The Brumadinho dam rupture disaster in Minas Gerais (Brazil) and the productivity: regional economic impacts using a computable general equilibrium approach

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ABSTRACT

The aim of this paper is to analyse the impact of the Brumadinho dam rupture that occurred in Minas Gerais (Brazil) on labour productivity. As a typical case of negative externalities, this type of disaster leaves behind large-scale environmental and economic damages at both local and regional levels. To account for these, we translated the environmental effects into labour productivity changes in the affected area. It is assumed that changes in the payment of workers is proportional to the labour productivity, which captures the economic responses. Regional economic effects are modelled using the BMaria-MG, a computable general equilibrium (CGE) model calibrated with data of 2015. The analysis is performed to fill a gap found in the literature, given this is a topic currently in growing development. The results indicate a small impact on GDP in all regions. This is due to the low significance of labour productivity in the sectors. Since the study provides only a partial perspective of the productivity changes, disregarding for example the effects on capital productivity, results are limited. This is an improvement considered for the next phase of the research, which will disaggregate the input-output analysis in a more appropriate manner to better capture the related impacts for the most affected areas.

Keywords: Brumadinho disaster; Computable General Equilibrium, BMaria-MG; Labour productivity; Regional Economics

JEL classification: Q51; R13; J24

1. Introduction

On 25 January 2019, the Brazilian village of Brumadinho, in the mining-heavy state of Minas Gerais, was taken by the tailings of Córrego do Feijão's

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dam. This dam rupture is arguably one of the worst human and environmental disasters, leaving over 250 people dead, and spreading a large amount of ore tailing into Paraopeba River and the surrounding area. A similar incident firstly occurred in November 2015 in the village of Mariana. The toxic waste of the mine dispersed towards the villages along the Doce River basin and reached the Atlantic coast. As a typical case of negative externalities, this type of disaster leaves behind large-scale environmental and economic damages at local but also regional levels. Besides the exposure of local population to the contamination and corresponding effects of the economic losses, there are geological impacts, degradation of the landscape and air pollution.

Immediately after the disaster, the mining, agricultural and tourism activities were paralysed, with material, cultural, socio-economic and health implications. Impacts on health are driven by water contamination, which directly affects labour productivity. Since economic sectors use water in the production process, water contamination can be also detrimental for their productivity. Changes in the agricultural productivity, on the other hand, are mostly associated to soil contamination. In addition to productivity effects, the economic impact of the environmental disaster can be substantial on local development, employment, and tax collection, for example.

At a larger scale, it may affect overall economic performance of the country due to the activity rupture. The share of the extractive sector in the Brazilian GDP is 2.5%, but Minas Gerais alone is responsible for 23.6% of that production. Characterised by an intensive use of capital and natural resources, the mining production is particularly oriented for international markets. From the economic point of view, public policies are urged in order to help with the regional recovery. This raises the question of what local and regional economic effects generated by the Brumadinho dam collapse are, but also how direct and indirect impacts are distributed among population arrangements.

As a manner of understanding the magnitude of these impacts, there has been an increasingly effort to model those events. The literature of the Brumadinho disaster is scarce. Most of it remains focused on elements of the social and environmental effects (Neves-Silva and Heller, 2020; Parente *et al*., 2020; Freitas and Silva, 2019). The aim of this study is to evaluate the economic effects of the disaster, with focus on the regional productivity. It is intended to translate environmental effects into economic phenomenon in an attempt to identify where interdependencies lies on and provide insights to help formulate impact mitigation policy for the long-term. The occurrence of interdependencies in the absorption of negative impacts by the surrounding areas is likely. For this reason, we specifically measure how the effects propagate to regions not directly affected by the dam rupture in Brumadinho, notably Belo Horizonte and the metropolitan area of Belo Horizonte.

To that end, we apply a stylized computable general equilibrium (CGE) model for Brazil based on the comparative-static B-Maria model. B-Maria is a Brazilian Regional and Interregional Analysis model developed at NEREUS in the University of São Paulo. It contains detailed information of interregional monetary flows, whereby the origin and destiny of imports and exports of each state are identified. The version of this paper has been adapted for the case of Minas Gerais, the BMaria-MG model. BMaria-MG divides Brazil into four distinct regions (Haddad *et al.*, 2020): the municipality of Belo Horizonte, the rest of the populational arrangement of Belo Horizonte, the rest of Minas Gerais and the rest of Brazil. This interregional system is calibrated with data of 2015 and 22 productive sectors are specified in each region. The model is run using GEMPACK.

The analysis assumes that the resulting economic impacts are associated to changes in the cost of production factors, specifically labour. Productivity changes of workers and economic sectors stem from water and soil contamination. From the scenarios simulated, the impacts are investigated for the regional output, GDP, employment, government expenditure.

The remainder of this paper is organised as follows. Section 2 characterises the developments in modelling economic impacts of natural disasters. Section 3 describes the modelling framework, including the model details and its closure besides data from which it has been calibrated. It also summarises the scenarios considered in the simulations. Section 4 presents the results and corresponding interpretations whereas Section 5 discusses the main conclusions.

2. Economic modelling and natural disasters

A study of the effects of natural disasters is considered to be an inexact science since its scenario happens only once regardless of the type of disaster and region affected (Hewings; Mahidhara, 1993). The attributes and limitations of the adopted methodology should, thus, be recognised in the economic modelling for a better quality of projections. Most of the literature in this regard has considered as direct impacts the loss in physical and human capital stock, that is, losses of machinery and equipment, infrastructure and lifes. The direct impacts unfold as indirect economic impacts, such as interruptions in the production and consumption, reduced work force due to the outflow of labour from the affected areas, among others (Okuyama, 2011).

The use of economic modelling to project the impacts of natural disaster is relatively recent in Brazil. To better frame the contribution of this paper to the literature, this section presents a structured bibliometric analysis from the Web of Science (WoS) database. The advantage of the bibliometric method is the ability to systematically represent the nature of specific disciplines by highlighting research hotspots and detecting research trends (Zhang *et. al* 2016).

The consultation occurred on the 25th of January 2021. A descriptor “Computable general equilibrium model” (CGE) was used in combination with a filter for papers, only. Table 1 summarises the main information on the metadata obtained. It demonstrates that there are studies developed from this topic since 1977, being published in more than 600 different sources. In total, more than 2000 papers in the area use an expressive number of references (more than 65,000). Economic modelling with computable general equilibrium is applied in distinct fields of research, as evidenced by the high number of Keywords. Nevertheless, research collaboration is significantly low, as suggested by the collaboration index (average number of authors in papers with more than one author).

Table 1 – Summary of the metadata from Web of Science

Description	Results
Timespan	1977:2021
Sources	614
Documents	2020
Average Citations per Documents	14.88

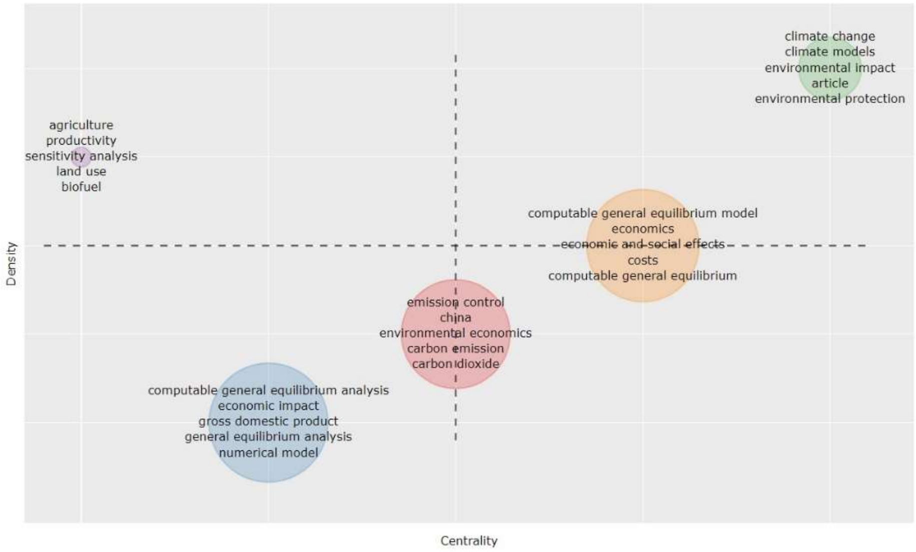
References	65,138
Keywords Plus (ID)	4,694
Author's Keywords (DE)	3,462
Authors	2973
Collaboration Index	1.66

Using the metadata for 2020 published documents, we implemented the thematic mapping technique. This is a method for grouping the metadata by themes (defined from Keywords plus[2]) of articles from a network of citations. Typically, the bibliometric analysis characterises the themes by two indicators: the centrality and density indicators. Whilst centrality measures the degree of interaction a network has with other networks, the density measures the strength of the network. The interpretation is based on the model developed in (Cobo *et al*., 2011). It allows defining what the themes trends in current research development are.

The two-dimensional diagram of the mapped research field is presented in Figure 1 below. It indicates that the use of CGE articles applied in the analysis of environmental impacts are drivers of research development in light of its high indicators of density and centrality. This fact brings evidence of the theoretical contribution of this paper since it aims precisely at conducting an economic impact analysis due to changes in labour productivity, and as a result of a natural disaster. The focus on the interregional approach is particularly relevant to account for the regional effects at a more comprehensive scale, whereby this study fills an additional gap in the literature.

[2] The Keyword plus differs from the commonly used Author keywords as a unit of analysis for its frequency distribution associated to the manuscript by Scopus and Thomas Reuters' ISI Web of Knowledge databases, rather than being related to the title of an article or as the author keywords.

Figure 1 – Thematic mapping analysis with bibliometric



3. Modelling framework

3.1. The BMaria-MG model

For modelling the regional economic impacts of the Brumadinho dam rupture in Minas Gerais, we employ the BMaria-MG model. This is a stylized CGE model for Brazil adapted for the case of Minas Gerais. It is based on the comparative-static B-Maria model. B-Maria is a Brazilian Regional and Interregional Analysis model developed at NEREUS in the University of São Paulo. As a CGE model, it is able to make projections of the local and surrounding economic impacts caused by the disaster. This ability accrues to the structural and interregional aspect of economic system that is considered in an integrated manner. For instance, the scenarios simulated can capture the effects on specific prices in the affected municipalities, and to map the resulting mobility of production factors as well as the shift in the productivity.

The model is calibrated with data of data of 2015, which is provided by the estimated Interregional Input-Output matrix in Haddad *et al*. (2020) based on the Interregional Input-Output Adjustment System (IIOAS) method, as detailed in Haddad *et al*. (2017). The IIOAS is a hybrid method in which the regionalisation process is flexible, allowing application to any country that reports both Supply and Use Tables (SUTs) and regionalised sectoral information.

We use GEMPACK to run the model, a system of software for implementing and solving CGE models. BMaria-MG is solved by representing it as a series of linear equations relating percentage changes in model variables, unless otherwise stated. The theory underlying these equations is typical of a CGE model. It establishes supply and demand relations for private-sector agents in accordance with optimisation assumptions of conventional neoclassical microeconomics, following certain market conditions. All markets reach a simultaneous equilibrium when zeroprofit, market-clearing and income balance conditions are satisfied.

BMaria-MG represents production and consumption in each region considering 22 productive sectors. It assumes region-specific prices, industries, and consumers. The set of production functions describes how primary factors (capital and labour), and intermediate inputs are transformed into goods and services in order to minimise costs, given a technology of constant returns to scale and market prices. The combination between intermediate inputs and primary factors is determined by fixed coefficients (Leontief).

The level of consumption is modelled through a representative agent that seeks to maximise a Stone-Geary utility function subject to a budget constraint. Interregional trading is accommodated through a constant elasticity of substitution (CES), whereby goods are treated as substitutes, being differentiated by region of origin, and having separate prices. Regional preferences for domestic or imported products are also specified based on CES functions. Moreover, BMaria-MG defines a wide range of regional aggregates, such as level of employment, GDP and price indices. Those are useful for our analysis in the Section 4.

3.2. Model closure

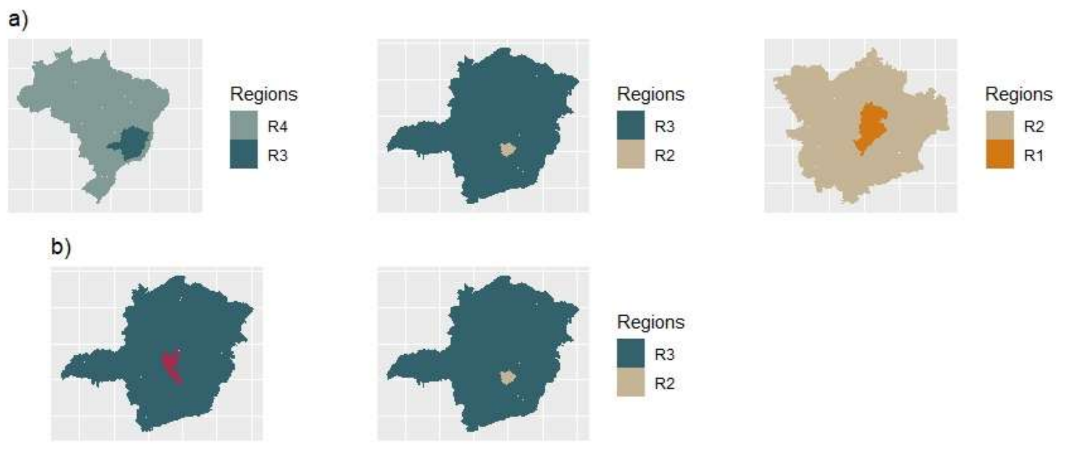
In economic modelling, the model closure plays an important role. The choice of closure in CGE modelling generally depends on two considerations. Firstly, it is affected by the needs of a particular simulation, as well as the view of the most appropriate assumption for the variables that the model does not explain. However, it can also reflect the incorporation of timescale in the simulation. In other words, the period for adjustment required by the economic variables to reach the new equilibrium. A common example is the capital stock. In short-run simulations, capital stocks are usually held fixed since the effects of the applied shocks take longer to install.

In order to address the scope of this study, the simulations were carried out under two standard closures, referring to the short run and long run. The main distinction between them is the treatment given for the capital stock, as encountered in the standard microeconomic approach to policy adjustments. For short-run simulations, the capital stock is held fixed while long-term projections allow for changes in the stock of capital.

3.3. Scenarios

BMaria-MG divides Brazil into four distinct regions, as summarised in Figure 2a: the municipality of Belo Horizonte (R1), the rest of the populational arrangement of Belo Horizonte (R2), the rest of Minas Gerais (R3) and the rest of Brazil (R4). This regionalisation enables accounting for the municipalities affected by the Córrego do Feijão's dam rupture in the simulations, and to measure how the effects propagate to other regions, particularly Belo Horizonte. Besides Brumadinho, Figure 2b shows the distribution of the Other 17 municipalities directly impacted in R2 and R3, namely: Betim, Curvelo, Esmeraldas, Felixlandia, Florestal, Fortuna de Minas, Igarape, Jautuba, Marabilhas, Mario Campos, Papagaios, Pará de Minas, Paraopeba, Pequi, Pompeu, São João das Bicas and São José da Varginha. In BMaria-MG, some of these integrate the rest of population arrangement of Minas Gerias while others are in the rest of Minas Gerais.

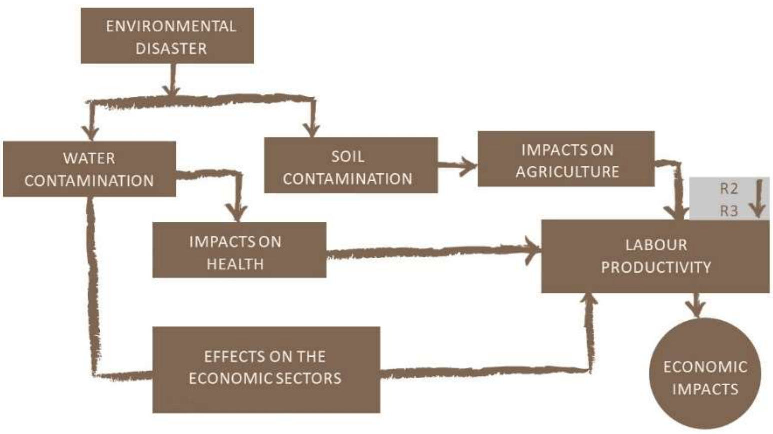
Figure 2 – Map of the BMaria-MG regions (a) and the area affected by the dam rupture (b)



To construct the scenarios, we used a proxy variable of the changes in productivity, the value added per employee, in each of the economic sectors of the abovementioned municipalities. This variable was calculated using the payments to workers average for the year of 2018 (*ex ante* data) and 2019 (*ex post* data), obtained from microdata available at the Annual Report of Social Information (RAIS, in portuguese). This database comprises formal labour statistics associated to economic activities in Brazil and reflects the costs of labour as a production factor in the model.

The environmental disaster caused water and soil contamination, which generate impacts on the economic sectors, especially agriculture, but also on the population health. Labour productivity was chosen for the shocks assuming that the disaster caused a shift in both the production (level and costs) and the number of workers occupied. Hence, the hypothesis is that changes in salaries are proportionally translated into labour productivity changes, which captures the regional economic losses. The relationship between the environmental externalities of the Brumadinho disaster, productivity and economic impacts is incorporated in the simulations, as organised in Figure 3.

Figure 3 – The relationship between the Brumadinho disaster, labour productivity, and economic impacts



Given that the economic importance of the municipalities varies in their respective region of BMaria-MG, the percentage changes in the labour productivity of each sector were weighted by the Gross Domestic Product (GDP) share of the municipality in the region it is located. This reweighting procedure used data provided by IBGE (2021). Figure 4 compares the average change in productivity in each municipality before and after weighting by the economic relevance. The percentage changes range from negative to positive values depending on the distance from the affected area.

According to Figure 4, Brumadinho is the most negatively impacted. The observed decline in labour productivity (-6.9%) in Brumadinho is mainly due to the Manufacture of Machinery and Equipment sector. When the productivity loss is compared with the importance of the municipality for the region, it is verified a greater negative impact in Betim (-1.08%), which is particularly driven by losses in the sector of Financial intermediation, insurance and related services activities. In contrast, there is a positive gain in the average labour productivity in São João de Bicas of 8.88% and 0.06% before and after the reweighting procedure, respectively. These positive effects on labour productivity occur as a result of an increase in the activities of two main sectors: the Information and Telecommunication and the Water, Sewage, Waste Management and Decontamination Activities.

Figure 4 – Labour productivity changes in the municipalities before(a) and after(b) weighting by GDP

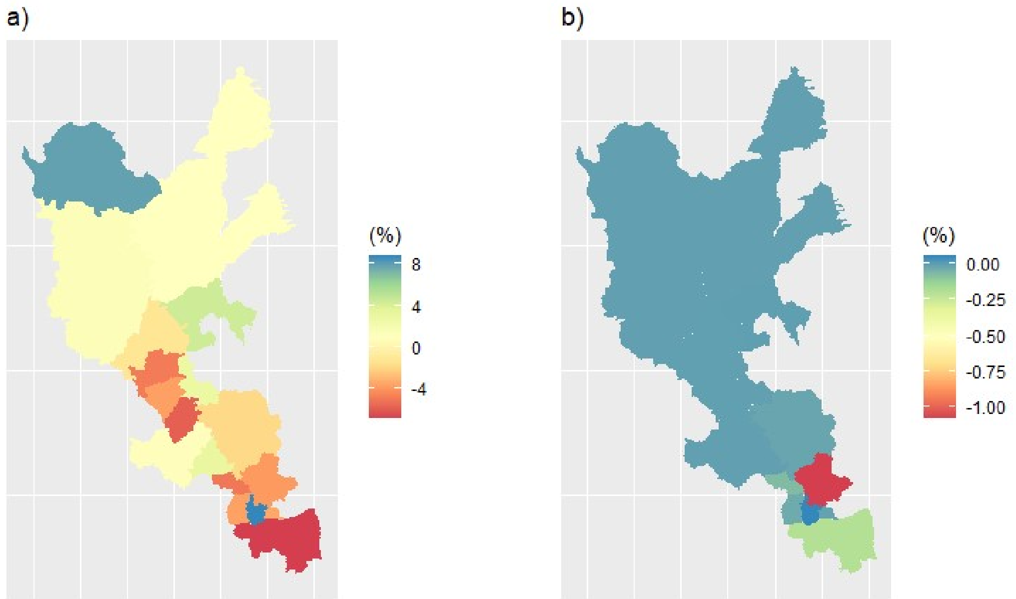
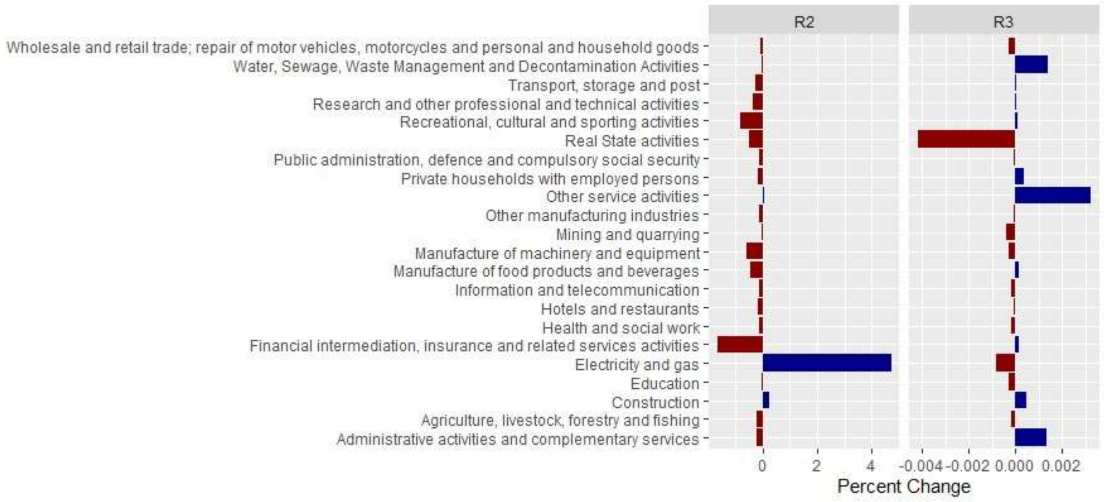


Figure 5 - Labour productivity changes in the R2 and R3 after weighting by GDP



Considering the regional aggregation of BMaria-MG, Figure 5 separates the impacts into the affected area of the rest of the populational arrangement of Belo Horizonte and the rest of Minas Gerais. It also summarises the magnitude of losses in the labour productivity average after weighting with the GDP share, being expressed in percentage change by sector in each region.

Overall, the rest of the populational arrangement of Belo Horizonte faces larger impacts since the region is geographically closer to the disaster and to the state capital, increasing its economic importance. The largest labour productivity losses in this region take place in the Financial intermediation, insurance, and related services activities sector. As for the rest of Minas Gerais, the deepest reduction in labour productivity is in the Real Estate Activities sector. This is understandable given that the tailings of Córrego do Feijão's dam destroyed houses and the infrastructure of Brumadinho and the surrounding area along the Paraopeba River.

Despite the negative impacts, the disaster led to gains in labour productivity of sectors responsible for providing essential services, as indicated by the considerable increase the Electricity, Gas and other activities related to services sector has over the others in both affected regions. In the reconstruction phase, this type of positive indirect impact could be a key driver of investments and stimulus to production and capital renovation. Both short-term and long-term stages after the disaster are represented in the 5-year simulation. The first and second years embody the full value of productivity change, as calculated from observed data. In the third year, we implemented a shock of 50% from the labour productivity in year 2. Economic recovery is expected for year 4 and year 5. There is an increase of 50% in the productivity of year 3 in year 4 whereas the shock for year 5 considers 100% recovery in labour productivity. To illustrate the magnitude of the effects, results are compared with the benchmark year.

4. Results

The Brumadinho dam rupture disaster in Minas Gerais (Brazil) had left behind economic and environmental damages for the local communities, but also to the regions in the surrounding areas. One aspect under investigation in this paper is the productivity changes incurred by economic sectors due to those environmental effects. According to simulations, changes in labour productivity impact negatively household consumption, mainly in regions R2 and R3, since they suffer the larger negative sectoral impacts because of the disaster. This is driven by increased prices in sectors with high consumption from households. For Region 1 (Belo Horizonte), it is observed a positive impact on consumption since the region is not dependent on R2 and R3 exports. The aggregated impact on household consumption is observed in Table 2.

Table 2 - Private consumption

Reg	Benchmark	Year 01	Year 02	Year 03	Year 04	Year 05	Total Variation (%)
R1	42,736.4	42,756.8	42,775.8	42,784.8	42,776.5	42,758.3	0.051%
R2	41,433.8	41,376.5	41,319.1	41,290.5	41,318.3	41,375.7	-0.140%
R3	200,133.4	200,115.8	200,115.6	200,119.2	200,114.5	200,112.5	-0.010%
Total	284,303.6	284,249.2	284,210.5	284,194.5	284,209.4	284,246.4	-0.020%

Table 2 indicates Region 2 as the more impacted since it experiences greater reductions in labour productivity. The most significant impact is in the first two years, with an immediate impact of 0.138% and 0.139%, respectively. Despite the upward trend of household consumption over the last two years (scenarios of economic recovery), the magnitude of the impact is small and negative (-0.140%) in Region 2 at the end of the period.

Region 1 (Belo Horizonte) faces an (not very significant) increase in private consumption. This means that in addition to the limited consumption of the regions mostly affected in the scenarios simulated, there is an exchange in consumption for regionally produced products - around 60% of the region's consumption occurs internally. Region 3 does not have a significant negative impact on private consumption. Even with these two facts, the aggregated impact on the state of Minas Gerais is -0.020%.

The federal government of all the regions under scrutinity basically consumes public administration, education, and health. Thus, the more significant the negative impact on these sectors, the greater the reduction of government consumption in the region. The impacts on Government Expenditure in each region is depicted in Table 3.

Table 3 - Government Expenditure

Reg	Benchmark	Year 01	Year 02	Year 03	Year 04	Year 05	Total Variation (%)
R1	1338.98677	1339.26057	1339.49412	1339.6009	1339.50027	1339.27589	0.022%
R2	1292.46088	1291.32394	1290.18072	1289.60755	1290.16942	1291.31405	-0.089%
R3	7791.18054	7792.84941	7794.23225	7794.85701	7794.26266	7792.92596	0.022%
Total	10,422.63	10,423.43	10,423.91	10,424.07	10,423.93	10,423.52	0.009%

The shocks applied to the government consumption sectors in Region 1 and Region 2 are not significant, although they are still negative. In fact, the impacts on the regional government's consumption are smooth for all regions and then, rapidly recovered in the following years. The only exception is Region 2, where the level of consumption does not fully recover over the period. However, given the interdependencies across the municipalities within the state alongside the capacity of Region 1 and Region 3 to economically recover , government consumption is positive at the end of the period.

Table 4 - Employment Variation

	Year 01	Year 02	Year 03	Year 04	Year 05
R1	0.050275	0.032187	0.011841	-0.009685	-0.028606
R2	-0.202989	-0.200013	-0.09912	0.099076	0.199231
R3	-0.020405	-0.020616	-0.010316	0.010371	0.020527

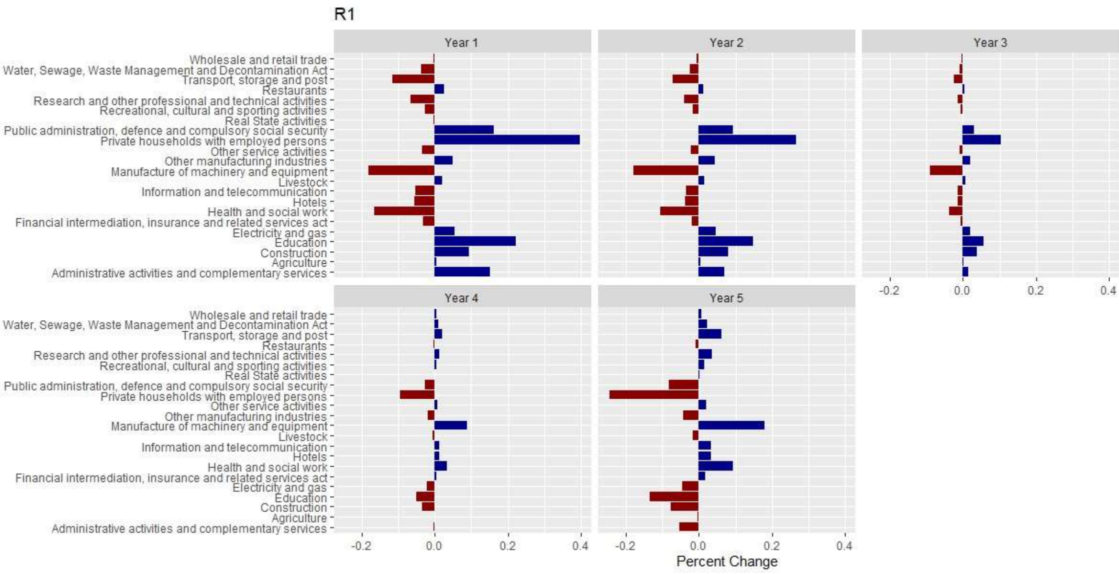
In the BMaria-MG model, employment is presented in an aggregated manner. In other words, it does not allow for obtaining results for each of the sectors separately. From this perspective, Region 2 is the mostly affected with the largest negative impacts on employment. This result is determined by the magnitude of the environmental impact assumed for the simulated scenarios. The same negative behaviour is observed in Region 3, although less expressive. Even though employment rates are favourable in the recovery scenario, these are insufficient to cover the first years of negative impacts.

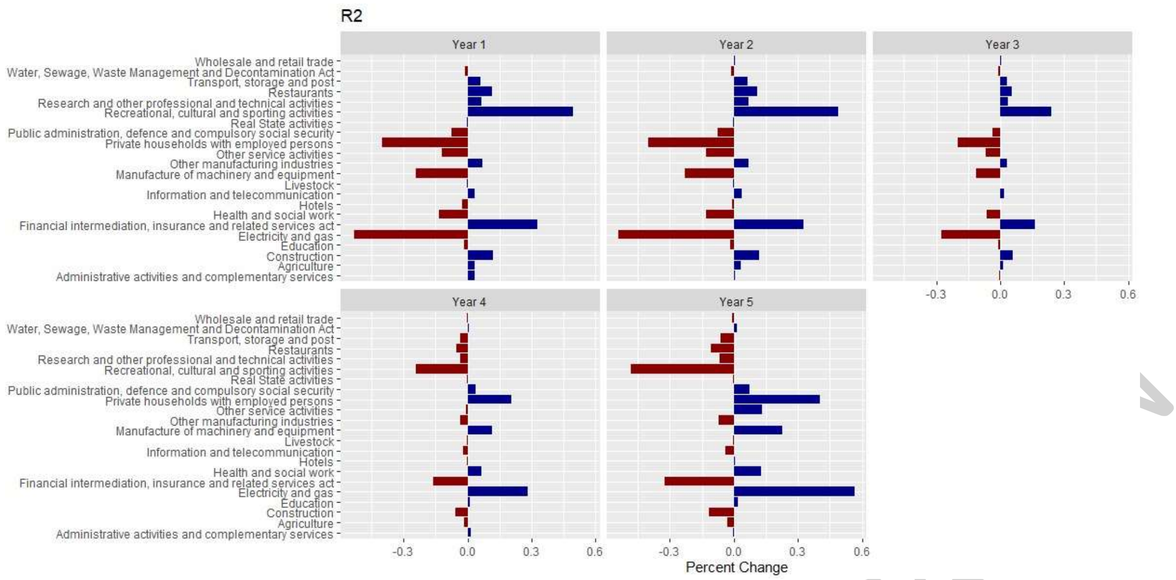
Table 5 presents GDP results for all regions of Minas Gerais (R1, R2 and R3). The economic performance of the rest of Minas Gerais is the most affected by changes in labour productivity, followed by the rest of the populational arrangement of Belo Horizonte. Belo Horizonte differs from the other two regions of Minas Gerais for the positive impact it faces. However, it is worth highlighting the small changes in GDP which associated to the small changes in labour productivity. Despite the small effects at aggregate level, Figure 6 shows impacts are significant and sector-specific in all regions.

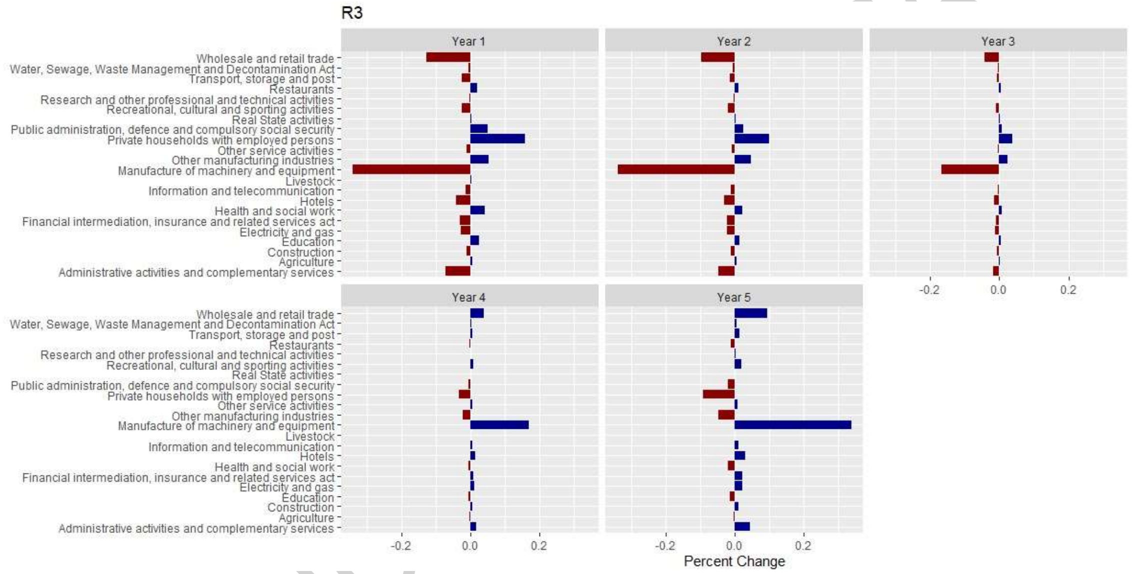
Table 5 - GDP

	Year 01	Year 02	Year 03	Year 04	Year 05
R1	0.030152	0.018969	0.006882	-0.0057	-0.01688
R2	-0.002513	-0.00096	-0.000152	-0.0001	0.001042
R3	-0.020334	-0.018995	-0.009176	0.0091	0.018775

Figure 6 - Sectoral impacts by region (R1, R2, R3) for each year







5. Conclusions

The dam rupture of Brumadinho in Minas Gerais affected directly 18 municipalities in the state. It generated severe socioeconomic and environmental effects. The objective of this study is to evaluate how pollution from the natural disaster affects the economy, whether driven by soil or water contamination, as it increases health problems and reduces the quality of inputs for several economic sectors. Consequently, there are changes in labour productivity, which translate into economic impacts.

With this study we fill a gap in the literature by providing some preliminary evidence of how these impacts from productivity propagate to other regions through economic modelling. Simulations using BMaria-MG reveal a smooth effect on the labour factor. The largest negative impact is observed for the consumption of households. Overall, the aggregated results are small. However, the sectoral analysis demonstrates that differences in the output of the sector are more significant.

The next step is to disaggregate data into more regions, separating Brumadinho and the municipalities affected the most by the dam rupture from the other regions. This data update enables disentangling details of the economic impacts that this version was not able to capture, particularly in terms of sectoral effects. Most importantly, it is relevant for the analysis to incorporate capital productivity in the simulations since the sectors most affected by the disruption are capital-intensive. Hence, another improvement under consideration is to deepen the analysis of productivity data, in addition to using econometric or non-parametric models that allow a more robust quantification of the impact of the Brumadinho disaster on labour productivity.

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