Assessing the effects of education investment policies in Brazil: Evidence from a CGE model with endogenous human capital

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Abstract: This paper examines the role of education in human capital formation and knowledge production in Brazil by developing a computable general equilibrium (CGE) model that explicitly links education investment, labor qualification, and the production structure. The model features endogenous labor supply, with workers' qualifications determined by years of schooling and relative wages across education levels, allowing human capital accumulation to emerge endogenously from education policies. Within this framework, we conducted counterfactual simulations inspired by the National Education Plan (PNE), considering an increase in public education investment to 10% of GDP and evaluating alternative allocation scenarios between the public and private education sectors across medium and long-term horizons. The main findings indicate that increased public investment in education generates positive effects on GDP, human capital accumulation, and research and development (R&D) in the medium and long term, whereas education expansion driven by subsidies to private education leads to negative impacts on economic growth. Despite these differences, all scenarios increase the supply of qualified workers, reinforcing the central role of education policy in strengthening human capital formation in Brazil.

Keywords: Education; Human Capital; Public Funding; Dynamic CGE Model

JEL classification: C68, J24; I25; O15, O38

1. Introduction

Since the 1950s, economic literature has emphasized the relationship between human capital and individuals' earnings and productivity (e.g., Mincer, 1958, 1962; Becker, 1962), as well as the broader externalities generated for society and reflected in aggregate economic outcomes (e.g., Romer, 1986, 1990; Lucas, 1988; Mankiw, Romer, and Weil, 1992). Schultz (1959, 1961) and Becker (1962) conceptualized human capital as the set of attributes, knowledge, and skills that enhance individuals' productive capacity, including education, professional training, and health. The incorporation of human capital into economic theory increased the relevance of formal education as a key determinant of labor productivity and economic growth, while also highlighting its connection to knowledge creation and technological progress. Within this framework, governments face decisions regarding the optimal level of educational investment, as spending on education augments individuals' human capital during the education process and subsequently contributes to the aggregate stock of human capital through enhanced skills supplied to the labor market (Chevalier et al., 2004; Sianesi and Van Reenen, 2003).

While access to education is a well-established element in developed countries, schooling has gradually expanded in low and middle-income countries over the last five decades. However, despite the increase in the formally educated population, exclusion persists at various levels of the educational system (World Bank Group, 2018). In Brazil, between 2012 and 2020, the average years of schooling of the population aged 18 to 29 increased from 9.8 to 11.8 years. During the same period, the gap between the average years of schooling of the 25% poorest and the 25% richest narrowed. Despite

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these advances, in 2021 approximately 12 million of the nearly 40 million young people in this age group had not completed high school. In higher education, although some progress, the proportion of young people aged 18 to 23 who were enrolled (20.1%) or had completed a degree (5.4%) remained low, suggesting delayed entry into higher education in Brazil. Moreover, results from the National Basic Education Assessment System (SAEB) point to low levels of academic achievement, which are associated with shortcomings in the quality of education in the country (INEP, 2021; INEP, 2022a).

Addressing these educational challenges requires the adoption of alternatives that ensure access to education for the Brazilian population, with aggregate effects on the economy and the labor market, particularly through the expansion of the supply of skilled labor (Nascimento; Verhine, 2017). In this context, educational investment constitutes a key policy instrument for promoting the inclusion of poorer families in the educational system. Nevertheless, Brazil has faced constraints regarding public spending on education. According to the National Institute of Educational Studies and Research (INEP, 2022b), total educational expenditure by the Brazilian government, including resources allocated to both public and private education, declined slightly between 2015 and 2020, from R$ 409.1 billion to R$ 404.1 billion. Spending directed exclusively to public education, in turn, showed a modest increase over the same period, rising from R$ 376 billion to R$ 381.8 billion. As a share of Gross Domestic Product (GDP), public investment in education remained relatively stable at around 5%, falling short of the targets established by the National Education Plan (PNE), which set goals of 7% for 2019 and 10% for 2024.

Given this context, the main objective of this study is to evaluate the economic effects of policies that expand public spending in Brazil. Specifically, the analysis examines how increased public investment in education directed to both the public and private sectors affects the country' economic structure, human capital accumulation, and knowledge production. This focus is justified by the growing role of public funding in Brazil's private education sector, particularly through subsidies and targeted policy instruments. Moreover, in light of the fiscal constraints faced by the Brazilian government, it is essential to explicitly incorporate private education into discussions on the expansion and allocation of educational investment.

For this purpose, we employed a national Computable General Equilibrium (CGE) model with recursive dynamics, specifying the mechanisms through which public spending on education affects human capital formation. Our model is based on the hypothesis that such investments increase average years of schooling, making individuals more educated and thereby promoting an expansion of the human capital stock and the supply of skilled labor. To operationalize this approach, we initially disaggregated the labor factor by skill level according to workers' educational attainment (low, medium, and high). Subsequently, drawing on Yeo and Lee (2020) and Jung and Thorbecke (2003), we modeled the stock of human capital as endogenous (proxied by skilled labor), evolving it as a function of two components: educational investment and the relative resources associated with returns to qualification. In addition, we calibrated the wage differentials associated with each additional year of schooling using parameters estimated from an econometric model based on Mincer (1974) and Heckman (1977, 1979).

From a methodological perspective, the main contribution of this research lies in the modeling of labor supply within a CGE framework explicitly linked to educational attainment, which allows workers' decisions to be related not only to relative prices but also to institutional conditions shaped by public education policies, consistent with the applied literature. In this regard, while a large share of the economic literature on human capital relies on partial equilibrium approaches, analyzing microeconomic and macroeconomic dimensions in isolation (e.g., Hartwig, 2014; Himaz and Aturupane, 2016; Kemelbayeva, 2020; Menad and Guennouni, 2020; Ozougwu, 2020), some studies have examined investments in education, and especially their labor market effects, using CGE models with human and knowledge capital accumulation (e.g., Jung and Thorbecke, 2003; Balma, 2012; Mardones, 2015). These models allow for an integrated analysis of the relationship between investments, human capital, and knowledge capital, as well as their direct and indirect effects on production, income, and consumption, based on the Social Accounting Matrix (SAM). In light of this, the present study advances the literature by incorporating into labor supply projections the semi-elasticity of income with respect to years of schooling, estimated econometrically, which updates the average price of labor supply by skill level.

Based on this CGE structure with endogenous human capital, and considering the National Education Plan (PNE) target of raising educational investment to 10% of GDP over a decade while contrasting public expenditures and subsidies allocated between the public and private education sectors, we simulated following scenarios: (i) an expansion of public spending on public education to 10% of GDP by 2034; (ii) an expansion of public spending on private education by 2034, matching the value projected in scenario (i); (iii) an expansion of public spending on public education to 10% of GDP by 2044; and (iv) an expansion of public spending on private education by 2044, matching the value projected in scenario (iii). These simulations make it possible to assess how alternative time horizons and public–private allocation patterns of educational investment generate differentiated impacts on the Brazilian productive system.

Besides this introduction, this paper consists of five other sections. The second section briefly reviews the economic literature on human capital and education. The third section shows how these concepts are modeled within CGE frameworks in different educational contexts around the word. The fourth paragraph describes the empirical strategy adopted in this study, including the econometric estimation of parameters, the CGE modeling framework, and the simulated policy scenarios. The proposed simulations and their results are presented and discussed in the fifth chapter.

2. Literature review on education and human capital

The expression "human capital" gained prominence in economic debates at the end of the 1950s with the development of human capital theory. The emergence of this theoretical field provided contributions to modern economic analysis, which began to consider the improvement of human skills as one of the preponderant elements for the advancement of nations. Mincer (1958), Schultz (1959), and Becker (1962) laid the foundations of the human capital literature, discussing a type of capital centered on people's abilities, which would be complementary to physical capital (Ehrlich and Murphy, 2007).

Schultz (1959) pointed out that in addition to the three usual foundations of economics (labor, physical capital and land), other underlying aspects should also be considered, with emphasis on the human efforts employed in economic production. According to this author, the scarcity of resources for the education and training of the workforce can explain the low economic growth of developing countries. In a later study, Schultz (1960) introduced formally the term "human capital", defining it as a type of capital resulting from investment in education, equivalent to an investment "in man".

In turn, Becker (1962) argued that people's future earnings and consumption can be affected by two types of resources: physical and human. In this context, investments in human capital were described as activities (such as education, professional training, and medical care) that by improving individuals' physical and mental abilities affect their real income and, consequently, their consumption capacity. Although these elements are recognized as important determinants of individual earnings, their effects are not homogeneous, differing in terms of the level of investment required and the returns generated.

Mincer (1958) pointed out an association between investments in human capital and the interpersonal distribution of income, arguing that differences in individuals' incomes stemmed from distinctions in educational formation. Under the light of rational choice theory, he assumed the existence of an intertemporal aspect in the decision to invest in education, considering that people postpone their individual earnings in favor of greater returns in the future. Empirically, Mincer (1974) developed the "Mincerian earnings equation," which depicts the relationship between formal education and workers' earnings over time.

In their analysis, Mincer (1962) and Becker (1962) also argued that worker qualification depends not only on formal education but also on on-the-job training. In this regard, Mincer (1962) demonstrated that while formal education is a preparatory stage for acquiring occupational skills, continuous training after entering the labor market constitutes a more prolonged and specialized stage, defined as the informal process of learning through experience. Similarly, Becker (1962) reinforced the importance of experience and training in the workplace itself, paying attention to its effects on individual earnings, suggesting the existence of two types of on-the-job training: general and specific, depending on how well the trained skills can be applied across different job positions and companies.

These approaches to human capital presented by Schultz (1959, 1960, 1961), Becker (1962) and Mincer (1962) have become accepted and reproduced in economics and other social sciences over the last four decades (Ehrlich and Murphy, 2007). According to Perepelkin, Perepelkina, and Morozova (2016), with its modernization, the concept has also come to include other aspects, such as the innate, the biological, and the social. With the exception of innate abilities, which are characteristics and predispositions that individuals carry from birth, the other aspects can be improved with appropriate investments. Such investments are effective in generating long-term returns, especially if made from the early stages of life, since the development of human capital is a continuous process of socialization, adaptation, and learning, with its returns varying according to its magnitude.

While related to the concepts discussed so far, the signaling theory introduced by Spence (1973) points out that formal education plays only a signaling role for the labor market. The author assumes that since employers cannot directly observe the productive capacity of people at the time of hiring, they rely on indicators that proxy their qualifications and marginal productivity, such as the level of schooling. Given the impossibility of employers identifying the real capacity of job candidates, the signaling costs, that is, the efforts and expenses undertaken by people to obtain signals, make the indicated professional qualifications more reliable to the extent that the costs of acquiring the signal are inversely proportional to the productivity of individuals. In the case of education, the opportunity cost of acquiring it would be higher the lower the individual's skills. Thus, only the most productive individuals would be able to obtain the signal, distinguishing themselves from the others.

The discussion so far reflects a microeconomic approach centered on individual returns to education. However, investments in human capital have broader implications, since their benefits are not limited to those who make them, and can generate positive externalities for the rest of the economy. In this regard, the gains generated for society are defined as social returns, and can be measured by the social rate of return. However, given the difficulty of obtaining strong and conclusive empirical evidence, the implementation of these procedures in the microeconomic field is limited. On the other hand, the macroeconomic approach addresses the broad effects of human capital more directly, especially by exploring the relationship between worker qualification and economic growth (Hosking, 1992; Sianesi and Van Reenen, 2003; Venniker, 2001).

In macroeconomic theory, two approaches stand out in analyzing the broader effects of education on the economy: endogenous growth models and the expanded neoclassical model. Endogenous growth models highlight the role of education in economic growth through two paths: the incorporation of human capital as a productive factor in the economy, which is affected by educational investment decisions and generates external effects; and the explicit representation of the interdependence between human capital and technological progress. Among the main contributions to the theory are the models of Romer (1986, 1990) and Lucas (1988) (Sianesi and Van Reenen, 2003).

Lucas (1988) adapted the conventional Solow model, incorporating human capital into it according to the definitions presented by Schultz (1963) and Becker (1962, 1974), conceiving the economy as a system with two types of capital: the physical capital, accumulated and used in the production of goods; and the human capital, which increases the productivity of labor and physical capital and, although intangible, can also be accumulated. In the specification known as the Uzawa-Lucas model, Lucas (1988) incorporated into the production function the hypothesis that people allocate their time between the productive and learning processes (Chakraborty; Gupta, 2006).

Similarly to Lucas (1988), Romer (1990) developed a model that highlights the endogenous sources of economic growth, stemming from technological changes resulting from investment decisions. The model consists of four inputs (physical capital, labor, technology, and human capital) and three productive sectors (research, intermediate goods, and final goods), interconnected, with the research sector using human capital and the stock of knowledge to generate new ideas, applied by the intermediate goods sector in the construction of machinery and equipment, which in turn are used in the production of final goods.

Mankiw, Romer, and Weil (1992) formulated an expanded version of the Solow-Swan growth model, commonly referred to as the augmented neoclassical model or MRW. It was developed from investigations into the empirical implications of the original model, after it was verified that a better fit could be achieved with the inclusion of human capital, given the observed differences in the quality of labor in different countries. Thus, the MRW models human capital in the same way as physical capital, treating it as an additional input, defined exogenously (Jones, 2000; Schütt, 2003).

3. CGE approaches to human capital and education policies

Both microeconomic and macroeconomic approaches to human capital in economic theory have been empirically tested in recent economic research. Although econometric models are more commonly used to empirically assess the effects of education on individual wages and economic growth, CGE modeling has been used to analyze the aggregate impacts of public investment policies in education because it allows to identify their systemic implications by representing the economy as a set of integrated markets. Overall, studies employing this modeling framework directly or indirectly examine the impacts of changes in public investment policies in education, particularly those resulting from changes in financing mechanisms, mainly associated with tax reforms, as will be illustrated in the examples below (Cardoso, 2016; Mardones, 2015; Yeo and Lee, 2020).

A seminal empirical contribution about it was conducted by Jung and Thorbecke (2003), who investigated the economic and distributional impacts of increased public spending on education in Tanzania and Zambia on the supply of skills in the labor market using a static CGE model. This model is composed of both physical and human capital, exogenously determined by population growth and endogenously shaped by investments in education. The authors incorporated into the model the hypothesis that families choose between temporarily investing in qualifications or keeping their members in the labor market without additional qualifications, based on expected wage returns. With this in mind, public spending on education would reduce costs and expand the supply of education, encouraging training and increasing the stock of human capital in both economies.

Adopting a similar approach, Cloutier, Cockburn, and Decluwé (2008) used a static CGE model with labor disaggregated into two categories based on educational attainment (skilled and unskilled workers) to assess the consequences of a cut in public subsidies for higher education on well-being and poverty in Vietnam. In addition to endogenously incorporating families' decisions to invest in education, the authors also defined public spending as dependent on private demand for higher education, since in the country the government subsidizes a fixed amount for each unit of education demanded by families. Under this hypothesis, an increase in public educational spending would lead to a reduction in the costs incurred by individuals, encouraging them to invest more in their education.

Inspired by the pioneering contributions of Jung and Thorbecke (2003) and Cloutier, Cockburn, and Decluwé (2008), other authors have also modeled human capital as an endogenously determined factor of production in an EGC framework. For example, Balma et al. (2012) developed a static EGC model to analyze the distributive implications of different tax mechanisms aimed at financing public education in Burkina Faso, also distinguishing labor into two types according to the level of schooling. They simulated an increase in public subsidies to the educational sector, under different forms of financing, with the results indicating that educational financing via income taxes would generate the most significant redistributive effects. In the same vein, Mardones (2015) employed a recursive dynamics EGC model to evaluate the effects of fiscal changes aimed at financing education in Chile, disaggregating the Chilean economy into 38 sectors, including four educational segments (primary, secondary and tertiary public education, as well as private education). The analysis considered increases of the income tax of the richest quintile, whose revenue collected would be entirely destined for higher education subsidies to reduce the price of public and private education or full funding of public higher education.

Similarly, Ojha (2017) sought to identify the impact of an increase in public education spending financed by higher direct taxes from a dynamic multisectoral CGE model for India, disaggregating the labor production factor into unschooled, secondary education, and higher education. He also considered that changes in the stock of human capital would occur as a function of public education spending, funded by government tax revenue, taking into account that this would affect the supply and demand for skilled labor, via changes in household behavior regarding their educational choices and in firms' hiring decisions. Karim and El Moussaoui (2020) assessed how changes in public spending on higher education affect inequality and poverty in Morocco, using a static CGE model, disaggregated into seven productive sectors, two categories of work (skilled and unskilled), and 7,062 representative families. The incorporation of microsimulation techniques into this model allowed for capturing the effects on family income more consistently than in the conventional approach. Giraldo, Arguello, and Herrera (2019) investigated how shocks in international commodity prices affect the composition of the labor market, population income, and the Colombian economy, using a recursive dynamic CGE framework consisting of three categories of work according to education level (unskilled, semi-skilled, and skilled). In addition to assuming that families maximize their lifetime income through investment in education, the authors also recognized the role of exogenous shocks on the supply of skilled workers.

Extending this modeling approach Verbič, Majcen, and Čok (2014) analyzed the effects of public investment in education and R&D in Slovenia using a recursive dynamics EGC model that incorporates, in addition to physical capital and human capital (disaggregated into three education-based skill groups), knowledge capital as a productive factor. In the model, families decide to invest in qualifications to maximize income, firms invest in physical capital, training, and innovation to increase profits, and the government influences these stocks through spending on education and R&D. Simulations indicate that the combination of reduced personal income tax with increased spending on education generates the most positive impacts on GDP and well-being. However, long-term gains are not immediate, due to the temporary reallocation of workers to the education system. As proposed by Verbič, Majcen, Ivanova and Čok (2010), Yeo and Lee (2020) also developed a dynamic EGC model with human capital and capital of endogenous knowledge to analyze the effects of investment policies in education and R&D in South Korea. According to the modeled hypotheses, shocks in education would expand the stock of human capital and indirectly influence firms' investments in R&D, while shocks in R&D would increase the demand for skilled workers, affecting families' educational decisions.

Departing from the previous modeling approach, Rao (2011) developed a dynamic EGC model to analyze in detail the supply and demand for labor in Australia, including into the ORANI static framework the private and social internal rates of return of education, associating training costs and average wages per qualification. These adaptations made it possible to capture the effects of investments in education and training on employment. From this, the author simulated two shocks: a 40% expansion in the number of graduates and an adjustment of the internal rate of return to 12%, considered socially ideal. The results indicated that an increase in the skilled workforce tends to raise GDP, GNP, and consumption in the Australian economy. However, when the social rate of return falls below the ideal level, distortions could occur, with overinvestment in some areas and underinvestment in others.

Also adopting an alternative modeling approach, Kim, Hewings, and Lee (2016) assessed the effects of increased educational investments in South Korea in a context of population aging, using an inter-regional GCE model with overlapping generations and population disaggregated by age group. To this end, they defined human capital as a function of the quantity and quality of the workforce, with the latter estimated through a Mincerian earnings equation. Shocks in public spending on education, converted into additional years of schooling, would raise qualifications, wages, and the stock of human capital. Simulations results indicated that, to compensate for the projected long-term decline in GDP, it would be necessary to extend educational investments aimed at the 25-29 age group for ten years. However, such measures could exacerbate interregional inequalities due to differences in returns to schooling across regions of the country.

In one of the most recent studies that incorporated human capital into the EGC model, Elnour, Siddig, and Grethe (2025) investigated the economic and distributive implications of different education and vocational training policies in Sudan, using a recursive-dynamic EGC model with detailed educational sectors and different levels of labor qualification. In this model, educational decisions were modeled endogenously based on socioeconomic determinants, whose influence is estimated using a logistic function, affecting the dynamics of human capital. Simulations of subsidies that reduced educational costs by 1% of GDP showed that support for primary education generates more lasting effects on enrollment and national economic growth, with external financing being more advantageous than internal financing. Furthermore, policies focused on agricultural education produced more positive long-term impacts on GDP and family income than direct incentives for agricultural production.

Table 1 summarizes the applied studies on education and human capital that employ CGE modeling, as discussed above.

Table 1. Summary of studies on education policies and human capital using the CGE analysis

Category	Region	Impact analysis	Reference
Static National Model	Vietnam	Impacts of a reduction in public subsidies for higher education on poverty	Cloutier, Cockburn and Decluwé (2008)
	Australia	Impacts of the increased participation of individuals with higher education in the workforce	Rao (2011)
	Burkina Faso	Effects of increased public spending on primary education on levels of well-being and poverty	Balma et al. (2012)
	Morocco	Effects of public subsidies for higher education on the economy and poverty	Karim and El Moussaoui (2020)
Dynamic National Model	Slovenia	The impact of investments in education and R&D on economic growth	Verbič, Majcen, Ivanova and Čok (2011)
	Chile	Macroeconomic and distributive effects of increases in income tax aimed at financing public spending on education	Mardones (2015)
	India	Impact of an increase in public spending on education on economic growth and income distribution	Ojha (2017)
	Colombia	Impacts of shocks in international commodity prices on income, families' educational demand, and the labor market	Giraldo, Arguello and Herrera (2019)
	South Korea	Effects of investments in innovation and human capital accumulation on economic growth	Yeo and Lee (2020)
	Sudan	Economic implications of public subsidy policies for education and vocational training	Elnour, Siddig and Grethe (2025)
Interregional Static Model	Zambia and Tanzania	Macroeconomic and distributive effects of a increase in government spending on education	Jung and Thorbecke (2003)
Interregional Model with OLG	South Korea	Economic effects of investments in education in a scenario of population aging	Kim, Hewings and Lee (2016)

Source: Authors' own table.

4. Empirical strategy

We developed our CGE model with endogenous human capital in two main steps. First, we econometrically estimated a Mincerian earnings equation to obtain the parameters corresponding to the returns to an additional year of schooling on individual earnings, by skill level (low, medium, and high) considered in our analysis. Subsequently, we developed our CGE model based on the theoretical framework of the BIM-RD (R&D-based Brazilian Intersectorial Model), a national model with recursive dynamics implemented by Betarelli Junior et al. (2020), which models the accumulation of knowledge capital, based on endogenous variations in R&D investments. As a modification to this original framework, we disaggregated the labor factor into low, medium-, and high-skilled categories, according to workers' years of schooling. Then, we modeled labor supply as an endogenous process determined by changes in public educational investment and by relative wages across different skill levels. As described in more detail below, the two stages are fully integrated, since the results of the econometric estimations are incorporated into the model to update workers' earnings according to skill-related differentials.

4.1. The estimation model

To derive the parameters used to update the wage vectors by qualification type, a Mincerian earnings equation was estimated, linking individual earnings to educational attainment, labor market experience, and other observable characteristics. However, as emphasized in the labor economics literature (e.g., Garen (1984), Kassouf (1994), and Silveira et al. (2015)), to correct for sample selection bias, which may arise from the non-randomness of the population sample, we implemented the modeling using Heckman's (1979) two-stage method. For this purpose, the labor market participation equation was first estimated using a Probit model, based on explanatory variables that reflect the factors considered in individuals' decisions to be employed:

$$Z_i^* = \beta_i W_i + e_i \tag{1}$$

where Z_i^* is the dependent variable representing the probability that individual i is employed (Z_i^* = 1) or not employed (Z_i^*= 0), conditional on the observable characteristics W_i such as years of schooling, age, whether the individual has children, gender, racial group, head-of-household status, and residence in a metropolitan area. Furthermore, an error term is added to capture unobserved factors (e_i).

Based on this estimation, we compute the inverse Mills ratio (λ) expressed as:

$$\lambda_i = \frac{\varepsilon(\frac{a\mathrm{W}_i}{\sigma_u})}{\epsilon(\frac{a\mathrm{W}_i}{\sigma_u})} \tag{2}$$

where, σ_u is the standard deviation of the error distribution of the selection equation, ε is the standard normal probability density function, and ϵ is the cumulative normal distribution function.

In the second stage, in which the earnings equation is estimated, the natural logarithm of individual labor income is regressed on a set of exogenous variables that affect wages, as well as on the correction term derived from the selection equation, namely the inverse Mills ratio. Thus, the earnings equation, estimated separately for the three levels of schooling considered in the CGE modeling (low, medium, and high qualification), can be represented as:

$$\begin{aligned} lnY_{sk\_level_i} = \beta_1 + \beta_2 educ_{sk\_level_i} + \beta_3 exp_{sk\_level_i} + \beta_4 (exp_{sk\_level_i})^2 \\ + \beta_5 x_{sk\_level_i} + \beta_6 \lambda_{sk\_level_i} + \varepsilon_{sk\_level_i} \end{aligned} \tag{3}$$

where $educ_{esc}$ is refers to the years of schooling, exp_{esc}, the experience in the labor market, $exp_{esc}{}^2$, the square of experience; λ_{esc}, the inverse Mills ratio; e x_{esc}, vector with the other predictors that may influence individual earnings (such as sex, color/race, whether the person is the head of the household, whether they reside in a metropolitan area, the state in which they reside, whether they are adequately educated for the occupation they perform, the productive sector in which they work, the interaction between years of schooling and the productive sector). Finally, esc_i is the level of schooling (i).

The econometric equations were estimated using pooled cross-sectional data from the Brazilian Continuous National Household Sample Survey for the period 2012–2019, considering only information from the first interview conducted in each year. This time span was selected because it encompasses distinct phases of the economic cycle and precedes the COVID-19 pandemic, thereby avoiding distortions in labor market indicators associated with the health crisis. Following Silveira (2015), the sample was restricted to employed and unemployed individuals aged 25 to 59. This restriction is justified by the assumption that individuals within this age range have typically completed their formal educational decisions and remain active in the labor market. The pooling procedure increased the effective sample size and enabled the estimation of a structural semi-elasticity parameter, while allowing for the inclusion of appropriate controls for year and quarter fixed effects.

Regarding the results of this econometric modeling, the estimated coefficients for β_2, applied as parameters in our CGE model, are consistent with what is widely described in the literature. For example, Silveira et al. (2015) highlight the positive return on education, that is, the impact of higher education on increasing the wage income of individuals. In this sense, it was estimated that, for individuals with a higher education degree (or enrolled in a higher education course), an additional year of study results in an average increase of 20.1% in individual income. For those with a secondary level of education, this gain is 15.9%, while for those with low levels of education, the increase is 10.3%, showing a progressive reduction in the return to education as the level of schooling decreases. These estimated coefficients were incorporated into the EGC model as a proxy for the elasticity of income with respect to years of schooling ($YEDU_o$), as will be further described in the following section. Complete results of these econometric estimations are available in Appendix A.

4.2. The CGE Model

The BIM-RDHC model developed and implemented in this study is a recursive-dynamic multi-sectoral CGE model, based on the Johansen-Australian tradition, formulated as blocks of linearized equations whose solutions are expressed in terms of growth rates. It was calibrated using a 2015 Social Accounting Matrix (SAM), which represents the Brazilian economic structure in the base year, and parameterized with additional behavioral and structural coefficients extracted from the literature, as detailed in Appendix B. As mentioned earlier, the BIM-RDHC is based on the BIM-RD framework, which in turn is based on the ORANIGRD model, by decomposing the capital stock into physical capital and intellectual capital, and on PHILGEM, with the introduction of a fiscal module and payment flows in its theoretical and data structure. The BIM-RD model incorporates changes in the theoretical specification of capital accumulation and the relationship between the rate of return on capital and investments, with the accumulation of intellectual capital occurring recursively, based on endogenous variations in R&D investments. Our specification expands this BIM-RD framework by incorporating the endogenous accumulation of human capital driven by changes in educational investment.

At the core of the model, the maximizing behavior of agents is assumed, where national production results from the combination carried out by each economic activity between domestic and imported intermediate inputs and primary factors: labor (L_i), land (T_i), physical capital ($K_{F,i}$), and knowledge capital ($K_{c,i}$). Thus, decisions follow a hierarchical structure, with firms initially seeking to minimize their costs, starting with the decision on which factors and inputs to demand through a Leontief function. Subsequently, the demand for intermediate inputs is divided between domestic and imported goods according to a CES function linked to Armington's (1969) hypothesis, which implies imperfect substitution of domestic and foreign goods. Added value is also modeled by a CES function, allowing for imperfect substitution between primary factors according to their prices. This process is represented in the modeling by Equation C.1, presented in Appendix C, which expresses the level of production of final goods by each economic sector i given the intermediate inputs X_i, the added value V_i and its equivalent productive efficiency a_i^X and a_i^V. In this context, ρ and δ, which appear in Equation C.2 (used to calculate X_i) and in Equation C.3 (used to estimates V_i), are defined, respectively, as the substitution parameter between X_i and V_i and the parameter satisfying $\sum_{i=1}^{s} \delta_{s,i} = 1$ and $\sum_{i=1}^{f} \delta_{f,i} = 1$.

Based on the assumptions outlined by BIM-RD, we assume that gross fixed capital formation (physical and knowledge) also involves the combination of inputs in a nested structure by investors, who, similarly to companies, initially combine the components of intermediate inputs using a Leontief function, and subsequently, the domestic and imported inputs of each component using a CES-type function. We represent this process using Equation C.4. In this context, the process of accumulating physical and knowledge capital, with a constant depreciation rate ($dep_{j,i}$), is expressed by Equation C.5, where $I_{K_F,i,t}$ represents the investment of sector i in period t directed towards the accumulation of physical capital, while $I_{K_C,i,t}$ refers to investments in R&D, with the capital stock being exogenously determined. The expected rate of return on capital investments is considered to be a positive function between the unit rental price and the unit capital price, symbolized by $E_{j,i} = f(R_{j,i}/P_{j,i}^I)$.

Our CGE model also assumes that the goods produced by firms using the procedures described above are consumed by all agents, including households. According Proque, Betarelli Junior and Perobelli (2022), they demand an optimal composition of commodities based on a Linear Expenditure System (LES), defined by a Klein-Rubin or Stone-Geary function. According to this type of function, a fixed share of the household budget is reserved for the consumption of subsistence goods, while the surplus can be used for "luxury spending," allowing changes in income to lead to changes in product consumption. Thus, initially, households choose the optimal proportion of subsistence goods and luxury goods according to their budget constraint, and subsequently choose between domestic and imported goods. This Linear Expenditure System, valid for each of the four representative families, is represented by Equation C.6, with Z_i symbolizing the total demand for good i, Z_i^{Sub} the demand of families that classify good i i as necessary, and $(Z_i - Z_i^{Sub})$ the demand of families that consider product i as a luxury good. In turn, S_i^{lux} refers to the share of luxury good i in the total expenditure on all luxury goods available to families in the economy.

Although the BIM-RDKC model follows the general patterns of the BIM-RD model presented above, they differ particularly in their modeling of labor supply and demand. In this sense, the first modification adopted by our model was the disaggregation of the labor production factor in SAM, the model's main calibration database, into three groups according to the workers' education level (low, medium, and high qualification). Then, following the study by Yeo and Lee (2020), the supply of human capital, defined as workers with medium or high qualifications, was established endogenously, varying according to public and private educational investments and the relative wages between different levels of education. In other words, we assume that, when seeking to accumulate skills, individuals take into account both the expected returns and their own capacity to invest in their qualifications, as well as the institutional conditions offered in the educational sphere, directly linked to public investments in education.

Thus, as detailed in Appendix C, the labor supply ls_o by occupation o is specified in Equation C.7. It reflects the assumption that the quantity of labor units supplied in hours per skill level varies both as a function of a composite of private and public spending on education edu_o weighted by the elasticity of investment in education $elas\_EDU_o$, and of the relative nominal wage between the average price of labor supply per skill level (w_edu_o) and the aggregate average wage of all labor supplied ($Wedu$), weighted by the elasticity of substitution of labor supply $elas\_LAB_o$.

In our CGE framework $elas\_LAB_o$ we assume the same value for the three types of work (0.8) based on the simplified hypothesis that the three types of occupations are imperfect substitutes, following Betarelli Júnior et al. (2020), while we estimated $elas\_EDU_o$ specifically for this study from the calculation described in Equation C.8. For this purpose, we used the data from the SCN of 2015, base year of the model, referring to government spending on education ($gov\_EDU_o^{tot}$) and the number of employed workers ($workers_o$), disaggregated by type of qualification, based on the Continuous National Household Sample Survey, and information provided by INEP (National Institute of Educational Studies and Research) on public spending per student ($gov\_EDU_o^{stud}$) and the number of enrolled ($grad_o$) and graduates ($enrol_o$) for each of the three school stages. Thus, the government's relative educational expenditure ($gov\_EDU_o^{stud}/gov\_EDU_o^{tot}$) per student was divided by the relative measure of a worker over the stock of jobs in the economy ($1/workers_o$), and subsequently weighted by the percentage between graduations and enrollments for each level of schooling. Due to the impossibility of calculating these elasticities for private education, it was decided to generalize it to the public and private education sectors in the modeling.

The composite edu_o was defined within the model (Equation C.9) as a function of the basic flows of private education demanded by families ($EduPriv$) and demanded domestically by the government ($EduPublic_{dom}$), with hou_d_{edu} and gov_d_{edu} being the variables associated with these measures. Similarly, the average price of labor supply per qualification ($Wedu_o$) was also calculated within the model (Equation C.11), but updated by the semi-elasticity of income with respect to years of schooling ($YEDU_o$), a parameter estimated econometrically using the Mincerian earnings equation, the estimation process of which was explained in the previous section. These estimates allow for updating wages according to the differentials associated with an additional year of schooling. Thus, each year of study marginally increases the average wage for the job offered and consequently the relative wages, with its intensity varying according to the worker's level of qualification.

The labor demand equation in BIM-RDHC followed the pattern conventionally adopted in EGC modeling (Equação C.4), relating where represents the amount of work in hours per skill level $Ld_{i,o}$ demanded by each of the economic activities i, and is the average labor demand ($averld_i$) and the relative wage of the demanded occupations ($W_{i,o}/Wo_i$), weighted by the CES substitution parameter between skill types (sub_LAB_i). Thus, the demand for low, medium, or high-skilled workers would be defined by producers as they seek to minimize their production costs, subject to a CES-type technology. That is, in seeking to obtain minimum costs, companies choose an optimal number of workers of each skill type, according to wage rates, technical parameters and requirements, and their budgetary constraints.

In the model, variations in the total number of employed workers result from the optimizing process that equates the supply of labor (Ls_o) with the aggregate demand for labor across all industries ($Ld_{i,o}$), both by occupation type (Equation C.12). Additionally, labor units in hours are weighted by the number of employees. Thus, the new supply of skilled labor is used to reshape the stock of the three different types of labor. In this sense, workers who have moved from low to medium skill are incorporated into the pre-existing stocks of medium-skilled labor, while workers who have become highly skilled are added to the pre-existing stocks of highly skilled labor. Finally, low-skilled labor is determined in each period as residual in relation to the stocks of the other two types of labor.

The total labor stock corresponds to the aggregate number of workers across all skill categories (Equation C.13). Since the supply and demand for workers adjust towards equilibrium, changes in the composition of the labor supply due to new policies can influence the quantity demanded of each type of work by skill level, consequently affecting added value and production. Therefore, it is assumed that exogenous shocks in public investment in education impact the process of human capital formation, inducing variations in the supply and demand for skilled workers.

Overall, the model adjusts through changes in the stock of physical capital, knowledge capital, and labor, with medium- and high-skilled workers being defined as proxies for human capital. Physical capital is considered to be increased by investment, while knowledge capital is determined by investments in R&D, and the supply of skilled labor varies primarily as a function of public spending on education. Finally, the model's recursive prospective dynamics update exogenous variables sequentially, year by year, as in an exercise of comparative statics. Based on the solutions for each period, intertemporal adjustments are made in the labor market and in the stocks of physical and knowledge capital, ensuring the connection and dynamic updating between periods.

4.3. Baseline and policy analysis

In general, simulations performed in CGE models are compared to a reference scenario, constructed from the actual variations of the main components of final demand in the observable and projected periods. In this study, we started with the baseline data of 2015, which were updated by historical simulations for the period from 2016 to 2023, generating a historical perspective of the Brazilian economy, from which the trajectory for 2024-2050 was projected. The annual variations of the macroeconomic aggregates of this reference scenario in the historical and prospective periods are presented in Table 2.

According to the baseline, in 2016, the first year of the historical simulation, a 3.3% drop in GDP was observed, which expresses the recession faced by the country that year, and which was negatively reflected in investments (-12.1%), household consumption and the national labor market. Between 2017 and 2019, there was a slight recovery in the Brazilian economy, which was interrupted in 2020 due to the Covid-19 pandemic, when the country experienced negative growth (-3.3%). In 2021, the national employment level, measured in hours worked and the effective number of employed individuals, fell by 0.6% and 0.8%, respectively, signaling the pandemic's effects on the Brazilian labor market. From 2021 onwards, the country returned to positive economic growth, driven by positive real variations in all aggregates that make up the GDP. In the reference scenario projected for 2024-2050, an average growth of 2.2% per year was predicted for the Brazilian GDP, as well as for government spending, according to projections from the Federal Development Strategy for Brazil (BRASIL, 2020).

Table 2. Real variations (%) of baseline shocks

	Observed								Prospective projections*
	2016	2017	2018	2019	2020	2021	2022	2023	2024-2050
GPD	-3,3	1,3	1,8	1,2	-3,3	4,8	3,0	2,9	2,2
Household consumption	-3,8	2,0	2,4	2,6	-4,6	3,0	4,2	3,1	-
Government demands	0,2	-0,7	0,8	-0,4	-3,7	3,5	2,1	1,7	2,2
Exports	0,9	4,9	4,1	-2,6	-2,3	4,4	5,7	9,1	-
Investiment	-12,1	-2,6	5,2	4,0	-1,8	12,9	1,1	-3,0	-
Employment	-0,2	0,0	0,1	0,0	-0,6	0,4	0,3	0,3	-
Number of workers	-1,4	0,6	0,4	0,6	-0,8	0,5	0,4	0,5	-

Source: Authors' own table.
Note: * Hidden values indicate that the variables are endogenous within the period.

Based on the reference scenario, the shifts caused by the simulated policy shocks in this study are analyzed, corresponding to the percentage deviation in the model results from the prospective scenario. Specifically, shocks associated with changes in public spending on public or private education are simulated, based on the proposal to expand public investment advocated by the National Education Plan (PNE). The PNE, established by Law No. 13,005/2014 and in effect between 2014 and 2024, set the goal of expanding public investment in education to at least 7% of GDP in the fifth year of its validity and 10% of GDP at the end of ten years. However, these goals were not achieved, making it necessary to develop a new plan for the next decade. Bill No. 2614/2024 proposes to repeat the previous goal, aiming to ensure sufficient resources for the expansion of Brazilian education at all stages and modalities. However, achieving this goal depends on the State's financial capacity, which is limited by the New Fiscal Framework (LC 200/2023), restricting the growth of public spending. In addition, public investments in education include transfers to the private sector, such as subsidies and tax exemptions, which implies that educational expansion policies must also consider these transfers to private education.

Based on these assumptions, in this study we propose the simulation of four scenarios for the expansion of public education spending in Brazil, as described in Table 3. In the first scenario, we simulate an increase in public spending on public education to reach 10% of GDP in 2034, with the shock, implemented in the government's domestic demand for public education, being distributed annually in a proportional manner to reach up to 7% of public spending on education in 2029, the fifth year of the scenario, and 10% of GDP at the end of the ten years. In the second scenario, the results obtained in the first simulation, equivalent to the accumulated variation in government spending on public education, were implemented as annual subsidy shocks to private education. In the third scenario, the growth of public spending on public education was also simulated, but in such a way that the simulated 10% shock to GDP was distributed uniformly over a longer horizon of twenty years until 2044. Finally, in the fourth scenario, the results of the accumulated variation in government spending on public education until 2044 obtained in the third scenario were used as a subsidy to private education. We emphasize that all these simulations described were carried out considering an environment in which external savings remain constant relative to GDP, while tax revenue adjusts endogenously to maintain stable public savings, without changes in other government spending.

Table 3. Policy Simulation Scenarios for Expanding Public Spending on Education

Policy scenario	Description	Instrument	Time horizon
Scenario 1	Increase in public spending on public education, reaching 7% in 2029 and 10% of GDP in 2034, according to the National Education Plan (PNE).	Variation in government demand for public education	2024-2034
Scenario 2	Increase in public spending on private education until 2034, according to the projected spending in Scenario 1.	Subsidies for private education	2024-2034
Scenario 3	Increase in public spending on public education, aiming to reach 10% of GDP by 2044.	Variation in government demand for public education	2024-2044
Scenario 4	Increase in public spending on private education until 2044, according to the projected spending in Scenario 3.	Subsidies for private education	2024-2044

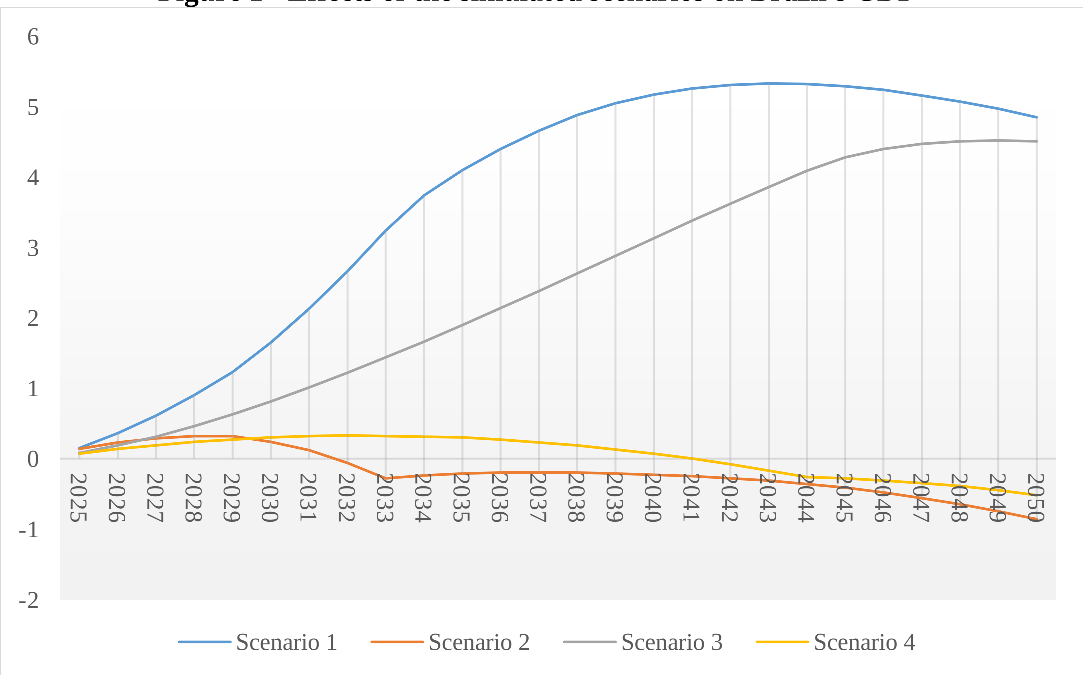
Source: Authors' own table.

It is also important to highlight that adaptations were made to the standard model closure to adapt it to the reference and policy scenarios, through the exchange between endogenous and exogenous variables, ensuring the consistency of the simulations and the solution of the system according to the projected objectives. In the historical simulation, variables that receive shocks (GDP from the expenditure perspective, household consumption, aggregate real investment, real government demand, and export volume) were treated as exogenous, maintaining their respective endogenous counterparts. In the policy scenarios, specific hypotheses were adopted regarding the functioning of the labor market and fiscal behavior. In all four scenarios, the exchange between the variables of wage displacement by qualification and labor supply was carried out, activating the labor supply equation and allowing wage adjustment via equalization between. Regarding the public sector, the maintenance of the savings/GDP ratio and other government spending (except public education) was ensured through the exchange between the general displacement of direct and indirect taxes and the variation in net government revenue. Specifically in scenarios simulating subsidies for private education via tax exemptions, a trade-off was made between the variation in revenue from the tax on the production of private education (endogenous) and the variation in the respective tax rate (exogenous), allowing subsidies to alter production costs and, consequently, the supply of this activity.

5. Results

As shown in Figure 1, the first scenario, which proposes increasing public spending on public education as a proportion of GDP to 7% in 2029 and 10% in 2034, the cumulative growth projected by the model for the implementation of the policy compared to the baseline scenario is 3.7% between 2025 and 2035, reaching even higher values in subsequent years. These results are mainly driven by private investment and government consumption, which varied by 42.4% and 17%, respectively, during the period. In both cases, this is related to the stimulus in investment in knowledge capital caused by the public education sector, which stands out in the production of national R&D. On the other hand, household consumption shows a decrease of 8.6%, which occurs to accommodate the increase in public spending. This reduction in domestic demand forces a decrease in national prices, with a negative implicit GDP deflator, which makes goods produced in the country more competitive in the international market, leading to an increase in exports of 15.5%.

Figure 1 - Effects of the simulated scenarios on Brazil's GDP*



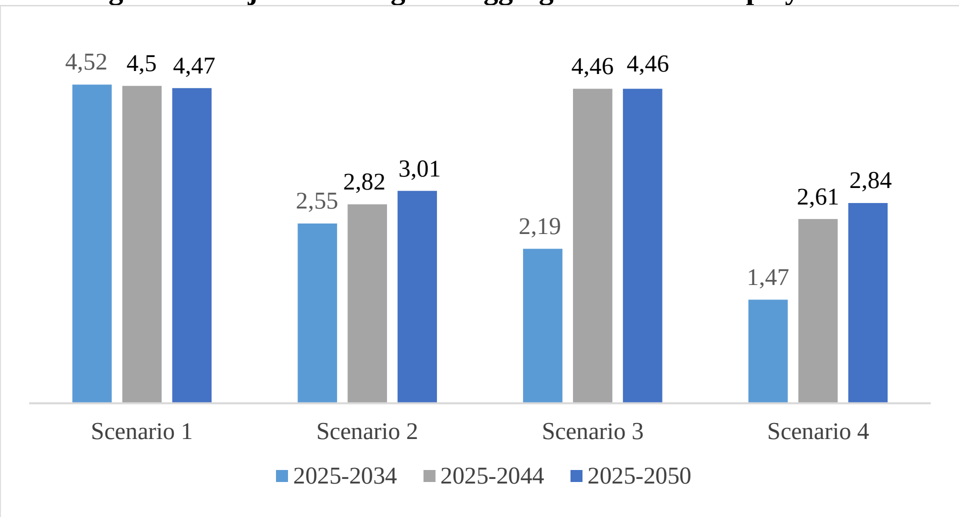
Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

The second scenario, marked by government subsidies to private education through tax exemptions for this activity, following the hypotheses adopted in the previous one, leads to negative percentage changes, both between 2025-2034, the period in which these shocks are implemented (-0.34%), and in the others analyzed for a longer horizon (-0.36% and 0.86% for 2025-2044 and 2025-2050, respectively). Despite this, in these three cases, with the exception of household consumption, all components of GDP show a positive cumulative variation compared to the baseline after the implementation of these shocks. For example, with this simulation, private investment shows a cumulative variation of 1.49% from 2025 to 2044, again highlighting more specifically the investment related to knowledge capital (10.15%), although to a lesser magnitude than the first scenario.

The third scenario, for which an increase in public spending on education of up to 10% of GDP, distributed uniformly over twenty years, was simulated, showed a similar trend to that observed in the first scenario regarding the effects on economic growth. Through this simulation, a percentage increase of 4.09% in Brazil's GDP was predicted until 2044, the last year of the shocks, but which would also be reflected in the indicators of the following years, until the end of the analysis in 2050. In this case, the behavior of the GDP aggregates, as in the previous scenarios, adapts to the shocks.

In addition to the aggregate macroeconomic effects, the four simulated policies have repercussions on the labor market, causing positive cumulative variations in national employment in the medium and long term, as illustrated in Figure 2. In this context, scenarios 1 and 3 stand out, in which the government expands its spending on public education. In both cases, a cumulative growth in the national employment level of around 4.5% was projected for the years in which the shocks were implemented (2025-2034 and 2025-2044, respectively). This positive effect follows the increase in the overall level of activity, with an expansion of skill levels and an increase in R&D, with positive impacts that spread throughout the economy and are sustained over time.

Figure 2. Projected changes in aggregate national employment*



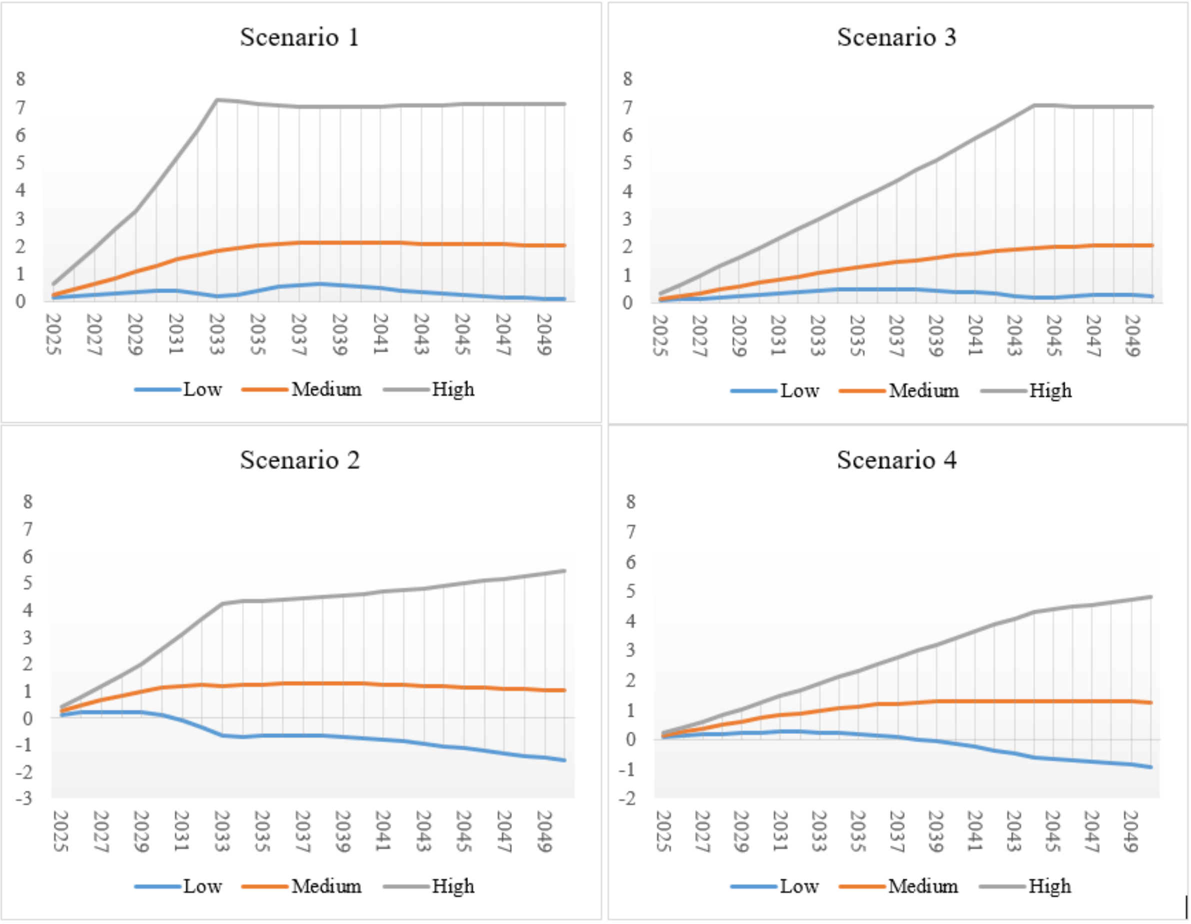
Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

Conversely, second and fourth scenarios in which public subsidies are given to private education through tax exemptions, stimulate less percentage growth in aggregate national employment, according to the simulations performed. Even so, they show positive variations compared to the baseline scenario, being 2.55% for the second scenario in the cumulative period from 2025 to 2030, and 2.61% for the third scenario between 2025-2044, periods in which the respective simulations were made. That is, in these cases, although the increase in the level of qualification of the population promotes an increase in income, the effects on R&D are modest, not allowing the gains in terms of activities to extend over time.

The transformations caused by the applied shocks are also reflected in the use of different types of workers (low, medium, and high educational attainment level) by economic activities. From this perspective, Figure 3 illustrates the projected annual changes in the composition of the labor factor, measured in effective hours, by qualification level, compared to the baseline of the analysis, for each simulated scenario. It is observed that under the first scenario, although there is a positive annual variation in the use of medium-skilled labor in national economic production, the effects are greater for the highly skilled. However, these impacts increasingly accompany the periods in which the shocks are introduced, from 2025 to 2034, settling linearly shortly afterwards and remaining so until the last projected year.

In the third scenario, which reproduces the hypothesis of increasing government spending on public education presented in scenario 1, but distributing it over twenty years, although the variations in the composition of labor follow a similar trajectory at the three levels of qualification, the cumulative growth in the use of highly qualified labor occurs more uniformly over time, reflecting the shocks given. But from 2045 onwards, the first year after the end of the simulated shocks, it also begins to show a linear trajectory that continues until 2050.

Figure 3 - Projected changes in hours worked by skill level (low, medium, and high)*



Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

In the second scenario which involves subsidies to private education over a decade, in the same proportion as the government would spend on public education in the first scenario, it is observed that in the medium and long term there would be a gradual decrease in the use of low-skilled labor in economic production, associated with a slight increase in medium-skilled labor and a more noticeable increase in the use of highly skilled labor. This increase in the cumulative percentage variation relative to the baseline scenario in highly skilled labor is also increasing during the period in which the policies are simulated, but despite its discontinuity after the end of the shocks, it continues to show a subtle cumulative advance until 2050. The fourth scenario, which also reproduces public subsidies to private education, distributed evenly over twenty years, points to percentage changes over the baseline that are also increasing throughout the analyzed period, but following an evolution with few discontinuities in the trajectory.

In summary, the four simulated scenarios showed positive results regarding percentage changes in the use of highly skilled labor in the Brazilian economy in the projected periods. In contrast, on average, there is a small fluctuation in low-skilled labor, tending to decline in some cases.

Intermediate-skilled labor showed a subtle evolution in the projections, especially when compared to the highest level of labor qualification.

Regarding the sectoral effects of the simulated policies on the use of the labor production factor, the results indicate that policies to expand public investment in education directly stimulate public and private educational activities, as expected, according to the shocks implemented in each of them. In parallel, the income effect increases overall demand and positively affects other sectors, spreading across the activity level of other sectors. These sectoral impacts are also reflected in variations in the types of labor, by skill level. In this regard, the expansion in the supply of highly skilled labor, driven by educational investment policies, makes this type of labor relatively cheaper through price equilibrium, leading to its increased use by different sectors of the economy. Since the types of labor complement each other, low and medium-skilled labor also generally vary in the same direction, reflecting the increase in their utilization in the production process. Thus, some sectors that demand skilled labor are indirectly benefited by the expansion in its supply.

Looking directly at the number of workers employed in the Brazilian economy, which constitutes aggregates of the labor measure in hours weighted by the number of workers employed in the country's labor market, it is observed that all four simulations adopted in this study generated positive impacts on the inclusion of highly skilled individuals in the national labor market. In other words, the simulations showed positive percentage variations, accumulated in the medium and long term, especially in the number of workers with higher education (completed or in progress) in the country, as shown in Table 4.

Table 4. Projected changes in the number of workers by skill level (low, medium, and high)*

	Skill level	2025-2034	2025-2044	2025-2050
Scenario 1	Low	-1,37	-0,01	-0,06
	Medium	-0,87	0,61	0,8
	High	4,6	5,52	5,69
Scenario 2	Low	-1,33	-1,57	-2,16
	Medium	1,09	1,42	1,33
	High	8,76	10,82	12,32
Scenario 3	Low	-0,1	-0,51	0,03
	Medium	0,21	0,01	0,73
	High	2,1	5,08	5,53
Scenario 4	Low	0,01	-1,12	-1,42
	Medium	1,2	1,45	1,58
	High	4,17	9,19	10,59

Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

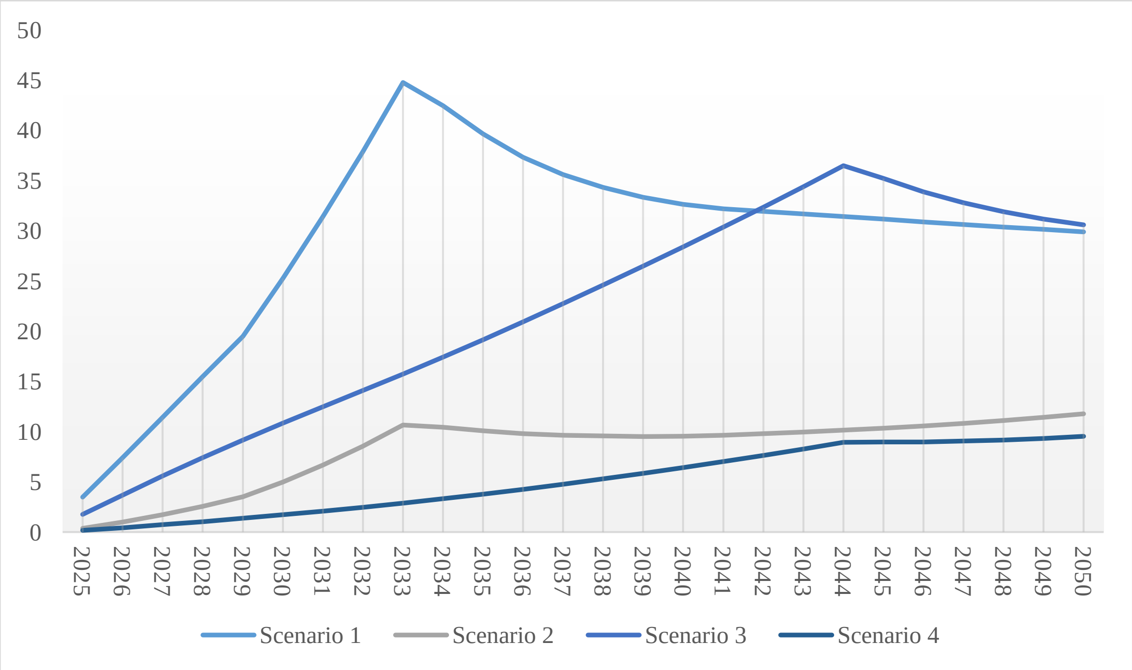
However, it is observed, more specifically, that the deviation from the baseline scenario was smaller in the two scenarios where an increase in government spending on public education was simulated, than in those where subsidies were distributed to private education. This may be linked to the fact that it is the Brazilian private higher education institutions that concentrate most of the enrollments in courses at this level, in contrast to public institutions. In this context, data from the Education Census indicate that in 2023, 79.3% of students enrolled in higher education courses in Brazil attended private colleges or universities, which is aligned with the high proliferation of these entities in the country since the 1990s. Furthermore, in general, public subsidies for private education in Brazil are linked to the provision of scholarships and educational financing programs, such as Prouni and Fies, which encourage individuals to enroll in these institutions.

According to the simulation results, the policy of expanding government spending on public education represented in the first scenario predicts, cumulatively from 2025 to 2034 – the desired period for its implementation and in which the shocks occur – a negative rate of change in the number of workers with average (-1.37%) or low qualifications (-0.87%). These negative percentage changes are less intense when considering the years following the shocks, after 2034. However, the positive effects on the number of highly educated individuals (high qualifications) intensify even further in the long term, by 2050.

This also occurs in the other scenarios, connecting with the hypothesis that, due to the years of study required to achieve higher levels of education, the effects of educational policies tend to be better reflected in subsequent periods. Consequently, it is evident that, under the implementation of different policies that lead to an increase in public educational expenditures, there is an accumulation of human capital, whose stock is equivalent to the number of highly qualified workers.

The four simulations of government spending and subsidy expansion policies in education also affect investments in R&D and the production of knowledge capital in Brazil, as observed in Graph 3, which shows the percentage change in R&D investments relative to the baseline scenario after the simulations were performed.

Figure 4. Projected variation in R&D investments in Brazil*



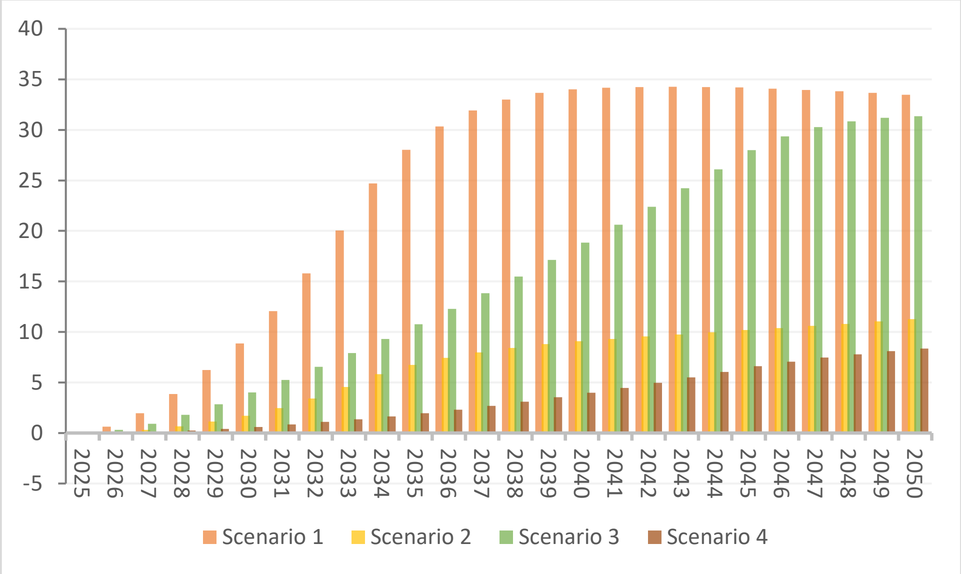
Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

The shocks that yielded the best results regarding this economic element were those aimed at increasing public spending on public education. Therefore, incentives in this sector are reflected in activities related to innovation in the country. It is also observed that, although the first simulation scenario initially presents the best results and an upward trajectory in the predicted variations of R&D until 2033, from that point onwards there is a decrease, becoming, in the long term, less favorable than the third scenario. This reduction begins to occur immediately after the last shock implemented, signaling that this intense incentive caused by educational investment policies imposed in a restricted time interval may occur in an unbalanced and unsustainable way. Thus, it is found that for scenario 3, given the longer time horizon over which the shocks are distributed, the effects on R&D investments are also distributed more smoothly over time.

The results of the other scenarios, referring to subsidy shocks on the private education sector, although less prominent, also generate positive effects on R&D investment. This is because private education produces a small portion of R&D in Brazil. Despite this, it can be observed that these two scenarios follow trajectories similar to those presented by the previous simulations with the same time horizon, but present more constant trends towards the long term.

When evaluating the changes in accumulated stocks of knowledge capital in relation to the baseline, shown in Figure 5, it is verified that in the first scenario, the relative deviations grow gradually until 2034, from which point they begin to have a smooth growth, until they remain constant. In the third scenario, this positive variation occurs to a lesser extent, but continuously. As expected, scenarios 2 and 4 show lower rates of variation in the stock of knowledge capital than those in which the shocks are in public education. However, the second scenario, in which subsidies for public education are implemented until 2034, has higher projected knowledge stocks than the one in which they are distributed uniformly until 2044.

Figure 5. Projeção de variação no estoque de capital de conhecimento no Brasil*



Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

In a sectoral view, shown in Table 5, it is observed that for the four simulated scenarios, both R&D investments and the stock of knowledge capital stand out predominantly in the services sector. This is associated with the fact that there is an expansion directly concentrated in the education sector, in addition to positive effects on other activities intensive in the production and demand for knowledge capital, such as those related to information and information technology, for example. Therefore, an expansion in educational services, via public or private education, stimulates an increase in the number of highly qualified workers in the Brazilian economy, leading to greater investments and consequently greater accumulation of this type of capital for the sectors that demand it most intensely.

On the other hand, consistent with what has already been observed in the aggregate results of the simulations, it is found that policies to expand government spending on public education are more effective in terms of R&D production and knowledge capital in all major sectors of the economy, even in those with less technological intensity, than those in which public subsidies are given to private education. In the second and fourth scenarios, which correspond to subsidy shocks in private education, the negative results stand out, in percentage variations, especially in the agricultural sector, in addition to the small or negative effect also generated on industry, albeit on a smaller scale.

Regarding the temporal effects in the simulations of the scenarios for the major sectors of the economy, it is observed that, in all cases, the results tend to be more intense in the accumulated periods in which the shocks are effectively carried out, although the effects of the policies continue to be reflected in subsequent years.

Table 5. Projection of sectoral variations in R&D investments and knowledge capital stock*

	2025-2034		2025-2044		2025-2050	
	R&D	Knowledge	P&D	Knowledge	P&D	Knowledge
Scenario 1						
Agriculture and livestock	-1,24	0,61	4,56	5,34	3,76	2,59
Manufacture	2,59	2,66	6,77	3,57	4,35	2,3
Services	28,77	50,31	39,32	36,87	38,87	35,28
Scenario 2						
Agriculture and livestock	-2,51	-3,74	-1,2	-1,05	-1,66	-2,34
Manufacture	-0,19	-0,45	1,47	0,94	-0,18	0,45
Services	6,96	12,59	-0,25	11,95	-1,47	13,99
Scenario 3						
Agriculture and livestock	-0,21	0,77	2,06	3,72	4,06	3,21
Manufacture	0,47	2,82	3,39	4,9	4,04	4,76
Services	10,96	20,3	30,38	42,64	36,53	35,63
Scenario 4						
Agriculture and livestock	-0,77	-1,32	-1,55	-1,93	-1,33	-1,9
Manufacture	-0,62	-0,43	-0,03	0,52	0,32	0,61
Services	2,09	4,04	7,21	10,57	9,93	11,28

Source: Authors' own elaboration based on research results.
Note: *Cumulative percentage deviation from the baseline scenario.

6. Concluding remarks

Based on the interrelationship discussed in the economic literature regarding education and the formation and accumulation of human and knowledge capital, and its repercussions on both the labor market and other aspects of the national economy, this study sought to evaluate the economic effects of policies expanding public investment in the public and private education sectors. To this end, a recursive-dynamic national CGE model is employed to represent the Brazilian economic structure, with labor supply specified as an endogenous process driven by changes in public educational investment and relative wages across skill groups. Within this CGE framework, four alternative scenarios were simulated involving an increase in public education expenditure to 10% of GDP, distributed over different time horizons and across educational public and private sectors.

Regarding the main macroeconomic indicators, the simulation results indicated that the scenarios assuming an increase in government spending on public education lead to greater economic growth in the period projected by the model, from 2024 to 2050, represented by the positive variation in GDP compared to the baseline scenario. According to the projections, this economic growth under these scenarios is driven mainly by total investment, a component of GDP, linked, in particular, to the promotion of public education and investment in R&D. On the other hand, the predicted macroeconomic effects were smaller in the scenarios of subsidies to private education.

In the analyses of the labor market, it was observed that all simulated scenarios had significant impacts on the total employment of workers in the Brazilian economy. In addition, positive effects were observed on the increased use of highly skilled labor (measured in hours) in the country's economic production, reiterating the importance of policies to expand public investment in education, whether directed to the public or private education sector. It was also found that these effects tend to stabilize in a smooth trajectory when distributed over a longer time horizon.

Although public investment policies in education impact employment and effective work, policies subsidizing private education proved to be more efficient in terms of the growth of the human capital stock, represented by skilled workers. This is possibly linked to the large supply of vacancies in private higher education in Brazil, responsible for the largest number of student enrollments at this level. Transfers to public education, on the other hand, were more efficient in terms of investments in R&D and the accumulation of knowledge capital, highlighting their importance to the country's technological development.

Even under different assumptions, the simulations results emphasize that the expansion of government spending on education impacts various aspects of the economy, especially the accumulation of human capital and knowledge capital. These findings suggest that the path forward for Brazil may involve the adoption of coordinated policies between the public and private education sectors.

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Appendix A. Econometric estimation results for the Mincerian earnings equation

Variables	Model 1 – Low skill level	Model 2 - Medium skill level	Model 3 – High skill level
Constant	5,755***	4,964***	4,594***
Years of Schooling	0,103***	0,159***	0,201***
Labor market experience	0,016***	0,028***	0,039***
(Labor market experience)²	-0,0004***	-0,0004***	-0,001***
Gender	-0,615***	-0,548***	-0,466***
Racial group	0,120***	0,118***	0,187***
Household head status	0,061***	0,066***	0,088***
Metropolitan area resident	0,162***	0,130***	0,296***
Brazil’s Northeast region resident	-0,330***	-0,186***	-0,118***
Brazil’s Southeast region resident	0,250***	0,187***	0,119***
Brazil’s South region resident	0,412***	0,304***	0,119***
Brazil’s Center-West region resident	0,386***	0,277***	0,207***
Undereducated workers	0,178***	0,214***	0,212***
Overeducated workers	-0,477***	-0,299***	-0,423***
Manufacturing workers	0,308***	0,335***	-0,615**
Construction-sector workers	0,610***	0,095	-0,335
Wholesale and retail trade workers	0,411***	0,495***	-0,204
Transportation workers	0,479***	0,901***	0,087
Food service workers	0,495***	1,026***	-0,06
Information and communication services workers	0,589***	0,337**	-0,762**
Public administration workers	0,792***	0,161	-1,219***
Health and education service workers	0,942***	0.524***	-1,397***

Other Service-sector workers	0,241***	0,355**	-0,387
Paid domestic workers	0,363***	-0,14	2,004***
Workers in other unspecified activities	0,268**	1,162	-0,027
Manufacturing workers x Skill level interaction	-0,020***	-0,020*	0,043**
Construction-sector workers x Skill level interaction	-0,054***	0,006	0,023
Whols. and ret. trade workers x Skill level interaction	-0,026***	-0,032***	0,008
Transportation workers x Skill level interaction	-0,022***	-0,061***	-0,01
Food service workers x Skill level interaction	-0,031***	-0,081***	-0,003
Info. and comm. Serv. workers x Skill level interaction	-0,052***	-0,016	0,046**
Public administration workers x Skill level interaction	-0,058***	0,01	0,086***
Health and education service workers	-0,073***	-0,033***	0.079***
Other service-sector workers x Skill level interaction	-0,019***	-0,033***	0.007
Paid domestic workers x Skill level interaction	-0,039***	0,008	-0,174***
Workers in other unsp. activities x Skill level interaction	-0,066***	-0,109	-0,012
Inverse Mills ratio (λ)	0,140***	0,301***	0,281***

Note: *p<0,1; **p<0,05; ***p<0,01.

Appendix B. Data structure and calibration

The model was calibrated based on a Social Accounting Matrix (SAM) developed from the 2015 Brazilian national input–output (I-O) matrix and other data released by the National Accounts System (SNC) of the Brazilian Institute of Geography and Statistics. The production data were aggregated into 28 economic sectors producing 126 commodities in the Brazilian economy. In addition, the model recognized components of final demand, namely government consumption, investment, exports, inventory changes, and four representative households defined by income class. These households were classified into four income groups, considering the 2015 minimum wage of R$ 788: (i) one to two minimum wages; (ii) two to five minimum wages; (iii) five to ten minimum wages; and (iv) more than ten minimum wages. The model also incorporates two types of margins (trade and freight transport), imports by product, and two primary factors of production (capital and labor). Finally, data on three types of indirect taxes (IPI, ICMS, and other taxes and subsidies) were included. To address inconsistencies arising from the use of multiple data sources in the construction of the SAM, the biproportional RAS procedure was employed to proportionally adjust matrix flows and ensure consistency between row and column totals.

It is important to note that, in the SAM constructed for model calibration, the labor factor was disaggregated by skill level based on data from the 2015 Continuous National Household Sample Survey. To this end, in addition to the sectoral and household disaggregation of the model, the occupation and labor income vectors were also disaggregated by qualification level. Workers were classified into three groups according to their educational attainment: (i) low-skilled, comprising individuals with no schooling or with incomplete or complete primary education; (ii) medium-skilled, including those with incomplete or complete secondary education; and (iii) high-skilled, consisting of workers with incomplete or complete higher education.

Additional elasticities and behavioral parameters were drawn from the literature and incorporated into the calibration of the CGE model. The Armington elasticities (1969) governing substitution between domestically produced and imported goods, for intermediate use, investment, and household consumption, were based on the estimates of Tourinho, Kume, and Pedroso (2007), ranging from 0.15 to 3.61 depending on the use category. Export demand elasticities for traditional and non-traditional goods followed Domingues (2002), varying from 0.08 to 9.33 for traditional goods and set at 1.28 for non-traditional goods. The CES substitution elasticities between primary factors ranged from 0.21 to 1.58, while the CET transformation elasticity was fixed at 0.50. Household behavior was parameterized using a Frisch parameter of −1.94, following Almeida (2011), and household expenditure elasticities ranging from 0.00 to 1.93, based on Hoffman (2010). Finally, the occupational substitution elasticity was set at 0.20, in line with the previous BIM-RD model.

Appendix C. Sectors and key variables, parameters and equations of BIM-RDHC model

The BIM-RDHC model was implemented in GEMPACK (General Equilibrium Modelling Software), a suite of software developed at the Centre of Policy Studies (CoPS), a group of CGE modellers based at Victoria University in Melbourne, Australia. Simulations were run using RunDynam, a GEMPACK software specifically designed for dynamic CGE modeling. Table C.1 describes the economic sectors that comprise the model's database, while Table C.2 describes the key variables and parameters, and Table C.3 presents the main equations of the model, according to the procedures described in the methodological section of this study.

Table C.1. Economic sectors classification used in the BIM-RDHC model

Classification	Description
S01	Agriculture and livestock
S02	Mining, quarrying, and oil and gas extraction
S03	Food, beverages and tobacco manufacturing
S04	Textile, apparel and footwear manufacturing
S05	Wood, pulp, paper and printing manufacturing
S06	Refined petroleum products and biofuels manufacturing
S07	Chemical, rubber and plastic products manufacturing
S08	Metals and non-metallic mineral products manufacturing
S09	Computer, electronics and optical equipment manufacturing
S10	Electrical machinery and equipment manufacturing
S11	Motor vehicles and other transport equipment manufacturing
S12	Manufacture of furniture and other manufacturing
S13	Electricity and utilities; water and waste services
S14	Building and construction activities
S15	Wholesale and retail trade
S16	Transport and storage services, including postal activities
S17	Accommodation and food service activities
S18	Information and communication services
S19	Financial services, insurance and pension funds
S20	Real estate services
S21	Professional, scientific and technical services
S22	Administrative, support, security and intellectual property services
S23	Public administration, defense, and social security
S24	Public education services
S25	Private education services
S26	Public health services
S27	Private health services
S28	Other services

Table C.2. Key variables and parameters used in the BIM-RDHC model

Symbol	Description
Z_i	Production level of economic sector i
X_i	Intermediate inputs used by the sector i
V_i	Added value of the sector i
$I_{j,i}$	Investments of sector i in j ($j = K_F$ or $j = K_C$)
K_F	Physical capital
K_C	Knowledge capital
Z_i	Total demand from families for good i

Z_i^{Sub}	Household demand for the good i retained for subsistence purposes
S_i^{lux}	Share of luxury good i in total spending on luxury goods
Ls_o	Labor hours supplied by skill level o
$Ld_{i,o}$	Labor hours demanded by sector i and skill level o
$Works_{tot}$	Total workers supplied on economic system
$Works_{low}$	Low-skilled workers are supplied by the economic system
$Works_{low}$	Medium-skilled workers are supplied by the economic system
$Works_{low}$	High-skilled workers are supplied by the economic system
$W_{i,o}$	Average wage paid by sector i for skill level o
Wo_i	Average aggregate wage paid by sector i across all skill levels
$Wedu_o$	Average wage of work offers skill level o
$Wedu$	Average aggregate of work offers by all skill levels
$gov\_EDU_o^{stud}$	Public spending per student by grade level by educational level o
$gov\_EDU_o^{tot}$	Total public spending by grade level by educational level o
$workers_o$	Number of employed workers
$Grad_o$	Number of graduates by educational level o
$Enrol_o$	Number of enrolled students by educational level o
edu_o	Composed of private and public spending on education by educational level o
hou_d_{edu}	Household demand for private education variable
gov_d_{edu}	Government domestic demand for private education variable
$EduPriv$	Household basic demand flows for private education
$EduPublic_{dom}$	Government domestic basic demand flows for private education
$averld_i$	Average labor demand by sector i
$elas\_EDU_o$	Elasticity of investment in education by skill level o
$elas\_LAB_o$	Elasticity of substitution in the labor supply by skill level o
sub_LAB_i	CES replacement parameter between skill levels by sector i
$YEDU_o$	Income semi-elasticity to schooling by skill level
a_i^X, a_i^V	X and V productive efficiency parameters
$year$	Additional year of schooling

Table C.3. Key equations applied in the BIM-RDHC model

Production of final goods in sectors (i)	$Z_i = min\left(\frac{X_i}{a_i^X}, \frac{V_i}{a_i^V}\right)$	Equation C.1
Intermediate inputs used by the sector i	$X_i = \left[\sum_{i=1}^{s} \delta_{s,i} X_{s,i}^{-\rho^X}\right]^{\frac{-1}{\rho^X}} \quad \forall \ s = (D, I)$	Equation C.2
Added value generated by the sector i	$V_i = \left[\sum_{i=1}^{f} \delta_{f,i} V_{f,i}^{-\rho^V}\right]^{\frac{-1}{\rho^V}} \quad \forall \ f = (L, T, K_F, K_C)$	Equation C.3
Investment decision modeling in physical and knowledge capital	$I_{j,i} = \min(X_{j.i}^I) \ \forall \ j = (K_F, K_C)$	Equation C.4
Accumulation of physical and knowledge capital	$K_{j,i,t+1} = (1 - dep_{j,i})K_{j,i,t} + I_{j,i,t} \ \forall \ j = j = (K_F, K_C)$	Equation C.5
Linear System of Household Expenditures	$U(Z_i, \ldots, Z_c) = \sum_{i=1}^{c} S_i^{lux} (Z_i - Z_i^{Sub})$	Equation C.6
Labor supply equation (hours)	$Ls_o = elas\_EDU_o edu_o + elas\_LAB_o (Wedu_o/Wedu)$	Equation C.7
Elasticity of investment in education	$ELAS\_EDU_o = \left(\frac{gov\_EDU_o^{stud}/gov\_EDU_o^{tot}}{1/workers_o}\right) * \frac{Grad_o}{Enrol_o}$	Equation C.8
Private and public spending	$edu = hou\_d_{edu} EduPriv + \ gov\_d_{edu} EduPublic_{dom}$	Equation C.9

component on education		
Average wage by skill level	$Wedu_o = Wi_o + YEDU_o * year$	Equation C.10
Labor demand equation (hours)	$Ld_{i,o} = \ averld_i - sub\_LAB_i(W_{i,o}/Wo_i)$	Equation C.11
Labor market equilibrium representation	$Ls_o = Ld_{i,o}$	Equation C.12
Total labor supply (number of workers)	$Works_{tot} = Works_{low} + Works_{medium} + Works_{high}$	Equation C.13

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