.0144 and 0.0203, respectively.

2. *Economy B*. An economy with sectoral differences in the factor bias of technological progress, but without sectoral bias of the neutral component. More precisely, we consider that the levels of A_i grow at the same constant rate in the three sectors, and it is equal to the growth rate $\widehat{\gamma}_m^a$ corresponding to the benchmark economy. Furthermore, we consider that B_m follows the same path as in the benchmark economy and the paths $\{B_a(t), B_s(t)\}_{t=1}^{20}$ are calibrated, so that this counterfactual economy replicates the same path of sectoral employment shares u_i generated by the benchmark economy. The average annual growth rate of the calibrated processes $B_a(t)$ and $B_s(t)$ are -0.1204 and -0.1492, respectively.

We simulate the equilibrium paths of these counterfactual economies, and then we compare them with those of the benchmark economy. By using the accounting procedure proposed in the preceding sections, we compute the contribution of the different propagation mechanisms in each economy. Even though the sectoral allocation of employment is the same in all those economies, the equilibrium paths of expenditure shares, prices and rental rates differ substantially. Table 4 illustrates these differences by showing the average growth rate of these other variables.[15] Therefore, the contribution of each propagation mechanism is also different in each economy.

[Insert Table 4]

Table 5 and Figure 7 show the results of the accounting exercises done for actual data, for the benchmark economy and for the two counterfactual economies, A and B. Actual data refers to the exercise performed in Section 4, whereas the other accounting exercises are based on the simulation of the equilibrium. To simplify the exposition, we focus on the dynamics of the ratio between the employment share on services and agriculture, u_s/u_a, as the share in manufacturing was computed as a residual. This ratio monotonously increased along the considered period at an average annual rate of 0.0666, whereas in the three simulated economies it increases at an average growth rate of 0.0717. We first observe that the benchmark economy replicates quite well the contribution of the income and technological change mechanisms, whereas it slightly overestimates the contribution of the technological substitution mechanism. Therefore, we can conclude that the deviation of the benchmark simulation with respect to data is basically due to an error in generating the variation in the rental rate ratios.

[Insert Table 5 and Figure 7]

From the comparison between the three simulated economies, we observe that the contribution of each propagation mechanism is very different depending on the particular technological progress. The contribution of the technological change mechanism largely differs across the simulated economies as a direct consequence of

[15] The online appendix provides the paths of expenditure, relative prices, rental rates and expenditure shares in all of the considered economies.

the different technological progress assumed. The remarkable result is the existence of also important differences in the contribution of the other mechanisms.

On the one hand, the contribution of the income mechanism in the counterfactual economies, especially in Economy B, is larger than in the benchmark economy. Even though the gap between the sectoral income elasticities in Economy A and in the benchmark is similar, the former exhibits a larger growth rate of expenditure, which translates into a larger contribution of the Marshallian income effect, and also a different behavior of the relative price of agriculture, which results in a different contribution of the Hicksian income effect. By the contrary, the Economy B also exhibits a larger gap between the sectoral income elasticities, which enlarge the relative contribution of the income mechanism in this economy with respect to the other two economies.[16]

On the other hand, the contribution of technological substitution mechanisms is similar in the two counterfactual economies but much larger than in the benchmark economy. From Table 4, we can conclude that this difference is driven by the different behavior of the capital income shares in the counterfactual economies with respect to the benchmark. In particular, the negative gap between α_s and α_a grows faster in the counterfactual economies.

In summary, we have shown that the mechanisms by which technological change drives structural change depend on the specific nature of technological change. Identifying the main mechanisms of propagation of technological change is crucial for building multi-sectoral growth models suitable for macroeconomic analysis of structural shocks such as, for example, technological changes or changes in fiscal policy. The proposed accounting method helps us in this identification.

6. Concluding remarks

We have developed a theoretical and empirical analysis to identify possible mechanisms driving structural change. We have found that the following mechanisms drive the dynamics of sectoral employment shares: (i) the income mechanism from the growth of nominal income and from the variation in relative prices; (ii) the demand substitution mechanism from changes in prices; (iii) the technological substitution mechanisms from changes in rental rates; and, (iv) both the level and the capital-bias effects derived from technological progress. We have shown that the reallocation of labor from agriculture to manufacturing and services is mainly explained by the technological mechanisms, whereas the income mechanism is the main driver of employment from manufacturing to services. We have also demonstrated that the factor bias of technological change has a sizeable effect on structural change. Furthermore, we have shown that the key variables that determine the contribution of each mechanisms are: (i) the income elasticities of the demand for consumption goods; (ii) the Allen-Uzawa elasticities of substitution between consumption goods; (iii) the capital income shares in sectoral outputs; (iv) the elasticity of substitution between capital and labor in each sector; (v) the sectoral bias of the neutral component of technological progress; and (vi) the degree of factor-bias in the sectoral technological change.

[16] Remember that income elasticities are endogenous and although the preferences parameters take the same values in the different economies, elasticities differ as a result of different values of prices and expenditure.

The research in this paper could be improved and extended in some directions. In the theoretical part, we could include international trade, home production and leisure. On the one hand, Uy et al. (2013), Swiecki (2017) and Teignier (2018) show that international trade may be an important channel to explain the observed structural change. We conjecture that an important variable driving the effect of international trade would be the elasticities of demand for imported goods and the Allen-Uzawa elasticities of substitution between domestic and foreign consumption goods. In this sense, the analysis should not be very different to that developed in this paper after having incorporated foreign consumption goods to the composite good from which individuals derive utility. On the other hand, in the case of leisure and home production, one would expect that the complementarity between goods and services would be crucial for structural change as was pointed out by Cruz and Raurich (2020).

The empirical part of our analysis might also be modified as follows. First, we might also estimate the demand elasticities by using more flexible functional forms for preferences and technologies. On the one hand, we might confront whether or not the use of a translog indirect utility function or a Rotterdam model of consumption demand gives a more precise estimation of the demand elasticities. On the other hand, we might also use a translog function for production costs in deriving a system of sectoral cost shares. We could estimate the sectoral elasticities of substitution between capital and labor by using this system.

A second empirical extension might consist on applying our analysis to alternative structures of production. Herrendorf et al. (2021) show that the share of services value-added in investment expenditure might be large. García-Santana et al. (2021) show that considering the fall in the investment rate is important to explain structural change when the sectoral composition of investment is considered. Therefore, a full characterization of the structural change would require not only accounting for the change in the sectoral composition of consumption but also in the sectoral composition of investment. Our approach could be easily applied to this framework by characterizing the demand of inputs from the sector producing the investment good.

Supplementary material

An online appendix with supplementary material is available.

References

[1] Acemoglu, D. and Guerrieri, V. (2008). Capital deepening and non-balanced economic growth. *Journal of Political Economy* 116, 467-498.

[2] Alder, S., Boppart, T., Müller, A. (2021). A theory of structural change that can fit the data. *American Economic Journal: Macroeconomics*, forthcoming.

[3] Alonso-Carrera, J. and Raurich, X. (2015). Demand-based structural change and balanced economic growth. *Journal of Macroeconomics* 46, 359-374.

[4] Alonso-Carrera, J. and Raurich, X. (2018). Labor mobility, structural change and economic growth. *Journal of Macroeconomics* 56, 292-310.

[5] Alvarez-Cuadrado, F., Van Long, N. and Poschke, M. (2017). Capital labor substitution, structural change and growth. *Theoretical Economics* 12, 1229-1266.

[6] Alvarez-Cuadrado, F., Van Long, N. and Poschke, M. (2018). Capital labor substitution, structural change and the labor income share. *Journal of Economic Dynamics and Control* 87, 206-231.

[7] Antras, P. (2004). Is the US aggregate production function Cobb-Douglas? New estimates of the elasticity of substitution. *The B.E. Journal of Macroeconomics* 4.

[8] Bárány, Z.L., Siegel, C. (2020). Engines of sectoral labor productivity growth. *Review of Economic Dynamics* 39, 304-343.

[9] Baumol, W. (1967). Macroeconomics of unbalanced growth: the anatomy of urban crisis. *American Economic Review* 57, 415-426.

[10] Boppart, T. (2014). Structural change and the Kaldor facts in a growth model with relative price effects and non-Gorman preferences. *Econometrica* 82, 2167-2196.

[11] Buera, F., Kaboski, J. (2009). Can traditional theories of structural change fit the data? *Journal of the European Economic Association* 7, 469-477.

[12] Buera, F., Kaboski, J., Rogerson, R., Vizcaino, J.I. (2022). Skill-biased structural change. *Review of Economic Studies* 89, 592-625.

[13] Caselli, F., Coleman, J.W. II. (2001). The U.S. structural transformation and regional convergence: A reinterpretation. *Journal of Political Economy* 109, 584-616.

[14] Comin, D., Lashkari, D., Mestieri, M. (2021). Structural change with long-run income and price effects. *Econometrica* 89, 311-374.

[15] Cruz, E., Raurich, R. (2020). Leisure time and the sectoral composition of employment. *Review of Economic Dynamics,* 38, 198-219.

[16] Dennis, B.N., Iscan, T.B. (2009). Engel versus Baumol: Accounting for structural change using two centuries of U.S. data. *Explorations in Economic History* 46, 186-202.

[17] Duarte, M., Restuccia, D. (2020). Relative prices and sectoral productivity. *Journal of the European Economic Association* 18, 1400-1443.

[18] Duernecker, G., Herrendorf, B., Valentinyi, A. (2020). Structural change within the service sector and the future of cost disease. CPER working paper DP12467.

[19] Echevarria, C. (1997). Changes in sectoral composition associated with economic growth. *International Economic Review* 38, 431-452.

[20] Foellmi, R., Zweimüller, J. (2008). Structural change, Engel's consumption cycles and Kaldor's facts of economic growth. *Journal of Monetary Economics* 55, 1317-1328.

[21] Gollin, D., Parente, S.L., Rogerson, R. (2002). The role of agriculture in development. *American Economic Review, Papers and Proceedings* 92, 160-164.

[22] García-Santana, M., Pijoan, J., Villacorta, L. (2021). Investment demand and structural change. *Econometrica* 89, 2751-2785.

[23] Herrendorf, B., Herrington, C. and Valentinyi, Á. (2015). Sectoral technology and structural transformation. *American Economic Journal: Macroeconomics* 7, 104-133.

[24] Herrendorf, B., Rogerson, R. and Valentinyi, Á. (2013). Two perspectives on preferences and structural transformation. *American Economic Review* 103, 2752-2789.

[25] Herrendorf, B., Rogerson, R. and Valentinyi, Á. (2014). Growth and structural transformation. *Handbook of Economic Growth,* P. Aghion and S.N. Durlauf (eds.). Amsterdam: North-Holland Publishing Company.

[26] Herrendorf, B., Rogerson, R. and Valentinyi, Á. (2019). Misallocation at the industry level. 2019 Meeting Papers 974, Society for Economic Dynamics.

[27] Herrendorf, B., Rogerson, R. and Valentinyi, Á. (2021). Structural change in investment and consumption. A unified analysis. *Review of Economic Studies* 88, 1311-1346.

[28] Herrendorf, B., Schoellman, T. (2018). Wages, human capital, and barriers to structural transformation. *American Economic Journal: Macroeconomics* 10, 1-23.

[29] Hubmer, J. (2021). The race between preference and technology. Manuscript, University of Pennsylvania.

[30] Kongsamut, P., Rebelo, S., Xie, D. (2001). Beyond balanced growth. *Review of Economic Studies* 68, 869-882.

[31] Laitner, J. (2000). Structural change and economic growth. *Review of Economic Studies* 67, 545-561.

[32] Matsuyama, D. (1992). A simple model of sectoral adjustment. *Review of Economic Studies* 59, 375-388.

[33] Moro, A., Moslehi, S., Tanaka, S. (2017). Does home production drive structural transformation? *American Economic Journal: Macroeconomics* 9, 116-146.

[34] Ngai, R., Pissarides, C. (2007). Structural change in a multisector model of growth. *American Economic Review* 97, 429-443.

[35] Peters, M., Langley, S., Westcott, P. (2009). Agricultural commodity price spikes in the 1970s and 1990s: Valuable lessons for today. *United States Department of Agriculture*, Economic Research Service, March 2009.

[36] Swiecki, T. (2017). Determinants of structural change. *Review of Economic Dynamics* 24, 95-131.

[37] Teignier, M. (2018). The role of trade in structural transformation. *Journal of Economic Development* 130, 45-65.

[38] Uy, T., Yi, K., Zhang, J. (2013). Structural change in an open economy. *Journal of Monetary Economics* 60, 667-682.

[39] Valentinyi, Á. and Herrendorf, B. (2008). Measuring factor income shares at the sectoral level. *Review of Economic Dynamics* 11, 820-835.

Table 1. Cross-time average values of consumption demand elasticities

Sector	Income Elasticities (μ_i)	Allen-Uzawa Elasticities (σ_{ij}) Agriculture	Manufactures	Services
Agriculture	0.26668	-0.03831	0.00053	0.00065
Manufactures	0.84840	0.00053	-0.00787	0.00217
Services	1.08365	0.00065	0.00217	-0.00068

Table 2. Performance of the simulations of sectoral employment shares

	Agriculture: u_a	*Services:* u_s	*Manufacturing:* u_m
Pearson's R	0.9858	0.9679	0.8469
RMSE	0.0149	0.0303	0.0462

Table 3. Average annual growth rate of employment shares in 1948-2010

	Agriculture	*Services*	Manufacturing
Data: G_i	-0.0343	0.0068	-0.0100
Predicted: $\widehat{G}_i$	-0.0401	0.0076	-0.0140
Decomposition :			
(a) Income mechanism: $\widehat{G}_i^I$	0.0046 (-0.1159)	0.0210 (2.7735)	-0.0562 (4.0219)
(a.1) Marshallian component	0.0118 (-0.2929)	0.0577 (7.6222)	-0.1566 (11.2136)
(a.2) Hicksian component	-0.0071 (0.1770)	-0.0367 (-4.8487)	0.1005 (-7.1917)
(b) Demand subst. mechanism: $\widehat{G}_i^{DS}$	1.1×10^{-5} (-0.0003)	-5.4×10^{-6} (-0.0007)	1.4×10^{-5} (-0.0010)
(c) Tech. subst. mechanism: $\widehat{G}_i^{TS}$	-0.0220 (0.5484)	-0.0024 (-0.3109)	0.0094 (-0.6704)
(d) Tech. change mechanism: $\widehat{G}_i^{TC}$	-0.0235 (0.5856)	-0.0118 (-1.5561)	0.0378 (-2.7066)
- Neutral component	-0.0500 (1.2463)	-0.0160 (-2.1120)	0.0535 (-3.8333)
- Capital deepening component	0.0265 (-0.6607)	0.0042 (0.5559)	-0.0157 (1.1267)
(e) Hours worked effect: $\widehat{G}_i^{HW}$	0.0007 (-0.0178)	0.0007 (0.0943)	-0.0050 (0.3561)

Notes: The decomposition satisfies $\widehat{G}_i = \widehat{G}_i^I + \widehat{G}_i^{DS} + \widehat{G}_i^{TS} + \widehat{G}_i^{TC} + \widehat{G}_i^{HW}$.
The value in parenthesis is the relative contribution of each mechanism: $\widehat{G}_i^j / \widehat{G}_i$.

Table 4. Average annual growth rates of some crucial variables

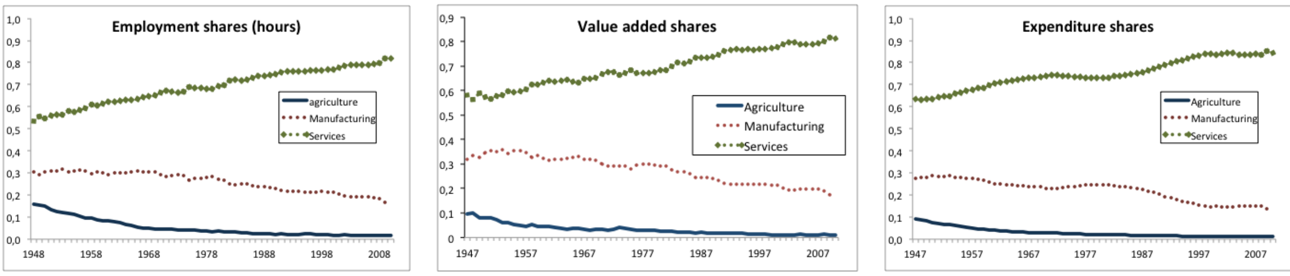
	Benchmark	*Economy A*	*Economy B*
Income elasticities:			
μ_a	0.0188	0.0305	0.1767
μ_s	-0.0064	-0.0059	-0.0094
Relative prices:			
p_a	-0.0127	0.0281	0.0245
p_s	0.0208	0.0232	0.0285
Capital income shares:			
α_a	0.0034	0.0129	0.0204
α_s	0.0000	-0.0089	-0.0177
Rental rate ratios:			
ω_a	0.0427	0.0737	0.1081
ω_s	0.0227	0.0530	0.0868
Consumption expenditure:			
e	0.0365	0.0546	0.1106
Expenditure shares:			
x_a	-0.0446	-0.0193	-0.0578
x_m	-0.0175	-0.0234	-0.0307
x_s	0.0100	0.0091	0.0130

Table 5. Average annual growth rate of simulated ratio u_s/u_a

	Data	*Benchmark*	*Economy A*	*Economy B*
Income mechanism: $\widehat{G}^{I}_{s/a}$	0.0223 (0.3832)	0.0228 (0.3175)	0.0344 (0.4801)	0.0677 (0.9448)
- Marshallian component	0.0433 (0.7449)	0.0368 (0.5126)	0.0533 (0.7434)	0.0858 (1.1963)
- Hicksian component	-0.0210 (-0.3616)	-0.0140 (-0.1951)	-0.0190 (-0.2634)	-0.0180 (-0.2514)
Demand subst. mechanism: $\widehat{G}^{DS}_{s/a}$	-1.5×10^{-5} (-2.6×10^{-4})	-3.4×10^{-5} (-4.2×10^{-4})	-6.5×10^{-6} (-9×10^{-5})	-1.8×10^{-5} (-2.5×10^{-4})
Tech. subst. mechanism: $\widehat{G}^{TS}_{s/a}$	0.0228 (0.3928)	0.0380 (0.5301)	0.0720 (1.0039)	0.0776 (1.0826)
Tech. change. mechanism: $\widehat{G}^{TC}_{s/a}$	0.0130 (0.2242)	0.0110 (0.1528)	-0.0347 (-0.4839)	-0.0736 (-1.0270)

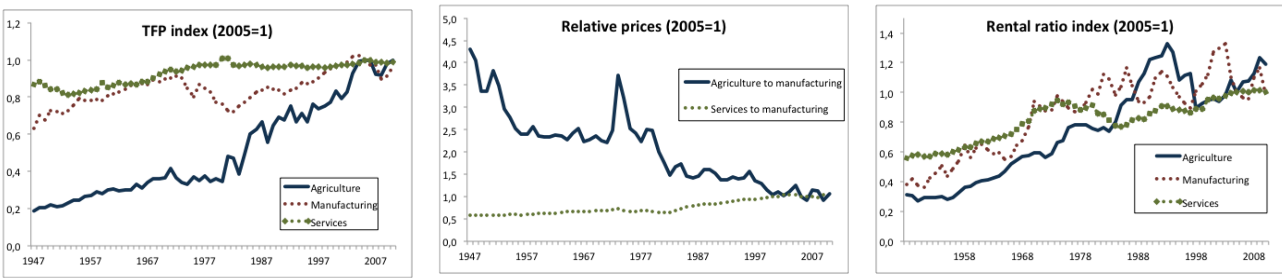
The variable $\widehat{G}^{j}_{s/a}$ denotes the growth of ratio u_s/u_a explained by the mechanism j.

The value in parenthesis is the relative contribution of each mechanism to total growth of the ratio: $\widehat{G}^{j}_{s/a}/\widehat{G}_{s/a}$.



Source: World KLEMS data 2013 release, Herrendorf et al. (2013) and Herrendorf et al. (2019)

Figure 1. Patterns of Structural Change in US



Source: World KLEMS data 2013 release, Herrendorf et al. (2013) and Herrendorf et al. (2019)

Figure 2. Sectoral dynamics in US

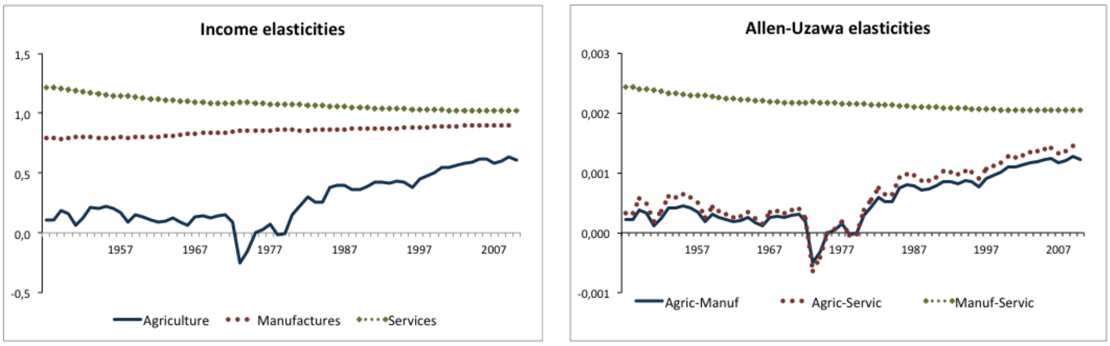


Figure 3. Dynamics of consumption demand elasticities

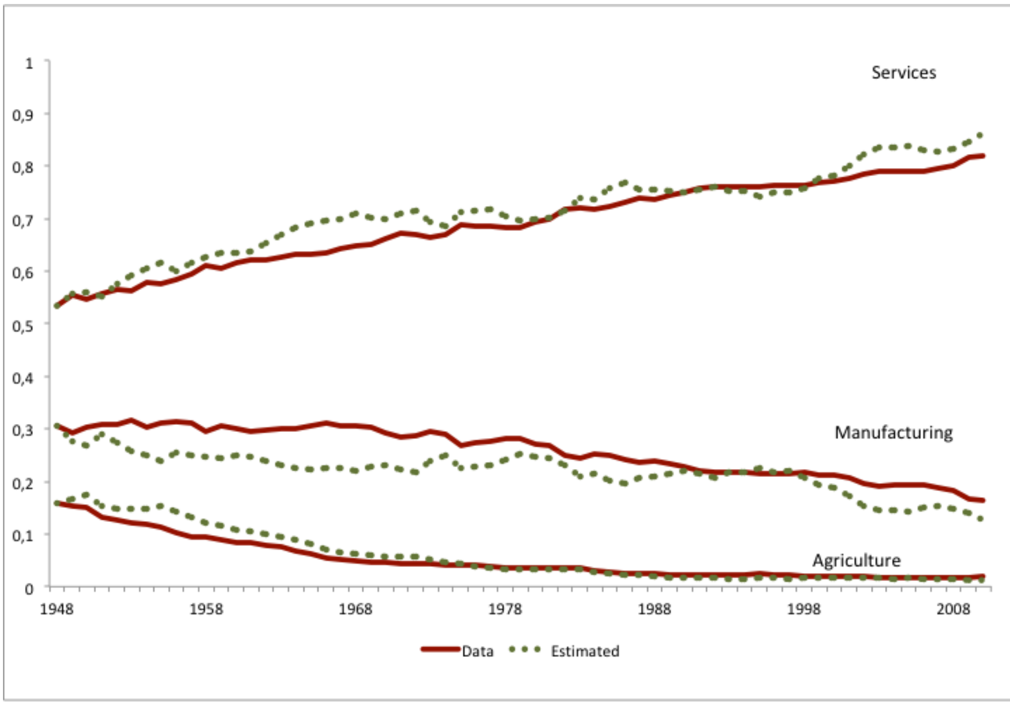


Figure 4. Fit of the sectoral employment shares

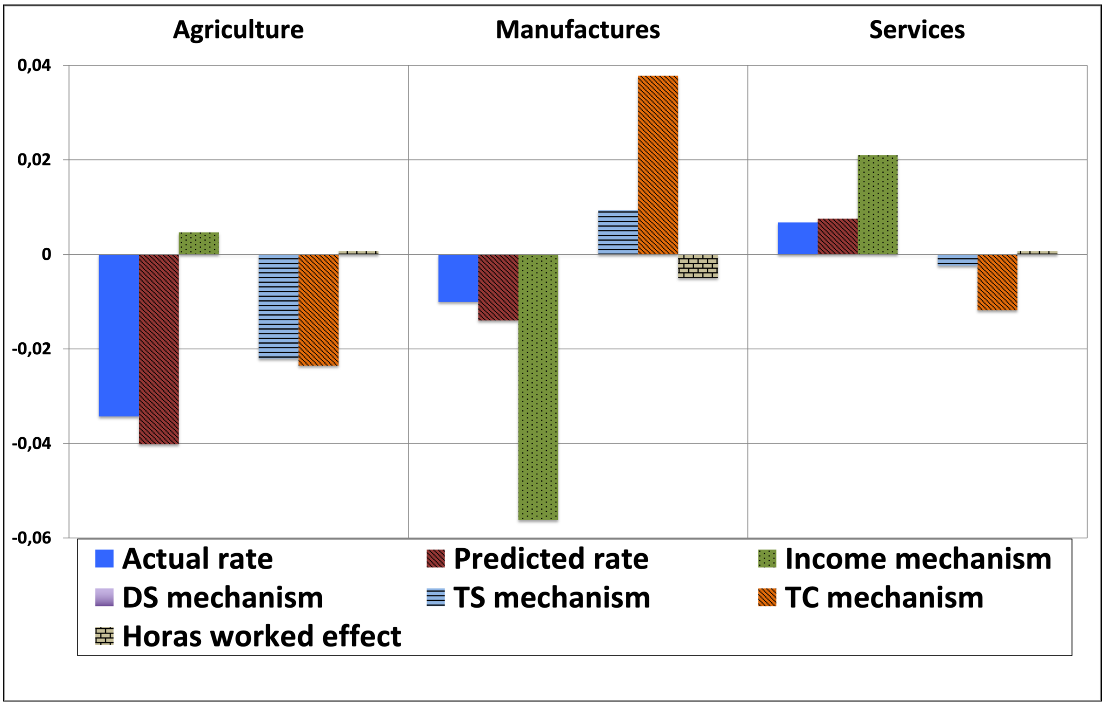


Figure 5. Contribution of different drivers to the growth of employment shares

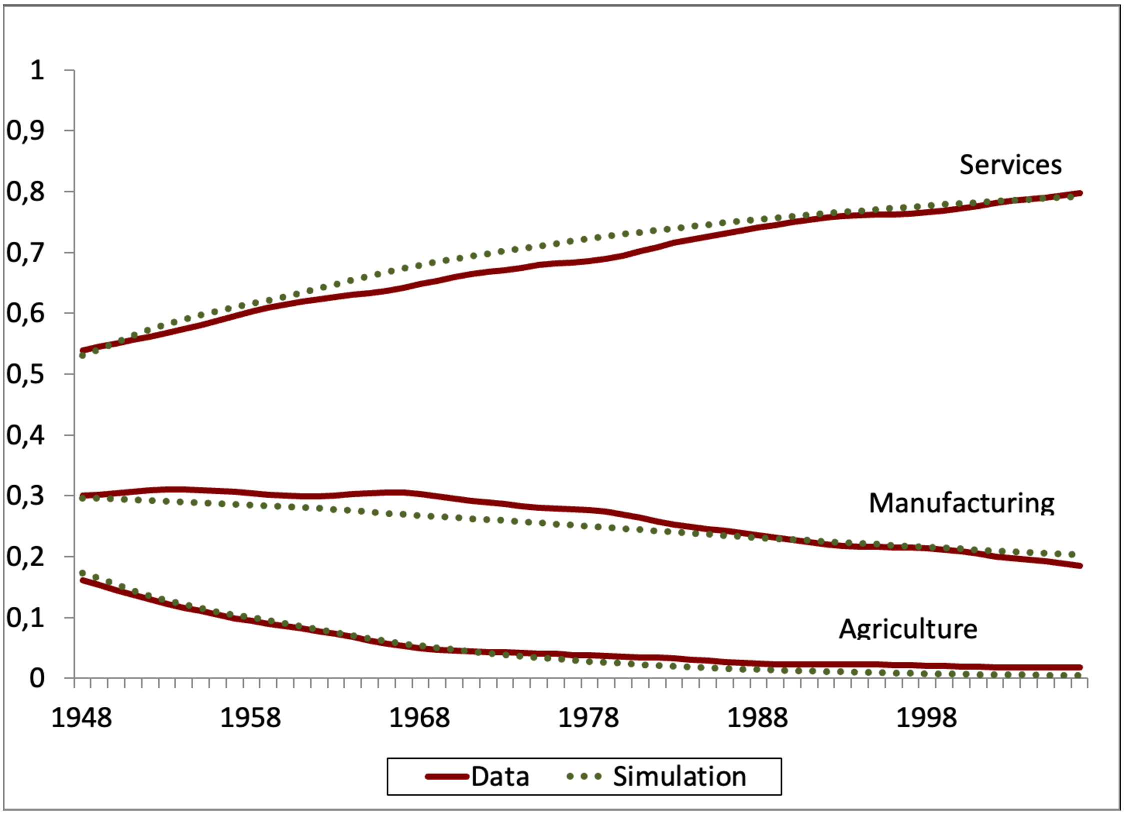


Figure 6. Simulated equilibrium shares of employment

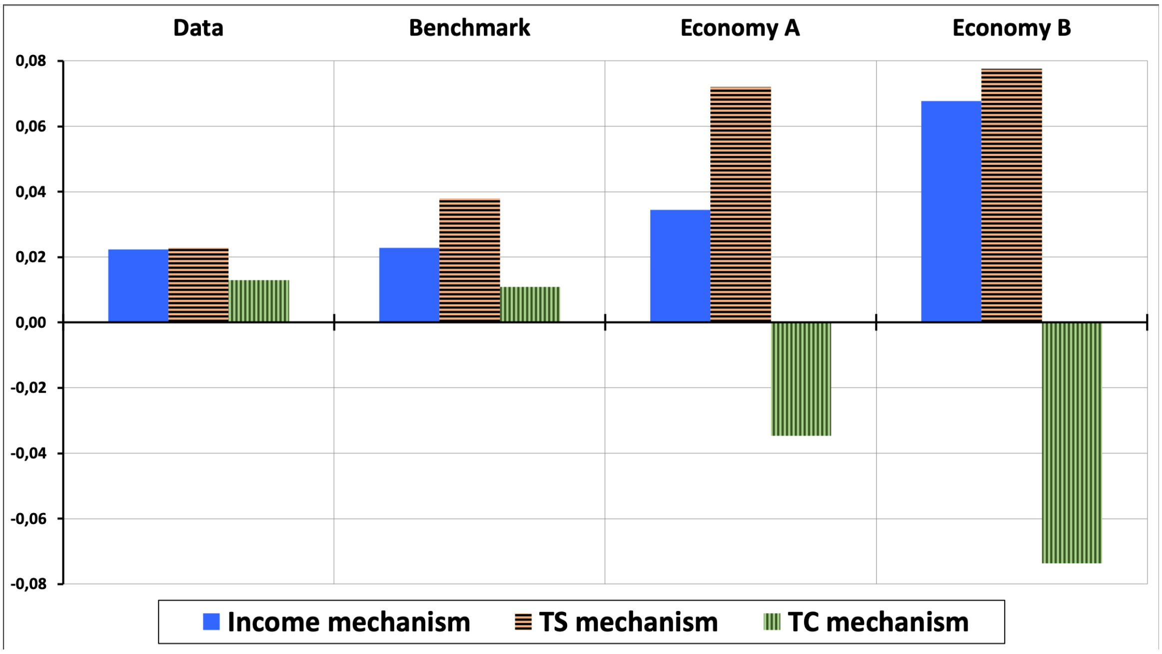


Figure 7. Contribution of different mechanisms in the simulated economies