Department of Economics and Statistics "Cognetti de Martiis"
Campus Luigi Einaudi, Lungo Dora Siena 100/A, 10153 Torino (Italy)
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DECENTRALIZATION IN HETEROGENEOUS REGIONS: A BIASED TECHNOLOGICAL CHANGE APPROACH

CHRISTOPHE FEDER and RODRIGO KATAISHI

UNIVERSITÀ DEGLI STUDI DI TORINO

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Decentralization in heterogeneous regions: A biased technological change approach

Christophe Feder[§,‡] and Rodrigo Kataishi[△,‡]

[§] *University of Aosta Valley - Aosta, Italy*
[△] *National University of Tierra del Fuego - Ushuaia, Argentina*
[‡] *University of Turin - Turin, Italy*

Abstract

Regional heterogeneity plays a determinant role in both the decentralization and the biased technological change literature. Merging these perspectives, this paper offers a novel approach on how productivity of firms can be affected by public policies within centralized and decentralized political systems. The contribution of this paper is to develop a theoretical model that introduces the biased technological change concept instead of the traditional Total Factor Productivity (TFP) to evaluate policy outcomes. By doing so, we find that public policies may not always have the *expected effect* in terms of efficiency. In our model, productivity and efficiency will depend on the level of regional heterogeneity, the inter-regional spillovers and the relative amount of regional endowments. In particular, our point argues that if there is regional heterogeneity but no inter-regional spillovers a centralized policy *can be* efficient and that if regions are homogeneous in the presence of inter-regional spillovers, a decentralized strategy *can be* efficient too. Last, we find that there are cases that may reach no efficient outcomes, regardless the political system.

JEL classification: O33, O25, O38, H73, R58.

Keywords: *Biased Technological Change, Decentralization Theorem, Localized Technological Change, Institutional Design, Geography, Policy.*

1 Introduction

Innovation and productivity are determinant features of economic systems, strongly related to growth patterns and performance of economies. These aspects can be influenced by policies, not being a solved matter how interventions need to be implemented. Regions with centralized or centralized political systems may face different outcomes from a given policy, as is denoted by the decentralization theorem (Oates, 1972). We will review and discuss the main conclusions of these ideas. By doing so, we propose an analysis that considers the implications of an innovation policy taking into account a number of regional[1] specificities, such as the centralization level of the political system, the regional heterogeneity and the existence of inter-regional spillovers. The findings and conclusions are oriented to contribute to both, decentralization and innovation research fields.

As so, this paper relates two branches of literature. The first branch of studies are focused on the impact that fiscal decentralization has on regional productivity performances. Following the standard decentralization theorem on this matter (Oates, 1972), it is pointed out that a centralized level of policymaking is able to consider the aggregate interest of an economic system, but they lack the elements to take into account the regional specificities of multiple, heterogeneous regions. At the same time, local policymakers are aware of the local necessities and interests, but they are not able to entirely take into account the centralized[2] interests derived from the inter-regional interactions[3]. This branch of literature evaluates productivity levels through the traditional total factor productivity (TFP) calculation, relying on the explanatory power of aggregated technological shifts. Recent developments on economics of innovation literature propose that technological change can be a biased process (Acemoglu, 1998; Antonelli and Quatraro, 2010). This breakthrough implies that TFP cannot capture important technological features under regional heterogeneity. Since the main conclusions on the decentralization literature are based on TFP, the actual impact of regional productivity due to the heterogeneous endowments per region (and hence, specialization patterns) might be missed in the analysis, leading to incomplete or inaccurate conclusions.

The second branch studies productivity variations using the biased technological change (BTC) concept, which is able to complement the TFP analysis by adding information about context specific technological effects. These ideas are novel contributions developed in the framework of recent economics of innovation field discussions (see Antonelli, 2010 and Antonelli and Quatraro, 2013 for further detail). The advantages of making use of the Biased Technological Change (BTC) consist in the introduction of the local dimension into the analysis of policies within heterogeneous contexts (that TFP omits due to neutrality assumptions). As so, this paper presents an approach that combines decentralization issues with the latest productivity related discussions, developing a model that considers a union of regions affected by biased shifts of technological change, inter-regional spillovers

[1]This work will consider no differences between local and regional dimensions. As so, the terms will be used indifferently from now on.

[2]The centralized level will be expressed as central level or the one representing the global interests interchangeably.

[3]One example of this is the work of Berliant and Yu, 2015

and heterogeneity.

Technological change affects each region differently. This process takes place because of the presence of heterogeneous productive structures, technological paths (the history of the region) and resource related singularities that make each context react differently to a given technological shock[4]. Different regional endowments *will* produce heterogeneous reactions to technological variations. The traditional measurement of productivity based on TFP does not consider these regional differences since it assumes that technological change is (Hicks) neutral[5]. In order to overcome this restriction a number of assumptions of the traditional TFP framework need to be relaxed.

If regions are heterogeneous, then the technological change's direction matters: a technological change that favors capital intensive technologies will tend to boost capital intensive regions (affecting with a stronger positive effect the output elasticities of that factor in disadvantage of other production factors). Analogously, regions with labor intensive endowments (and specialization patterns) will face relative disadvantages with respect to the capital intensive regions given the same shock. A relevant portion of the impact of technological changes is reflected in the factor output elasticities (making a factor be relatively more productive than others). This logic proposes that output elasticities may vary over time and be different for each productive factor and for each particular environment (i.e. regions). To capture the differential effects of technology per region the neutrality assumption is dropped. As so, affirming that technology is not neutral implies that how much and in which direction the output elasticities of each factor vary are a critical aspect of the analysis.

This idea comes formalized in the BTC approach. By changing factor output elasticities, a novel indicator is produced, sensible enough to capture variations on the use of productive factors in each region and allowing one to trace the particular effect that technological shocks have in local economies. Hence, the BTC approach complements the TFP adding the localized effect of technological change.

This work proposes to mix the BTC analysis with the decentralization literature. The combination of these theories is not only a novelty in terms of a conceptual analysis, but also directly affects the main conclusions achieved by the decentralization literature (e.g. the decentralization theorem), allowing new tools and perspectives to evaluate policy outcomes.

As so, the general objective of this paper is to build a macroeconomic model considering the relations between decentralized (centralized) policymaking and their impact on firm's productivity. In order to do so, we depart from the decentralization theorem (Oates, 1972) and combine it with the seminal contributions of Solow (1957) and Griliches (1979) to evaluate policy outcomes within heterogeneous contexts, incorporating Acemoglu (1998, 2010, 2015) and Antonelli and Quatraro's (2010, 2014) BTC ideas.

The departing point of this paper stands on the idea that political decentralization

[4]In this work, technological shocks are understood to be particular events of technological change with exogenous nature.

[5]Meaning that technological change affects *in the same* proportion the productive factors, disregarding the particular productive structure of each region and hence the heterogeneous impact that technology may generate (different specialization processes, movements of factors, etc).

could affect innovation and productivity performances (Becker, 2014a, 2014b; Cerniglia and Longaretti, 2013; Hammond and Tosum, 2011). According to Oates (1972), there are information failures between central and regional levels of policymaking. These failures are manifested in asymmetries regarding regional specificities, which are known by the local policymakers but ignored by the central policymaking level. Analogously, for the central policymakers priorities the consideration of aggregate efficiency is determinant, but this element is an aspect that the local level tend to omit. Following this framework, if there are inter-regional spillovers, only the centralized policies are able to consider the overall effect in an efficient way. The outcome of these processes are uniform policies that fix average distributions of wealth aiming to overcome the regional *veil of ignorance* (Besley and Coate, 2003; Hindriks and Lockwood, 2009). Contrastingly, decentralized policies are focused on the characteristics of each region, arguing local efficiency as the predominant criteria (omitting the aggregated effect that spillovers may generate when regions interact), increasing the systemic heterogeneity through the maximization of endowment of factors. Due to the nature of a localized criteria of maximization, region specific productivity variations might affect negatively other regions and generate inefficient results at the aggregated level (Tiebout, 1956; Bodman et al., 2012).

The statements mentioned above are synthesized in the decentralization theorem (Oates, 1972) establishing that: i) if there are no spillovers and regions are homogeneous then centralization and decentralization cases are equally efficient; (ii) if there are no spillovers and regions are heterogeneous then centralization is *always* inefficient; (iii) if there are spillovers and regions are homogeneous decentralization is *always* inefficient; (iv) if there are spillovers and regions are heterogeneous then inter-regional spillovers and regional heterogeneity are the key variables to determine the efficient systems. These four points will be considered as the decentralization theorem in this paper.

The evidence surrounding the effects that a centralized (decentralized) system has on the productivity performance is inconclusive. On the one hand, the most diffused theoretical discussions (Oates, 1999; Brueckner, 2006; Hatfield, 2015) propose that a decentralized system provides higher efficiency levels and avoids the potential inefficiencies derived from the application of a uniform policy. Following this idea, *a priori*, the expected impact on productivity performance may select a decentralization strategy as the preferred choice. On the other hand, empirical evidence found contrasting results on this matter, refuting or supporting the existence of these relations (Fernández-Ribas, 2009; Busom and Fernández-Ribas, 2007; Becker, 2014a; Allers and Geertsema, 2016), even with the use of similar empirical samples (Behnisch et al., 2002; Belitz et al., 2010; Becker, 2014b). However, no scholar considered the biased component of technological change (Antonelli and Quatraro, 2010) in the outcome evaluation[6], centering their conclusions on TFP figures that only take into account neutral shifts on production techniques[7]. Our main statement points out the need to include additional elements to these discussions: the BTC effect as

[6]Recalling that the decentralization literature used the TFP to measure productivity, discarding the heterogeneous, region specific effects that technology have on each context. The BTC is able to capture these processes due to the focus it presents on both the factor output elasticities and the endowments variations.

[7]Implying that heterogeneous regions are equally affected by exogenous technological shocks.

a complementary measurement of TFP estimations is a critical feature that explores the impact of a policy within regions.

The advantages of using the bias instead of the traditional TFP approach rely on the sensibility gained by the first, which allows to better understand the localized impact that technology changes have on heterogeneous contexts. If regions vary in their endowment of factors, then their specialization patterns should differ (Helpman, 1998) and an external shock should affect them in different ways. From a theoretical point, two effects derived from technological change will affect each region and the overall system: the shift of the isoquant map, and the variation of its slope. The BTC effect is concentrated in the analysis of the latter and represents a novelty within the decentralization discussion. Moreover, these two effects interact when technological change occur: the biased effect, BTC, and the neutral effect, NTC, are the two components of technological change.

From a technical point, departing from a Cobb-Douglas production function with two input factors, K and L, and constant returns to scale (the sum of the output elasticities, α and β, is 1), if the technological change is neutral then the output level is $Y_t = NTC_t \cdot K_t^{\alpha_t} L_t^{\beta_t} = TFP_t \cdot K_t^{\alpha_t} L_t^{1-\alpha_t}$. Due to the fact that both K and L are related to α, this formulation can be re-expressed in terms of output elasticities. Moreover, by construction we obtain that $NTC_t = TFP_t$. If the output elasticities react to technological change (Acemoglu, 1998; Accetturo et. al., 2014) there is a biased component, implying that the former estimation needs the inclusion of an additional effect to the TFP. Let $\tilde{K}_t$ and $\tilde{L}_t$ be K and L at time t if the output elasticity does not change over time respect to the base moment $t = 0$. Then $Y_t = (NTC_t \cdot BTC_t) \cdot \tilde{K}_t^{\alpha_0} \tilde{L}_t^{\beta_0} = TFP \cdot \tilde{K}_t^{\alpha_0} \tilde{L}_t^{1-\alpha_0}$. Note that $ln(TFP_t) = ln(NTC_t) + ln(BTC_t)$ so the (logarithmic) NTC and the (logarithmic) BTC effects are two distinct and uncorrelated components of technological change, which signifies that we can study the two components separately. In other words, the methods and conclusions proposed in this paper are complementary to the previous studies.

Thus, two broad types of technological change can be identified. The first takes place when techniques variations affect the entire system through general-purpose technologies, altering the ways in which the production is carried and disregarding the regional specificity. If technology is neutral, this case tends to account for the total technological change. The second considers idiosyncratic reactions to a technological change from sectors and regions based on the idea that production processes rely on a specific endowment of factors that are embedded in each context, having impact on specific production assets and labor skills (Accetturo et. al., 2014). A technological change may modify (if it's not neutral) the nature of productive factors, altering the way in which they interact to produce output, and changing the output elasticity over time and local context. The BTC reflects the latter, whilst the NTC (or Solow's technological change) is only able to capture the neutral shifts of the production functions.

The paper next section will present the model considering regional heterogeneity, spillovers, BTC and its effect on different political contexts. Section 3 will discuss our findings making use of a systemic approach to the corollaries of our theoretical development. The last section of the paper will offer the concluding remarks.

2 The model

2.1 Assumptions

We consider a country with 2 regions, $j = 1, 2$. In each region there is a public sector (in charge of policymaking) and a private sector (firms). The public sector is characterized by its institutional design i, where i represents a centralized or a decentralized design. In the first step, the public sector produces public goods, G_j^i, that affect the level of innovation using a lump-sum tax, T_j, paid by the private sector. In the second step, given the public decision, the private sector produces goods and services, Y_j, using capital, K_j, and labor, L_j.

Let A_j be the (Hicks-)neutral augmentation of the inputs. Like in Griliches (1998), we assume that the production function has a Cobb-Douglas specification:

$$Y_j = A_j K_{-j}^{\gamma_j} K_j^{\alpha_j} L_j^{\beta_j}, \tag{1}$$

where γ_j are the inter-regional spillovers[8].

Assume that in each region there are constant returns to scale, $\beta_j = 1 - \alpha_j$, while at the country level there may be increasing returns to scale, $\gamma_j \geq 0$ (Griliches, 1979). In addition, we assume that the effect of K_j within a region j is greater than the indirect effect of K_{-j} over other regions $-j$, i.e. this imply that $\gamma_j < \alpha_j$. Finally, to simplify the explanation, we assume that K_j/L_j is high enough to represent an actual economic relation; if this is not the case, all the first-best comparisons between centralization and decentralization systems simply become second-best comparisons[9].

The main literature considers A_j as the total technological change (Solow, 1957). However, this may only represent a partial component of technological variations on production. As shown by Acemoglu (1998), technological change can also be described in relation to the input elasticities. More precisely, when A_j varies there is a parallel shift of the isoquant map to the origin, which is manifested in the NTC effect; and, when the output elasticities vary, there is a slope shift of the isoquant map to the cheaper input factor, that is called the BTC effect.

Let C_j be the total production cost for the region j:

$$C_j - T_j = r_j K_j + w_j L_j, \tag{2}$$

where r_j and w_j are, respectively, the capital and labor unitary costs in region j. Therefore, input factors may have different costs between regions. T_j stands for the lump-sum tax.

[8]Although we implemented a traditional fashion to represent spillovers following Griliches approach for j regions, it is worth noting that in this model the spillover effects are captured as an expansion of K. This decision has three main arguments: first, that is consistent with the idea that exogenous innovations are embodied in technologies that can be transferred within capital related determinants. Second, in a two factors production function the expansion of K due to spillovers seems more appropriate and realistic than an expansion of L, which is clearly determined by a fixed quantity of workers in each region. Third, if some kind of complementarity of production factors exist (as, indeed, the economics of innovation literature states) this model can be modified to include more detailed spillover mechanisms. Future versions of this work may explore, amongst other improvements, more realistic interactions in the inter-regional spillovers.

[9]In particular, we assume that $\ln(K_j/L_j) > 1/(2\alpha_j^2 - \alpha_j(1-\gamma_j) + \gamma_j)$.

Firms maximize their own profits. This part of the model is standard, assuming that the decision that determines the amount of input depends on their abundance but also on their output elasticities. We assume that the public sector is able to modify the output elasticities using public expenditure G_j^i. Additionally, we concentrate our analysis on policies that are oriented to modify technological relations by affecting output elasticities, leaving out of the analysis those interventions that are oriented to generate massive technological shifts (i.e. those that affect A_j, like general purpose technologies and diffused patents). In other words, starting from Aghion (2011) and Antonelli (2012), we assume that there are policies that are able to affect productivity towards the use of one factor or other[10]. If that's so, the public expenditure can be expressed as:

$$\alpha_j = a_j + b_j G_j^i, \tag{3}$$

where $a_j, b_j \geq 0$ are two coefficients. This idea is based on Acemoglu (1998)'s intuition on policy issues and represents a novel contribution to this approach.

Let G_j^i be the public expenditure oriented to boost productivity, able to modify α in region j with the institution design i. Therefore, $G_j^i > 0$ implies policies oriented to increase α_j; vice versa, $G_j^i < 0$ implies policies oriented to decreases α_j, i.e. to increase β_j. In other words, if $G_j^i < 0$ then the policy increases the productivity of capital; and if $G_j^i > 0$ then the policy increases the productivity of labor[11]. Considering the public budget constraint, we know that $|G_j^i| \leq T_j$; so $G_j^i \in [-T_j, T_j]$. The decision about G_j^i is affected by the institutional design i, that can take two parameters: the decentralized institutional design, d, and the centralized institutional design, c. In the first case, the public sector considers only the region j and it chooses the optimal level of G_j^d, called G_j^D. In the second case, the public sector considers the country level and it chooses the optimal level of G_j^c, called G_j^C.

Let I_j^i be the set of information for the region j, with the institutional design i. Both institutional designs maximize the expected productivity, given a set of information. Indeed, we assume that in the public sector there is global information related to the regional level, $E(V_j) = \bar{V}$. This implies that in the decentralized institutional design the decisions do not consider the spillovers effects; while in the centralized one, the decisions are uniform. This setup is coherent with the literature on decentralization (Oates, 1972; Besley and Coates, 2003; Lorz and Willmann, 2013).

[10]Indeed, it is feasible to think that policies can boost productivity by promoting technological improvements. For instance, programs like Horizon 2020 define specific sets of policies that can be oriented to the acquisition or update of physical capital (which may have a stronger effect towards the productivity of one factor, i.e. K and particularly α) and other sets of policies oriented to training, organization and learning processes that are more oriented to human resources capabilities, which affect the role of the labor factor (L) and its participation in the output (hence, β according to our setup). Following this logic we can argue that, in a general way, policies can affect productivity. Also, we can say that these relations can be biased towards favoring the use of one factor over the other, affecting the values of α or β in different ways.

[11]For instance, an example of a $G_j^i > 0$ policy can be a subsidy to the acquisition of specific types of technology like ICTs or green technologies.

2.2 Results

We solve the model backwards. The maximization problem for the private sector in region j is $\max_{K_j,L_j} Y_j$ given equations (2) and (3). Solving the problem, we find a typical microeconomics result that can be summarized by the following Lemma:

Lemma 1 *From equations (1), (2) and (3), the optimal level of capital is:*

$$K_j^* = \frac{\alpha_j(C_j - T_j)}{r_j}; \tag{4}$$

and the optimal level of labor is:

$$L_j^* = \frac{(1-\alpha_j)(C_j - T_j)}{w_j}. \tag{5}$$

Therefore, the private sector does not consider the inter-regional spillovers. This implies that the level of capital is insufficient. Of course, the inputs of each region are (potentially) different between regions because the output elasticity and the input costs could be different in j (e.g., by geographical or historical reasons).

In the second stage of the game, a decentralized public sector chooses the best G_j^d that maximizes the regional production expectation, $E(Y_j|I_j^d)$, given the equation (3) and $I_j^d = \{K_j^*, L_j^*, a_j, b_j\}$. Solving it, we obtain:

$$\frac{dY_j}{dG_j^d} = Y_j \ln\left(\frac{K_j^*}{L_j^*}\right) b_j. \tag{6}$$

Therefore, if $L_j^* < (>) K_j^*$ then only an increase (reduction) of G_j^d, $dG_j^d > (<) 0$ is able to increase the regional productivity, $dY_j > 0$; if $L_j^* = K_j^*$ each possible policy G_j^d does not affect the regional productivity. The following Proposition summarizes the policy implications of the model:

Proposition 1 *With a decentralized institutional design, the public sector solution is:*

- $G_j^D = T_j$ *when* $L_j^* < K_j^*$;
- $G_j^D = -T_j$ *when* $L_j^* > K_j^*$;
- $G_j^D \in [-T_j, T_j]$ *when* $L_j^* = K_j^*$.

Intuitively, with the decentralized institutional design, if the regional level of capital is the most abundant factor in the region, then the public sector will address all its efforts towards increasing α_j in order to stimulate the private sector and increase its capital level. If the regional level of labor is the most abundant factor in the region, then the public sector directs all its efforts towards encouraging the increase of labor for the private sector. If there is not an abundant factor, then the direction of public policy is irrelevant. However, the regional public sector does not take into account the inter-regional spillovers, which can lead to the emergence of an externality failure. Therefore, there is an underproduction on the level of capital. In this case, this type of failure emerges only when the more abundant factor in the region is the capital.

Considering a centralized public sector, the best G_j^c maximizes the whole production expectation of the country, $E(Y_1 + Y_2 | I_1^c, I_2^c)$, given equation (3) and the available set of information $I_j^c = \{\bar{K}^*, \bar{L}^*, \bar{a}, \bar{b}\} = I^c$. Solving it, we obtain:

$$\frac{dY_j}{dG_j^c} = Y\left(\ln\left(\frac{\bar{K}^*}{\bar{L}^*}\right) + \frac{\bar{\gamma}}{\bar{\alpha}}\right)\bar{b}. \tag{7}$$

Similarly as before, if $\bar{L}^* < (>) \bar{K}^* \bar{\xi}$ where $ln(\bar{\xi}) = \bar{\gamma}/\bar{\alpha}$, then only the increase (reduction) of G_j^c, $dG_j^c > (<)0$ increases the regional productivity $dY_j > 0$. Also, is worth to mention that if $\bar{L}^* = \bar{K}^* \bar{\xi}$ each possible policy G_j^c does not affect the regional productivity. The following Proposition shows the policy implications:

Proposition 2 *With a centralized institutional design, the public sector solution is:*

- $G_j^C = T_j$ *when* $\bar{L}^* < \bar{K}^* \bar{\xi}$*;*
- $G_j^C = -T_j$ *when* $\bar{L}^* > \bar{K}^* \bar{\xi}$*;*
- $G_j^C \in [-T_j, T_j]$ *when* $\bar{L}^* = \bar{K}^* \bar{\xi}$*.*

where $ln(\bar{\xi}) = \bar{\gamma}/\bar{\alpha}$*.*

Thus, with the centralized institutional design, if the country level of capital plus the spillovers effects is the most abundant factor in the country, then the public sector will direct all its efforts towards increasing α_j in order to stimulate the private sector and increase its capital level. If the country level of labor minus the spillovers effects is the most abundant factor in the country, then the public sector directs all its efforts towards encouraging the increase of labor for the private sector. Otherwise, the direction of public policy is irrelevant. However, if the central public sector does not (perfectly) know the regional specificity, then information failure emerges, which can result in a miss-allocation of resources, either in the level of capital or labor. In this case, this failure emerges only when the regional ratio of endowment of factors has a different composition (the opposite direction) than the one present at the country level.

Finally, in order to compare the solutions of both institutional designs we calculate a benchmark of public expenditure, G_j^B. It is assumed that politicians choose the best policy G_j^b that maximizes the whole production expectation in the country, $E(Y_1 + Y_2 | I_j^b)$, given equation (3) and perfect information $I_j^b = \{K_j^*, L_j^*, a_j, b_j\} (= I_j^d)$. The solution to this system is the optimal policy derived from *ideal* (far from reality) conditions on the public sector, given the private sector decisions. This system is analogous to assume either a decentralized public sector where no regions are self-interested or a centralized public sector with perfect information. Solving it, we obtain:

$$\frac{dY_j}{dG_j} = \left(Y_j \ln\left(\frac{K_j^*}{L_j^*}\right) + Y_{-j}\frac{\gamma_j}{\alpha_j}\right) b_j. \tag{8}$$

In this case, as in the previous ones, if $L_j^* < (>) K_j^* \xi_j$ and $ln(\xi_j) = (\gamma_j Y_{-j}^*)/(\alpha_j Y_j^*)$, then only the increase (reduction) of G_j, $dG_j > (<) 0$ may increase the regional productivity $dY_j > 0$. If $L_j^* = K_j^* \xi_j$ each possible policy characterized by G_j does not affect the regional productivity. Then, the benchmark situation can be summarized in the following Proposition:

Proposition 3 *The public sector benchmark solution is:*

- $G_j^B = T_j$ *when* $L_j^* < K_j^* \xi_j$;
- $G_j^B = -T_j$ *when* $L_j^* > K_j^* \xi_j$;
- $G_j^B \in [-T_j, T_j]$ *when* $L_j^* = K_j^* \xi_j$;

where $ln(\xi_j) = (\gamma_j Y_{-j}^*)/(\alpha_j Y_j^*)$.

Intuitively, with the benchmark institutional design, if the regional level of capital plus the spillovers effects is the most abundant factor in the region, then the public sector will direct all its efforts towards increasing α_j in order to stimulate the private sector and increase its capital level. If the regional level of labor minus the spillovers effects is the most abundant factor in the region, then the public sector directs all its efforts towards encouraging the increase of labor for the private sector. Otherwise, the direction of public policy is irrelevant. By definition, in the benchmark solution the politicians consider both spillovers and local specificity, then both the information and externality failures never emerge.

In particular, given $\xi_j > 1$, we know that $K^* < K^* \xi_j$. Hence, the decentralized public sector is expected to show the same policy as the optimal one, except in the case of $K_j^* < L_j^* < K_j^* \xi_j$ in which the decentralized public sector tends to favor the wrong input. This outcome derives from the fact that the decentralized institutional design underestimates the importance of spillovers. Regarding the benchmark within the centralized institutional design, an optimal policy takes place when $L^* < K^* \bar{\xi}$ and $L_j^* < K_j^* \xi_j$ or when $L^* > K^* \bar{\xi}$ and $L_j^* > K_j^* \xi_j$. In other words, there are two different effects. First, when $Y_j = Y_{-j}$ the most abundant factor in the region j is the same as the one of the country, so the centralized policy is optimal (and vice versa). Second, if the public sector decisions $I_j^b = I_j^c$ and $K_j^* \bar{\xi} < L_j^* < K_j^* \xi_j$ ($K_j^* \xi_j < L_j^* < \bar{\xi}$) hold, then the centralized institutional design under-estimates (over-estimates) the importance of spillovers. These two effects derive from the fact that the centralized institutional design does not consider local specificity in their complete complexity.

3 Discussion

The model developed above entails a number of implications that affect conceptual and theoretical discussions. Figure 1 shows an immediate result of the Propositions (1)-(3). A set of nine different situations can be identified (clustered in four patterns). The decentralization theorem's statements are shown as a particular case of our theorem due to the inclusion of the BTC effect, heterogeneity and spillovers interactions.

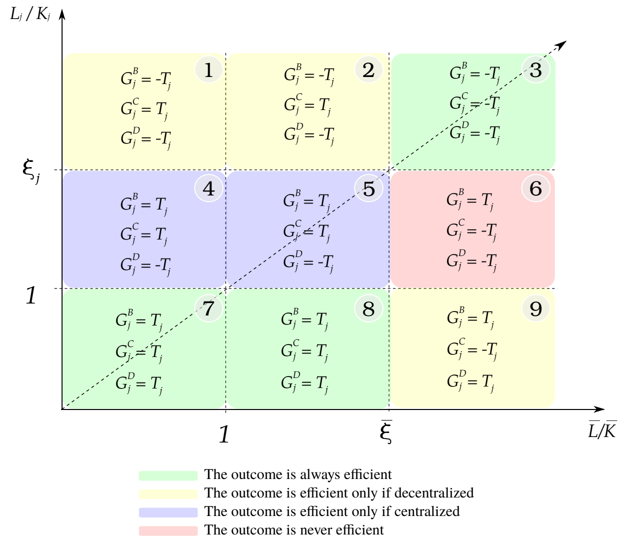


Figure 1: Model's propositions

This model, due to the interactions amongst BTC, regional heterogeneity and inter-regional spillovers, is able to explain the existence of negative results (in terms of productivity performance) in centralized and decentralized systems. The recognition of the importance of spillovers effects is critical for deeply understand the incentives to the private sector, determined by the policy maker, and for the direction of technological change at the regional level. In particular, Figure 1 establishes a benchmark exercise amongst different combinations of centralized and decentralized cases, considering the spillovers effects for heterogeneous regions, combined with the total effect of technological change. It is clear to see that even if policymakers do not consider the spillovers as a determinant aspect of their regulatory policies, these actually have an effect on the whole economy. Due to this effect, and the potential complementarity[12] of regions, a decentralized system may provide incentives that lead production to an inefficient direction of localized technological change. In contrast, a centralized system may be exposed to a similar situation: it may not consider the heterogeneity of regions and the potential complementarity of their endowments, leading to a potential inefficient path.

In Figure 1 both axes are measured in relative factors, L/K, where the vertical axes represents the regional level, L_j/K_j, and the horizontal axes represents the average level in the country, $\overline{L}/\overline{K}$. The thresholds points are 1, i.e. $L = K$, and ξ_j (in horizontal the axis $\bar{\xi}$) which represent the amount of factorial expansion due to the existence of spillovers.

Each area of Figure 1 represents an outcome in which both the local and the (aggregated) average levels interact. For example, in the area 1 the optimal political choice of technological direction is on the labor factor, i.e. $G^B = -T_j$, it is equal to the centralized

[12]Due to, for instance, the spillovers effects.

choice $G^C = T_j$ but it is the opposite with respect to the decentralized choice $G^D = -T_j$. The efficient outcome is noted as G^B, achieved only if perfect information assumptions hold. G^C and G^D stands, respectively, for the decentralized and centralized criteria of decision-making. The first only considers the effects of spillovers, while the second only considers the regional heterogeneity.

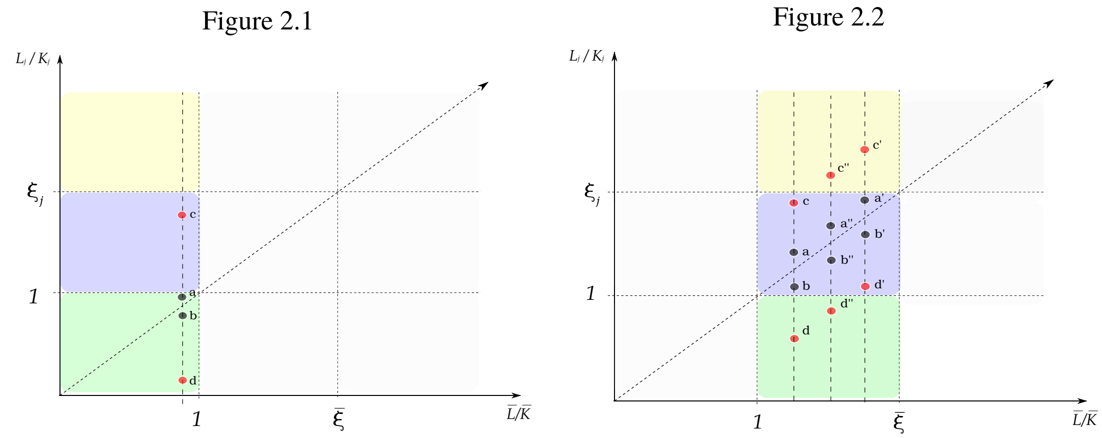
In the cases where $\bar{L} > \bar{K}\bar{\xi}$ and $L_j > K_j\xi_j$ or $\bar{L} < \bar{K}\bar{\xi}$ and $L_j < K_j$, the outcomes lead to optimal results in which the efficiency is achieved in both systems, meaning that they are indifferent (summarized in areas 3, 7 and 8). Instead, if $\bar{L} < \bar{K}\bar{\xi}$ and $L_j > K_j\xi_j$ or $\bar{L} > \bar{K}\bar{\xi}$ and $L_j < K_j$ only the decentralization is efficient (areas 1, 2 and 9). Similarly, when $\bar{L} < \bar{K}\bar{\xi}$ and $K_j < L_j < K_j\xi_j$ only the centralization is efficient (areas 4 and 5). Finally, if $K_j < L_j < K_j\xi_j$ and $\bar{L} > \bar{K}\bar{\xi}$ neither centralization nor decentralization offer an efficient policy (area 6).

Focusing on the novel BTC concept, a positive effect of BTC implies a congruent specialization since the (regional and/or country level) endowments are coherent with the technological event that modified the productive relations, such as a policy intervention (Antonelli and Quatraro, 2014). Given the endowments and the political system of each region, the effects that a policy generates impact diversely. There are two main situations: the decentralization of the innovation policy is always coherent with the regional endowments; and the centralization of the innovation policy is coherent with the regional endowments only under specific circumstances. Decentralized interventions always choose mechanisms that enforce the technological direction in its own region so, the local direction of technological change always has a positive effect of BTC. Only in the areas 3, 6, 7 and 8 the effect of BTC is positive for a centralized situation. Of course, in all of these areas (and only in these areas) the bias effect is positive because the direction of technological change is necessarily the same for the two political systems (see Figure 1). However, in area 6 the decision between centralized and decentralized interventions is indifferent under an outcome that is always inefficient; this inefficiency leads to lower productivity on the country and the regions. Area 6 can be considered as a *double trap* since the direction of the policy is efficient, i.e. the effect of BTC is positive; but, it is inefficient, because both systems choose a suboptimal policy.

The diagonal dashed line in Figure 1 represents the situation in which there is no regional heterogeneity (which can take place amongst areas 7, 5 and 3). The absence of heterogeneity equals local and aggregate levels of relative factorial endowments, giving a main role to the centralized policy. Centralization is the optimal choice when $K_j < L_j < K_j\xi_j$ and $\bar{K} < \bar{L} < \bar{K}\bar{\xi}$. However, there are two cases that are not considered in the decentralization theorem: when $L_j < K_j$ and $\bar{L} < \bar{K}$ or when $L_j > K_j\xi_j$ and $L_j > K\bar{\xi}$. Indeed, in both situations the application of particular types of policies (centralized or decentralized) is indifferent in terms of outcome efficiency, leading to an efficient technological change direction[13].

In the situation in which there are no spillovers, i.e. $\gamma = 0$, decentralization is the best choice only under two scenarios: $L_j < K_j$ and $\bar{L} > \bar{K}$ or $L_j > K_j$ and $\bar{L} < \bar{K}$. This paper

[13]In different contexts, also Ogawa and Wildasin (2009) and Brueckner (2013) also find that decentralization could efficiently solve the the inter-regional spillovers problem.



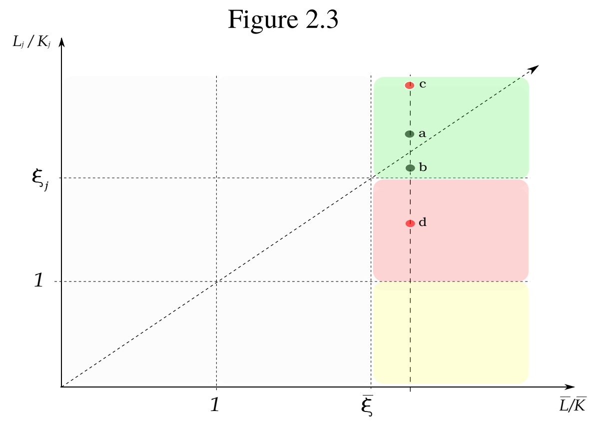


Figure 2: Heterogeneity in regions affects the outcome in terms of efficiency, given the existence of a fixed amount of spillovers. When the less heterogeneous pair a,b is compared with more heterogenous cases like the pair c,d the outcome is directly affected due to the interaction of regional heterogeneity and the spillovers effects.

Figure 2: Model's propositions and regional heterogeneity implications

signals that there are also two other possibilities that may derive in indifferent outcomes (this occur when $L_j > K_j$ and $\bar{L} > \bar{K}$ or $L_j < K_j$ and $\bar{L} < \bar{K}$). With the absence of spillovers, the decentralized case is the main optimal choice. However, as in quadrants 2 and 3, the centralized policy could be equally efficient. In other words, the decentralization theorem states that without spillovers the efficient policy is to decentralize. We prove that even without spillovers, there are cases in which centralization is an efficient alternative. As we will analyze below, the level of regional heterogeneity may affect the policy outcome. From a theoretical point of view, a centralized policy can be efficient, even when there are not spillovers. As so, our framework transcends the second and the third point of the decentralization theorem.

Summarizing, Figure 1 shows that if there are spillovers and regional homogeneity, there are cases in which decentralization leads to the optimal solution for the region j (on the diagonal dashed line in the areas 3 and 7). Equivalently, there are cases in which centralization leads to the optimal solution, even if there are regional heterogeneity but not spillovers (areas 3 and 7). Finally, there are cases in which neither centralization nor decentralization leads to the optimal solution (area 6). All of these conclusions show important modifications of the main structure of the decentralization theorem.

On top of the formerly described cases, there are other sets of implications of the model that are focused on the heterogeneity component. Figures 2 (a, b and c) and 3 (a and b) describe this, using particular situations based on heterogeneous regions with and without spillovers. All these cases offer additional elements to explain situations in which the traditional decentralization theorem do not apply. In particular, they show that the consideration of factor endowments in heterogeneous regions contexts are a fundamental aspect to take into account in the efficiency evaluation of policies.

Figure 2.1 shows two cases in which the average relative endowments $\bar{L}/\bar{K}$ are less than 1, i.e. $\bar{L} < \bar{K}$. Considering a pair of heterogeneous regions a and b on area 7, the two regions are indifferent about the political power decision. However, if heterogeneity increases (regions c and d) it is possible to find different conclusions since region c is now in area 4 (in which only the centralized choice is optimal). In this case, the outcome of the model is not compatible with the decentralization theorem. Indeed, if regions show low levels of heterogeneity, both solutions (centralized and decentralized) can be optimal; but if the heterogeneity increases, there is a threshold where centralization can be more efficient. In other words, contrasting the traditional findings, increments in region's heterogeneity cannot lead only to decentralized recommendations, but also to centralized policies.

Figure 2.2 shows additional cases in which the average relative endowments and heterogeneity interact $\bar{K} < \bar{L} < \bar{K}\bar{\xi}$. This figure, as the previous one, entails several scenarios that are not necessarily considered in the traditional decentralization theorem. Movements from the couple of regions a, b to the couple c, d point the case explained in Figure 2.1. Couples a', b' and c', d' represent contexts of higher average relative endowments that may offer different conclusions. First, couples a', b' signal, as before, a centralized policy as the most efficient outcome. However, when heterogeneity increases to c', d' an *unpredictable outcome* rises. Under higher average relative endowments the efficient policy is changed to decentralization for region c' and to centralization for region d', presenting a situation in which there is necessarily one region that is not able to implement an efficient policy. This drastically opposes the conclusions of the decentralization theorem. Finally, the couples a'', b'' and c'', d'' represent a mirrored case to the one explained in Figure 2.1, but offering a decentralized outcome as the efficient choice for region c''. Comparing the three cases, with the same level of heterogeneity the policy outcomes vary on the average relative endowments. This entails another important inference: same levels of heterogeneity may lead to different policies if the factor endowment of the country changes.

Figure 2.3 stands for contexts in which $\bar{L} > \bar{K}\bar{\xi}$. In this case, if heterogeneity is sufficiently low then the policy recommendations are indifferent between centralized and decentralized policies. However, if regional heterogeneity increases then at least one of the regions will confront an inefficient policy, as in d. Departing from a, b in which regions are indifferent, the case of c, d implies a critical scenario for the two of them: both are still indifferent, but d will always confront an inefficient outcome no matter the decision of c. This also imply that in a case of indifferent decisions, regions may be affected in different ways. The situation described in Figure 2.3 can be useful to analyze developing contexts

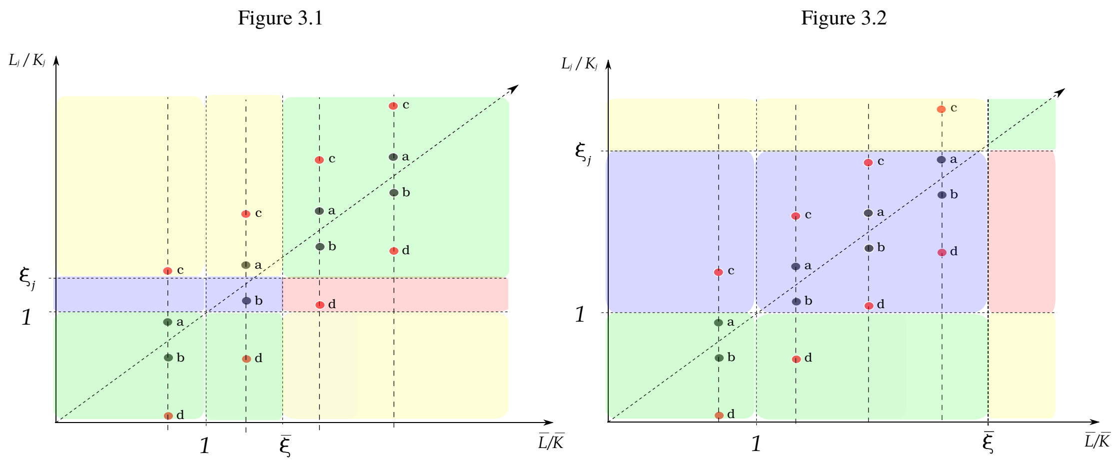


Figure 3: Model's propositions with low (3.1) and high (3.2) spillovers and regional heterogeneity

($\bar{L}/\bar{K}$ is high). Special attention should be payed to the *double trap* of area 6, because in addition to the heterogeneity conflict in terms of political choice there is an issue of inefficient direction of the technological change, even with positive effect of BTC.

The importance of *unpredictable outcomes* (showed in Figure 2.2 but also possible in other situations) might be particularly relevant within developing contexts. The regional heterogeneity is often a feature of recently industrialized countries (such as South-American or Asian economies with recent strong productive and technological transformations) pointing out the need to acknowledge these characteristics within technological policies in order to gain sustained productivity growth. Now, we will show that a possible solution to this problem is to increase the level of inter-regional spillovers.

Figure 3 deals with heterogeneity and spillovers variations. When the level of spillovers changes the *middle area* of Figure is affected. A lower level of spillovers turns that area thicker, higher level of spillovers increases it (Figure 3.1). Given heterogeneity variations from a, b to c, d, the endowment factors level affects the efficient policy outcome. A lower level of spillovers tends to transform centralized optimal situations into decentralized ones (in particular with the average of capital intensive regions). However, the indifferent situation possibility also increases (particularly with the average of labor intensive regions).

Figure 3.2 shows a spillovers increase situation. The middle area of the graph increases, tending to favor the choosing of centralized policy outcomes. The place for aggregated economies with labor intensive structures decreases, replacing them with the spillovers effects. This expansion has a negative effect on the probability of selecting a decentralization policy as dominant strategy. From Figure 3, we conclude that, given heterogeneity levels, the higher level of spillovers tends to favor a centralized policy, as the last point of the decentralization theorem shows. However, this is only true if the regional economic system is capital intensive and, in general, it depends on the factor endowment of the country.

To conclude, the decentralization theorem's results are contemplated in our model as a particular case. As so, the centralized case constitutes a not less than efficient choice if there are no inter-regional spillovers and the regions are heterogeneous. The decentralized case constitutes a not less than efficient choice if there are regional homogeneity without spillovers. We called the formal expression of these statements the *weak* decentralization theorem. Our contribution adds sensibility to these results by giving a determinant role to the spillovers thresholds. There are thresholds levels where the choice of one system or the other is conditioned to the relation that each region has with the rest of their neighbors[14]. Then, within the thresholds there is a unique efficient choice between centralized and decentralized incentives: if a group of heterogeneous regions has endowments that are congruent with the direction of the technological change (and the region to be affected is not) and inter-regional spillovers exist, then centralization is always the efficient choice. This is because the decentralized case underestimates the importance of the effects of inter-regional spillovers. If the heterogeneous regions within a country are not congruent with the direction of the technological change and the region to be affected is, then the decentralized case is more efficient since the centralized case does not consider the particularities of the current policies. On top of this, in some cases both types of systems may lead to the inefficient direction of technological change. This is the case where neither centralized nor decentralized policies are able to provide an efficient policy (area 6 of Figure 1).

Moreover, from Propositions (1)-(3) and the set of figures presented in this section we can formulate the weak decentralization theorem:

> (i) if there are no spillovers and regions are homogeneous then centralization and decentralization cases are equally efficient; (ii) if there are no spillovers and regions are heterogeneous then centralization *can be* an inefficient outcome, but also *can be* indifferent (and efficient) with respect to decentralized policies; (iii) if there are spillovers and regions are homogeneous then decentralization *can be* an inefficient outcome, but also *can be* indifferent (and efficient) with respect to centralized policies; (iv) if there are spillovers and regions are heterogeneous then inter-regional spillovers, regional heterogeneity and *endowment of factors* are the key variables to determine the efficiency of the outcomes.

The incorporation of the BTC notion to policy evaluation discussions, combined with regional heterogeneity and spillovers implies a reformulation of the main conclusions of the decentralization theorem. The sensibility added in our model not only explains with detail several oucomes that the traditional theorem is not able to, but also considers it as a particular case, granting comparability of different outcomes. The differences between the two approaches can be summarized in Table 1.

[14]The thresholds levels are $\bar{L} < \bar{K}\bar{\xi}$ and $L_j > K_j\xi_j$ or $\bar{L} > \bar{K}\bar{\xi}$ and $L_j < K_j$ to decentralization and they are $\bar{L} < \bar{K}\bar{\xi}$ and $K_j < L_j < K_j\xi_j$ to centralization.

Table 1: Implications of Considering the Biased Technological Change in Policy Evaluation

(a) The Oates' decentralization theorem

	Homogeneous	Heterogeneous
No Spillovers	$D \sim C$	$D \succ C$
Spillovers	$D \prec C$	Depend on: spillovers and heterogeneity

(b) The weak decentralization theorem based on BTC

	Homogeneous	Heterogeneous
No Spillovers	$D \sim C$	$D \succeq C$
Spillovers	$D \preceq C$	Depends on: spillovers, heterogeneity and endowment of factors

The weakness of the theorem we developed, as shown in Table 1, considers and includes the notions of the traditional view. However, stronger differences with respect to the mainstream perspective take place when heterogeneous regions interact in the presence of spillovers. Additionally, the weak decentralization theorem allows us to propose implications in terms of the effects of technological policies, which do not always have the desired effect on heterogeneous regions.

4 Conclusions

Departing from the most disseminated decentralization literature, we developed a theoretical model to explore how different political frameworks affect productivity of regions within an economy. The novelty of this paper relies on the inclusion of the BTC concept to empower the decentralization theorem. The main result of our model is a new theorem that considers endowment, heterogeneity and spillovers interacting, offering new insights to evaluate policies. This new theorem challenges the conclusions of the traditional view since it argues that a policy might have undesired effects in specific contexts. Indeed, the efficiency of an outcome will depend on the level of regional heterogeneity, the inter-regional spillovers and the endowment of factors at the country level.

We find that the use of traditional TFP indicator limits the analysis of the technological effects, misleading the evaluation of policy interventions. Since decentralization discussions are based on the existence of heterogeneity amongst regions the BTC concept allows one to understand particular effects that specific policies have on a region.

Typically, the decentralization studies are addressed using microeconomics foundations to explain the impact of different political systems. One of the implications of this paper is the provision of a new perspective, integrating the classic vision with a state-of-the-art macroeconomics approach. This contribution allows us to integrate the analysis of political contexts with regional heterogeneity, spillovers, productivity and growth.

The weak decentralization theorem allows us to conclude that a policy may not always have the desired effect on heterogeneous regions. This is so because of the inclusion of the BTC concept in the decentralization analysis. Technological trajectories of regions are affected by their endowments, affecting the direction of technological change.

The impact of this work can be synthesized as a novel (or more precisely, an improved) approach to evaluate productivity related policies under regions that involve heterogeneous components. For instance, in the case of programs like Horizon 2020, the impact that each policy may find in particular regions is still a matter of evaluation that, *a priori*, can have undesired results (as we show in the previous sections). For example, policies that may appear favorable to any context, like those favoring the acquisition of physical capital[15] (e.g. by hand of subsidies), may have undesired effects if some key elements are not taken into account. The capital intensive policy will change the relative factor output elasticities relations and hence transform the productive structure of a region, making more productive regions with capital oriented endowments (and less in the others). These transformations are strongly affected by how important the differences amongst regions (regional heterogeneity) are and how connected in terms of knowledge and capabilities (inter-regional spillovers) these different productive systems are. If the differences are too pronounced or the spillovers too low, then outcomes actually vary from efficient to inefficient for both centralized and decentralized political systems. This is probably one of the most important corollaries of this work. In the same line, this framework is relevant to assess discussions on smart specialization strategies and future regional development. Last, the inclusion of these elements in economies under development could signify important advances in productivity boosting policies.

Regarding the future challenges, there are multiple lines to develop from this paper. First, there are several challenges regarding the relaxation of the most restrictive assumptions carried in our model. For example, we modeled a world with two regions that can be extended to N regions or can be considered with a more general interaction between output elasticities and policies. Second, we can analyze in depth specific sets of policies by using the ideas developed in the previous chapters, offering a new perspective to understand productivity related policies. Third, we can include policies that affect A_j *and* the local use of factors (α_j and β_j), which attempts to define, endogenously, an interaction between the shifts of isoquants and their slope within our setup. Finally, the main challenge is to measure the empirical validity of our model and to contrast our results with those offered by the traditional views.

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[15]Following the same logic, an example on labor intensive policy can be sketched: the case of specialized training, or a firms' organization issues that affect directly the way in which the labor component produces can be equally taken into consideration, with favor towards regions that are labor intensive.

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Appendix

Proof of Lemma 1

The optimal problem for the firm is maximized equation (1) given the cost function (2), politician's decision and constant return to scale. Then, formally, the optimal problem is:

$$\max_{K_j,L_j}\left[A_j K_{-j}^{\gamma_{-j}} K_j{}^{\bar{\alpha}_j} L_j^{1-\bar{\alpha}_j} - \lambda\left(r_j K_j + w_j L_j + T_j - C_j\right)\right];$$

where $\bar{\alpha}_j$ is the local level of capital output elasticity when the policy is $\bar{G}_j^i$. Solving it, we obtain:

$$\frac{dY_j}{dK_j} = 0 \rightarrow \bar{\alpha}_j A_j K_{-j}^{\gamma_{-j}} L_j^{1-\bar{\alpha}_j} K_j{}^{\bar{\alpha}_j-1} = r_j, \tag{9}$$

$$\frac{dY_j}{dL_j} = 0 \rightarrow (1-\bar{\alpha}_j) A_j K_{-j}^{\gamma_{-j}} L_j^{-\bar{\alpha}_j} K_j{}^{\bar{\alpha}_j} = w_j, \tag{10}$$

$$\frac{dY_j}{d\lambda} = 0 \rightarrow -\left(r_j K_j + w_j L_j + T_j - C_j\right) = 0. \tag{11}$$

Then, combining equations (9) and (10), we find:

$$L_j^* = \frac{r_j}{w_j}\frac{(1-\bar{\alpha}_j)}{\bar{\alpha}_j} K_j. \tag{12}$$

Finally, we put (11) in (12) and we obtain equations (4) and (5). ■

Proof of Proposition 1

The optimal problem for the decentralized policy is $\max_{G_j^d} E(Y_j^*|I_j^d)$ where equations (1), (3), (4), (5), constant return to scale and $I_j^d = \{C_j, r_j, w_j, a_j, b_j, \gamma_{-j}\}$ hold. Note that $E(Y_j^*|I_j^d) = Y_j^*$. Then, formally the optimal problem is:

$$\max_{G_j^d} A_j K_{-j}^{\gamma_{-j}} \left(\frac{\left(a_j + b_j G_j^d\right)\left(C_j - T_j\right)}{r_j}\right)^{a_j + b_j G_j^d} \left(\frac{\left(1 - a_j - b_j G_j^d\right)\left(C_j - T_j\right)}{w_j}\right)^{1 - a_j - b_j G_j^d}.$$

The potential optimal point is:

$$\frac{dY_j^*}{dG_j^d} = \frac{dY_j^*}{d\alpha_j}\frac{d\alpha_j}{dG_j^d} = 0.$$

Using Lemma 2, we obtain:

$$Y_j^* \ln\left(\frac{K_j}{L_j}\right) b_j = 0,$$

we know that $Y_j^*,\ b_j > 0$, then the potential maximum point is when $\ln(K_j/L_j) = 0$, i.e. when $K_j = L_j$. Now it is necessary to find the second derivative. It is:

$$\frac{d^2 Y_j^*}{dG_j^d dG_j^d} = \frac{dY_j^*}{dG_j^d}\ln\left(\frac{K_j}{L_j}\right) b_j + Y_j^* \frac{d\ln\left(\frac{K_j}{L_j}\right)}{dG_j^d} b_j.$$

Furthermore, the second derivative in the optimal point is:

$$\left.\frac{d^2Y_j^*}{dG_j^d dG_j^d}\right|_{\frac{dY_j^*}{dG_j^d}=0} = Y_j^* \frac{d\ln\left(\frac{K_j}{L_j}\right)}{dG_j^d} b_j$$

$$= Y_j^* \frac{1}{\alpha_j\left(1-\alpha_j\right)} b_j^2 > 0.$$

It is a minimum point. So, when $\ln(K_j/L_j) > 0$ then Y_j^* increases in G_j^d; and when $\ln(K_j/L_j) < 0$ then Y_j^* decreases in G_j^d. ■

Proof of Proposition 4

The optimal problem for the central policy is $\max_{G_j^c} E(Y_1^* + Y_2^* | I_1^c, I_2^c)$ where equations (1), (3), (4), (5), constant return to scale and $I_i^c = \{\bar{r}, \bar{w}, \bar{a}, \bar{b}, \bar{\gamma}, \bar{C}\} = I^c$ hold. Note that $E(Y_1^* + Y_2^* | I^c) = 2\bar{Y}$. Putting all the constraints, we obtain:

$$\max_{G_j^c}\left(A\left(\frac{\left(\bar{a}+\bar{b}G_j^c\right)\left(\bar{C}-T_j\right)}{\bar{r}}\right)^{\bar{\gamma}+\bar{a}+\bar{b}G_j^c}\left(\frac{\left(1-\bar{a}-\bar{b}G_j^c\right)\left(\bar{C}-T_j\right)}{\bar{w}}\right)^{1-\bar{a}-\bar{b}G_j^c}\right).$$

Now, the potential optimal point is:

$$\frac{d\bar{Y}}{dG_j^c} = \frac{d\bar{Y}}{d\bar{\alpha}}\frac{d\bar{\alpha}}{dG_j^c} = 0.$$

Then:

$$\bar{Y}\left(\frac{\bar{\gamma}}{\bar{\alpha}} + \ln\frac{\bar{K}}{\bar{L}}\right)\bar{b} = 0.$$

By definition $\bar{Y}, \bar{b} > 0$, then the potential maximum point is when $\ln(\bar{K}/\bar{L}) = \bar{\gamma}/\bar{\alpha}$, i.e. $\bar{K}e^{\bar{\gamma}/\bar{\alpha}} = \bar{L}$. We show that it is a minimum point. Indeed, with the second derivative, we find:

$$\frac{d^2\bar{Y}}{dG_j^c dG_j^c} = \frac{d\bar{Y}}{dG_j^c}\left(\frac{\bar{\gamma}}{\bar{\alpha}} + \ln\frac{\bar{K}}{\bar{L}}\right)\bar{b} + \bar{Y}\frac{d\left(\frac{\bar{\gamma}}{\bar{\alpha}} + \ln\frac{\bar{K}}{\bar{L}}\right)}{d\bar{\alpha}}\frac{d\bar{\alpha}}{dG_j^c}\bar{b}.$$

Furthermore, the second derivative in the optimal point is:

$$\left.\frac{d^2\bar{Y}}{dG_j^c dG_j^c}\right|_{\frac{d\bar{Y}}{dG_j^c}=0} = \bar{Y}\frac{d\left(\frac{\bar{\gamma}}{\bar{\alpha}} + \ln\frac{\bar{K}}{\bar{L}}\right)}{d\bar{\alpha}}\bar{b}^2$$

$$= \frac{\bar{\alpha} - \left(1-\bar{\alpha}\right)\bar{\gamma}}{\bar{\alpha}^2\left(1-\bar{\alpha}\right)} > 0.$$

Indeed, by $\bar{\alpha} > \bar{\gamma}$, we know that $\bar{\alpha} > (1-\bar{\alpha})\bar{\gamma}$. So, when $\ln(\bar{K}/\bar{L}) > \bar{\gamma}/\bar{\alpha}$ then $\bar{Y}$ increases in G_j^c; and when $\ln(\bar{K}/\bar{L}) < \bar{\gamma}/\bar{\alpha}$ then $\bar{Y}$ decreases in G_j^c. ■

Proof of Proposition 5

The optimal problem in the benchmark situation is $\max_{G_j^b} E(Y_1^* + Y_2^* | I_j^b)$ where equations (1), (3), (4), (5), constant return to scale and $I_j^b = I_j^d$ hold. Note that $E(Y_1^* + Y_2^* | I_j^b) = Y_1^* + Y_2^*$. Then the optimal problem is:

$$\max_{G_j^b}\left[A_j K_{-j}^{\gamma_{-j}} K_j^{\alpha_j} L_j^{\beta_j} + A_{-j} K_j^{\gamma_j} K_{-j}^{\alpha_{-j}} L_{-j}^{\beta_{-j}}\right].$$

The potential optimal point is:

$$\frac{d\left(Y_1^*+Y_2^*\right)}{dG_j^b}=\frac{d\left(Y_1^*+Y_2^*\right)}{d\alpha_j}\frac{d\alpha_j}{dG_j^b}=0,$$

so:

$$\left[Y_j^*\left(\ln\frac{K_j^*}{L_j^*}\right)+Y_{-j}^*\frac{\gamma_j}{\alpha_j}\right]b_j=0.$$

Then $\ln(K_j^*/L_j^*) = -Y_{-j}^*\gamma_j/(Y_j^*\alpha_j)$ it is a potential maximum point. We obtain the second derivative:

$$\frac{d^2\left(Y_1^*+Y_2^*\right)}{dG_j^b dG_j^b}=\frac{dY_j^*}{dG_j^b}\left(\ln\frac{K_j^*}{L_j^*}\right)b_j+Y_j^*\frac{d\left(\ln\frac{K_j^*}{L_j^*}\right)}{dG_j^b}b_j+\frac{dY_{-j}^*}{dG_j^b}\frac{\gamma_j}{\alpha_j}b_j+Y_{-j}^*\frac{d\left(\frac{\gamma_j}{\alpha_j}\right)}{dG_j^b}b_j.$$

More precisely, the second derivative in the optimal point is:

$$\begin{aligned}\left.\frac{d^2\left(Y_1^*+Y_2^*\right)}{dG_j^b dG_j^b}\right|_{\frac{d\left(Y_1^*+Y_2^*\right)}{dG_j^b}=0} &= Y_j^* b_j^2\ln\left(\frac{K_j}{L_j}\right)^2+Y_j^* b_j^2\frac{1}{\alpha_j\left(1-\alpha_j\right)}-Y_j^* b_j^2\ln\left(\frac{K_j}{L_j}\right)\frac{\gamma_j}{\alpha_j}-\frac{\gamma_j}{\alpha_j^2}Y_{-j}^* b_j^2\\ &= \left(\ln\left(\frac{K_j}{L_j}\right)^2+\frac{1}{\alpha_j\left(1-\alpha_j\right)}+\frac{1-\gamma_j}{\alpha_j}\ln\left(\frac{K_j}{L_j}\right)\right)Y_j^* b_j^2\\ &= \left(\left(2+\frac{1-\gamma_j}{\alpha_j}\right)\ln\left(\frac{K_j}{L_j}\right)+\frac{1}{\alpha_j\left(1-\alpha_j\right)}\right)Y_j^* b_j^2>0.\end{aligned}$$

The inequality is because, by assumption, $\ln(K_j/L_j) > 1/(2\alpha_j^2+\alpha_j(\gamma_j-1)+\gamma_j)$ then $\ln(K_j/L_j) > -1/(\alpha_j(1-\alpha_j)(2+(1-\gamma_j)/\alpha_j))$. It is a minimum point. So when $\ln(K_j/L_j) > -Y_{-j}^*\gamma_j/(Y_j^*\alpha_j)$ then $(Y_1^*+Y_2^*)$ increases in G_j^b; and when $\ln(K_j/L_j) < -Y_{-j}^*\gamma_j/(Y_j^*\alpha_j)$ then $(Y_1^*+Y_2^*)$ decreases in G_j^b. ∎