A minimum-disruption approach to input–output disaster analysis

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ABSTRACT
The frequency of disasters has been increasing over the past decades, fuelled by natural phenomena and climate-related events. Policymakers require robust methodologies to assess supply-chain impacts of disasters. Input–output-based disaster approaches are able to assess such impacts; however, they rely on some assumptions, such as the fixed production-recipe assumption for industries or the possibility of negative final demand. This study presents an improved disaster analysis approach, called minimum disruption, in order to assess more realistically the impacts of a disaster on essential and non-essential sectors. In particular, we propose a priority-weighted approach for incorporating decision-makers’ priorities for transitioning economies to post-disaster equilibrium. We showcase the new approach by modelling the actual occurrences during Venezuela’s economic crises.

KEYWORDS
minimum disruption, input–output disaster analysis, priority-weighted approach, input substitution

INTRODUCTION

Policymakers and professionals have to make difficult decisions about the allocation of limited resources across sectors. For instance, professionals are faced with the task of channelling limited government funding to appropriate health services for maximizing benefits. Economic evaluations are often used as a tool for informing such decision-making processes (van Velden et al., 2005). Within these evaluations, equity weights or distributional weights are applied, which involve setting priority criteria and weights to derive scores that are used for healthcare planning and policy (Round & Paulden, 2018). In other words, weighting approaches focus on answering questions such as: Should priority be given, and if so on what basis and who receives priority? Much of the literature on this topic focuses on the attributes or factors that should be
considered in a priority setting. A comprehensive systematic review of priority setting in healthcare provided insights into the preferences for weighting, based on the age and health condition of people (Gu et al., 2015).

Priority-weighting approaches are also applied in other economic sectors, such as transport (Yannis et al., 2020), water (Karleuša et al., 2019) and energy (Linares & Romero, 2000), for decision-making. Here we combine disaster analysis with priority weighting in order to propose a new method for analysing supply-chain impacts of disasters.

**Literature review**

Several disaster analysis streams make use of input–output (IO) analysis. Okuyama (2007) provides a comprehensive review of early methodological approaches for modelling the economic impact of disasters, focusing on the IO-based approaches, social accounting matrix and computable general equilibrium (CGE) approaches. A further update of this review, including a discussion of how different disaster IO approaches have evolved over time, is presented by Okuyama and Santos (2014). Specifically, for IO-based disaster modelling techniques, Galbusera and Giannopoulos (2018) review the existing literature to summarize how static and dynamic, demand- and supply-side approaches have evolved over time.

There are, amongst others, CGE (Galbusera & Giannopoulos, 2018), hypothetical extractions (Dietzenbacher et al., 2019; Xia et al., 2019), the inoperability model (Santos et al., 2013; Dietzenbacher & Miller, 2015; Oosterhaven, 2017; Okuyama & Yu, 2019), and (non-)linear programming (LP) (Oosterhaven & Bouwmeester, 2016; Oosterhaven & Többen, 2017). Here, we highlight some examples of these approaches and their application to specific questions.

In one of the first disaster assessments, Guimaraes et al. (1993) use a regional econometric model to assess the impacts of Hurricane Hugo, specifically post-Hugo economic gains and losses for South Carolina, by assessing two scenarios (‘with-and-without’ analysis) to compare economic paths: projected economic activity and actual activity post-Hugo. The authors conclude that the catastrophe had a net negative economic effect. Rose and Liao (2005) model regional economic resilience to disasters by performing a CGE analysis of supply chain disruptions after a major earthquake. As a key methodological advance, the authors calibrate production function parameters to incorporate adaptive resilience. A spatial CGE model can be integrated with transportation models in order to analyse interregional flows in terms of freight movement. Such an integrated framework is helpful in assessing the economic impacts of transport infrastructure disruptions (Tsuchiya et al., 2007). A comparison of IO-based disaster approaches and CGE-based approaches is provided by Koks and Thissen (2016) who use the case study of foods in Italy to compare outputs across the various models and conclude that the results can vary by up to a factor of seven. Santos and Haimes (2004) implement an inoperability input–output model (IIM) to assess the economic impacts of terrorism. Specifically, they model how demand-related risks in a sector can propagate to other interconnected economic sectors. IIM is particularly useful in analysing temporal frames of recovery and sector adjustments that are needed to reach new production levels post-disaster (Haimes et al., 2005). The dynamic version of the IIM can inform management strategies for assessing the risk of terrorism to interdependent economic systems, and how to prioritize and manage critical sectors (Lian & Haimes, 2006). In addition to CGE- and IIM-based models, research has also focused on methods for hypothetically modelling the shutdown of certain industries. For example, Temursho (2010) employs hypothetical extractions to identify key sectors and key groups of sectors in single- and multi-region input–output (MRIO) contexts.

IO-based disaster assessments are also useful in evaluating disaster preparedness and recovery strategies. Cole et al. (1993) showcase the power of a social accounting matrix approach at a local scale to quantify the economy-wide impacts of an island losing water for five days. Cole highlights the need to take the interests of various actors into account (e.g., by weighting) for a fair allocation of resources when formulating disaster responses.
Recently, disaster analysis has been applied to regional and MRIO frameworks. Yamano et al. (2007) apply a regional disaggregation method to an MRIO model to estimate the effects according to specific districts. Pan et al. (2009) use an IO model specific to the Los Angeles area to examine potential terrorist attacks. Hertel et al. (2014) apply the Global Trade Analysis Project (GTAP) database to examine the vulnerability of Asian supply chains to localized disasters. Koks and Thissen (2016) combine an MRIO database for 256 European regions with an LP model to assess the impact of floods in the Netherlands. Pakoksung et al. (2019) also use an MRIO–LP combination to analyse the economic losses from tsunami events in Okinawa, Japan. Unsurprisingly, the Coronavirus pandemic attracted MRIO-based models, for example, based on GTAP (Shan et al., 2021) or the Global MRIO Lab (Lenzen et al., 2020). Bouwmeester and Oosterhaven (2017) use a non-linear programming model to assess economic impacts of Russian gas boycott scenarios on the European economy. A number of authors focus IO-based methods on post-disaster recovery paths from disasters (Li et al., 2013; Zeng et al., 2019; Mendoza-Tinoco et al., 2020; Steenge & Reyes, 2020). For example, Steenge and Bočkarjova (2007) use IO analysis for investigating changes in consumption possibilities after the loss of production capacity in parts of the economy. We build on their approach in this study.

**Aim and novelty of this work**

In this work we are particularly interested in using MRIO frameworks for investigating changes in consumption possibilities as a result of disaster-induced production shortfalls (described by an event matrix $G$), as proposed by Steenge and Bočkarjova (2007). There are several shortcomings in Steenge and Bočkarjova’s approach, amongst which are: the possibility of negative final demand, the constancy of the production recipe, the inability to describe downstream effects and the inability to incorporate decision-makers’ priorities. To overcome these shortcomings (whilst retaining the event matrix formulation), we use ideas documented by Oosterhaven and Bouwmeester (2016) and Oosterhaven (2017), and add our own innovations for minimum disruption, input substitutability and priority-setting.

First, in its original form, the disaster analysis method by Steenge and Bočkarjova (2007) searches for a post-disaster equilibrium where some total outputs are reduced by losses, yielding reductions in consumption possibilities. There is no provision for situations in which the production loss is larger than total final demand, that is where Steenge and Bočkarjova’s approach yields negative final demand. We follow Oosterhaven and Bouwmeester (2016) and Faturay et al. (2020) in overcoming this problem by including a condition for final demand being strictly positive.

Second, their assumption of a fixed production recipe leads to a ‘proportionally shrunken economy’, that is, restrictive scenarios in which any input reduction results in a proportionate reduction in output. We address this problem by allowing for input substitution.

Third, as Oosterhaven (2017) explains, the demand-driven Leontief model underlying many disaster analysis methods focuses on negative upstream (backward) effects and is largely incapable of describing the positive and/or downstream (forward) effects of supply shocks, as well as substitution of replaceable inputs. In the present paper we follow the ideas documented by Oosterhaven and Bouwmeester (2016) and Oosterhaven (2017) in that we use constrained optimization, and assume:

that both firms and households, in the short run after a disaster, try to stick as much as possible to their old pattern of sales and purchases. (Oosterhaven, 2017, p. 459)

and that

other firms will step in to replace … losses and may thus experience positive impacts due to technical and/or spatial substitution effects. (p. 453)
Fourth, existing methods establish optimality by shifting as much as possible of the production loss onto final demand, and sparing intermediate demand. This is because reductions within intermediate demand cause subsequent knock-on effects that affect other intermediate sectors, setting in motion a cascade of impacts that can lead to large reductions in overall economic activity. The outcomes of methods where losses are shifted onto final demand may be quite unrealistic, since it is vital in any disaster situation to guarantee as much as possible the supply of the population with food and energy, for example.

In this study we propose an improved disaster analysis approach, characterized mainly by the relaxation of the fixed-production-recipe assumption, and by the ability to control for which parts of the economy need to be shielded from the disaster. The first improvement is especially important for multi-region settings, in which spatial substitution means that, in cases of a localized loss, a region is able to draw on imports. More specifically we want:

- to be able to specify that a disaster will affect some intermediate or final demanders less than others, and some not at all – for example, partial power blackouts should affect schools only temporarily, supermarkets and cool-store facilities even less, and hospitals not at all;
- to allow industries to substitute alternative inputs for reduced inputs – for example, industries may substitute unavailable inputs with imports of the identical product, or may use alternative technologies or materials; and
- to capture not just upstream impacts of a disaster but also downstream, and in general, economy-wide impacts.

The first innovation includes any type of decision-maker intervention, whether it is beneficial in the sense of protecting vulnerable segments of society (e.g., children) and critical resources (e.g., food), or detrimental in the sense of creating additional cost and losses (e.g., because of political and industry lobbying, lack of civil rights, information censorship or Coasean transaction cost (Coase, 1960).

The remainder of the paper is structured as follows. We will next describe our methods, and then explain how we apply these to our case study: the consequences of Venezuela’s oil revenue plunge and drought. The purpose of this case study is to establish whether the minimum-disruption approach proposed here is able to replicate the actual consequences resulting from Venezuela’s economic crises. We proceed by presenting and discussing results, and finally conclude.

**METHODS, CASE STUDY AND DATA**

**MRIO disaster method**

Let an economy be described by an \( N \times N \) intermediate transactions matrix \( T \), an \( N \times N \) input coefficients matrix \( A = T^{-1} \), an \( N \times M \) final demand \( Y \), a \( L \times N \) value-added \( V \), and an \( N \times 1 \) total output \( x = Ti^T + Yi^V \). Let \( I \) be a suitable identity matrix, \( i^T \) and \( i^Y \) be suitable column summation operators of the form \([1, 1, \ldots, 1]'\), the prime ‘\(^{\prime}\)’ denote vector and matrix transposition, \( i^V \) be a suitable row summation operator of the form \([1, 1, \ldots, 1]\), and the hat ‘\(^\hat{}\)’ symbol denote vector diagonalization. This economy is in equilibrium, when \( Ax + Y = x \). Let \( S = \begin{bmatrix} T & Y \\ V & 0 \end{bmatrix} \) be a \((L + N) \times (N + M)\) compound IO transactions matrix incorporating intermediate demand, final demand and value added. Let \( B = S(Ti^T)^{-1} \) be a compound input coefficients matrix, the equivalent of \( A \) for \( T \) (Lenzen & Rueda-Cantuche, 2012). Define an \( N \times N \) diagonal matrix \( \Gamma \) of sectoral production losses, where the \( \Gamma_{ii} \in [0, 1] \) describes the fractional loss of production of sector \( i \). Define \([\hat{x}, \hat{Y}, \ldots]\) as the post-disaster quantities of \([x, Y, \ldots]\).
We now develop an approach for controlling the spread of disaster-borne production losses away from those parts of the economy that need to be shielded from the disaster. We propose a minimum–disruption method to establish post-disaster production and consumption possibilities \( \mathbf{S} \) that are as close as possible to pre-disaster conditions \( \bar{\mathbf{S}} \), subject to penalty weights. We follow Proops et al. (1993, p. 228; see also Cornwell, 1996; Creedy & Sleeman, 2005) in defining a disruption function:

\[
D(\mathbf{S}, \bar{\mathbf{S}}, \mathbf{w}) = \sum_{ij} S_{ij}^2 w_{ij} = \sum_{ij} (S_{ij} - \bar{S}_{ij})^2 w_{ij},
\]

(1)

where \( w_{ij} \) are penalty weights. A large \( w_{ij} \) characterizes inflexible transactions \( S_{ij} \) that, when affected, would cause significant social disruption, and that therefore should not be altered when moving to the post-disaster equilibrium. Examples for such inflexible transactions are domestic food, water and energy supply, or health services. Small \( w_{ij} \) characterize non-essential and therefore adjustable transactions \( \bar{S}_{ij} \) such as gambling or entertainment services. Food exports may also attract a small weight, because in case of a disaster affecting food production (e.g., a cyclone), a government may decide to curtail food exports for the sake of safeguarding the local population. Through these adjustability weights, disaster-borne changes \( \Delta S_{ij} \) attract a more or less high penalty in the disruption function \( D \).

The post-disaster economy \( \bar{\mathbf{S}} \) is then characterized by minimizing disruption as:

\[
\min_{\bar{\mathbf{S}}_{ij}} \sum_{ij} (S_{ij} - \bar{S}_{ij})^2 w_{ij}
\]

(2)

subject to the following five conditions (cf. Oosterhaven & Bouwmeester, 2016):5

- **Loss of production output**: for every sector \( i \) we ask that post-disaster production possibilities \( \tilde{x} \) are bound by \( \tilde{x}_i \leq (1 - \Gamma_{ii})x_i \), where \( \Gamma_{ii} \) is the relative production loss of sector \( i \), and \( 1 - \Gamma_{ii} \) is the relative remaining productive capacity of sector \( i \). Negative values of \( \Gamma_{ii} \) can be used to simulate slack capacity that can be mobilized to compensate losses elsewhere.

- **Equilibrium**: as in Steenge and Bočkarjova (2007), the post-disaster economy \( \{\tilde{x}, \bar{Y}\} \) is in a new equilibrium, leading to the sectoral IO balance \( \bar{T}_{i}^T + \tilde{Y}_{iV} = [\mathbf{I}^T \tilde{V} + \mathbf{i}^T \tilde{S}] \).

- **Country-wise trade balance**: as an optional constraint, we allow imposing a trade balance condition to reflect cases where a country may not be able to increase its trade deficit in the short term. The trade balance constraint then becomes \( m_k = e_k \forall k \), where \( \mathbf{m} \) and \( \mathbf{e} \) are imports and exports vectors, respectively, and the index \( k \) runs over countries or regions.

- **Non-negative transactions**: except for items such as net taxes, subsidies and changes in inventories, all IO transactions shall be non-negative: \( T_{ij} \geq 0 \forall i, j \); \( Y_{ij} \geq 0 \forall i, j \); \( V_{ij} \geq 0 \forall i, j \).

- **Aggregate production recipe constancy**: let \( \mathbf{C} \) be a rectangular \( K \times (L + N) \) concordance matrix connecting substitutes, that is, \( C_{ii} = 1 \) for all products \( i \) that are alternative choices of inputs for an aggregate product \( j \), and \( C_{ji} = 0 \) otherwise (Duchin & Levine, 2011). In a multi-regional context, products \( i \) can be sectors producing the same product in different countries. \( \mathbf{CB} \) is then a compressed input coefficients matrix, distinguishing \( K \) un-substitutable aggregate inputs into \( N \) sectors. Whilst imposing constancy of \( \mathbf{B} \) would fix every individual input coefficient, requiring \( \mathbf{CB} \) to be constant \( (\mathbf{CB} = \bar{\mathbf{C}}B) \) allows for input substitution during the adjustment to post-disaster conditions. Asking that \( |\mathbf{CB} - \bar{\mathbf{C}}B| \leq \varepsilon \) provides further flexibility in that not only input coefficients can be altered within the limits of the \( e_{ij} \), but marginal inputs smaller than \( e_{ij} \) can be omitted from the production recipe altogether. Note that \( \mathbf{B} \) and \( \mathbf{CB} \) include value added and final demand, and thus the condition \( |\mathbf{CB} - \bar{\mathbf{C}}B| \leq \varepsilon \) encompasses substitution of labour for intermediate inputs, and final demand structure.
The minimum-disruption approach (equation 1) follows – at least in principle – the approach in Oosterhaven (2017), in that ‘economic actors try to maintain their pre-disaster pattern of economic transactions’ (p. 459). However, we do not use their Kullback–Theil information measure, but the quadratic minimum-disruption form introduced by Proops et al. (1993) and used by Cornwell (1996) and Creedy and Sleeman (2005). This is because, as a common error function (e.g., used in estimating large IO frameworks) (Harrigan & Buchanan, 1984; Nagurney & Chen, 1989; Nagurney & Robinson, 1992), a quadratic form is free of singularities and differentiable over its entire definition space (Bernas et al., 2008). This choice becomes important practically when configuring a large-scale solver for equation (2) and its constraints, because these solvers perform at much improved runtimes when informed with the gradients and Hessians of the objective function and nonlinear constraints. For this reason, we have also specified the aggregate production recipe constancy as $(\mathbf{CB} - \mathbf{CB})^2 \leq \epsilon^2$.

Case study

The purpose of our case study is to provide an illustrative example that demonstrates the functioning and utility of our new disaster analysis approach. We choose the downfall in crude oil and electricity production in Venezuela because this example deals with: (1) an economy that is relatively underreported in the IO literature, and therefore worth examining, (2) a type of adverse event that is not commonly described in the literature on IO disaster methods, (3) a wide range of commodities involved in the disaster impacts (crude oil, petrol, food), and (4) an interesting application of an economic model, the rentier capitalism, which was doomed from its origins to collapse.

Since the mid-20th century, the analysis of the Venezuelan economy, and in particular that of the oil industry, has long been labelled from the perspective of rentier capitalism (Mommer, 1990; Baptista, 1997; Hellinger, 2017). In this theoretical framework, four common denominators stand out in the process of productive decay in the country’s economy: oil rent, the curse of natural resources, crisis and collapse.

Crude oil production is managed by the state-run oil company Petroleos de Venezuela (PDVSA), bringing up the first element to highlight in the Venezuela rentier economy. The norm in an oil economy establishes that oil revenues are an international rent from the ground, and therefore an income that does not originate from the internal productive effort of a country; the oil is there, nobody produced it (Baptista, 1997).6

Venezuela’s rentier capitalism model creates a tremendous paradox that makes it unfeasible in the long term. On the one hand, it fosters greater dependence on oil income since it encourages the demands of all economic and social sectors. On the other hand, it weakens the oil industry in fundamental aspects of the business, such as productivity and investment, which in the long run translates into less oil income to meet the needs of society and the industry itself, arising the genesis of the second denominator: the curse of natural resources.7

In his seminal work on Venezuela’s rentier capitalism, Baptista (1997) explains that from the late 1970s the Venezuelan productive system could no longer absorb rents to increase productivity. The oil output disruption that we observe nowadays is fundamentally explained by the fact that oil income overflowed the capital absorption capacity of the economy. In this context, the Venezuelan development effort was not based within a more or less coherent economic policy framework, but was the natural result of the disaster caused by external reality and the collapse of a traditional economic policy.

As Mommer (1990) and Baptista (1997) pointed out almost two decades ago, the model that previously seemed to be successfully turned out to be outdated. Therefore, the current Venezuelan crisis is the consequence of its oil industry having wasted an opportunity to increase
investments and production during the most recent oil price boom observed between 2002 and 2013. After a decade of some of the most promising economic conditions in the country’s history given the relatively prolonged period of strong oil prices and low international interest rates, the country was already in difficult economic straits before the oil price drop. Moreover, when the collapse of oil prices occurred in mid-2014, although most of the oil-exporting countries showed a significant level of stress, Venezuela stood out as one of the most affected among its peers (Bull & Rosales, 2020).

The collapse of oil prices triggered the collapse of Venezuela’s rentier model. Venezuela was among the most vulnerable of the major oil producers in terms of its macroeconomic situation even before the oil price decline in 2014. At the end of the Hugo Chávez government (2011–12), and before the end of the oil price cycle, the country was running very high public sector deficits of around 17% of gross domestic product (GDP), the external debt increased at an unsustainable rate, the domestic currency was severely overvalued, shortages of basic goods were widespread and a recession had begun (Bull & Rosales, 2020).

Since 2014, Venezuela’s oil-reliant economy has been significantly battered, as ongoing production problems were magnified by the drop in oil prices (Halff et al., 2017), and moreover, since 2012, the government of President Nicolás Maduro has been unwilling to take the tough decisions that the situation demands, with disastrous economic consequences.

The state oil company has been struggling as a result of the global oil price crash that began in 2014, and that severely slashed the revenue for its crude oil exports. Problems at refineries arose, which were largely the result of component failures and the departure of staff in PDVSA’s trade and supply unit who were key to ensuring that fuel would get to where it was required to generate revenues that would, in turn, provide the basis of payments for much-needed imports (Gillespie, 2017; Parraga & Ulmer, 2017; Ulmer & Parraga, 2017). This resulted in a shortage of basic necessities (petrol: Buitrago, 2019; Pozzebon, 2019; power: Daniels, 2019; food: Benzaquen, 2017; Graham-Harrison, 2017; Otis, 2018) and a deepening economic crisis under President Maduro. Interestingly, Maduro’s predecessor Chávez initially curtailed exports to ensure there was sufficient fuel at home, but domestic petrol shortages occurred under Maduro as fuel exports to foreign allies such as Cuba and Nicaragua were increased to meet export commitments (Parraga & Ulmer, 2017).

In this case study, we simulate two concurrent trends. First, between 2013 and 2016, crude oil production and refinery throughput halved in physical terms. This trend was accompanied by a...
fall of global crude oil prices from US$100 to around US$50 per barrel, slashing Venezuela’s export revenues (90% of which are derived from crude oil) by about three-quarters (Figure 1) (Reuters, 2017). Second, again between 2013 and 2016, Venezuela’s hydroelectricity production (representing roughly three-quarters of installed capacity) fell from 18.9 to 13.9 million tonnes of oil equivalent, leading to a 9.4% decrease in electricity consumption over the same period (Figure 1) and to rolling blackouts in 2016. The main reason for this decline was a shortage of reservoir stores in the Caroni River hydropower installations in Venezuela’s Guayana Region, caused by ongoing drought conditions, peaking during the 2016 El Niño event (Kingsbury, 2020).

Data
In this study, the economy $S$ (or $\{T, Y, V\}$) is a global economy comprising $R = 11$ regions (Figure 2) with $S = 15$ sectors each (see Appendix 2 in the supplemental data online), specified by MRIO tables constructed in the Global MRIO Virtual Laboratory (Lenzen et al., 2017). This lab offers the user to tailor the construction of an MRIO database to their research question at hand by offering flexibility for choosing regional and sectoral classifications. Given that the case study revolves around the effect of the global oil price plunge on Venezuela’s society, a regional classification was chosen that preserved its trading characteristics as well as important oil producers, and that aggregated the rest of the world into key regions (Figure 2), roughly following per capita income groupings, geopolitical constellations (e.g., allies and OPEC), and the GTAP 9 delineation (GTAP, 2017).

Accordingly, $S$ was constructed in the lab based on a multitude of data sources: the United Nations’ (UN) Main Aggregates (United Nations Statistics Division (UNSD), 2017) and Official Country (UNSD, 2016b) databases, UN ComTrade (UNSD, 2016c) and ServicesTrade (UNSD, 2016d) databases, the World Bank’s global consumption database (World Bank, 2017), the UN’s industrial commodity production statistics (UNSD, 2016a), the United Nations Industrial Development Organization’s (UNIDO) database on industrial statistics (UNIDO, 2016), and national IO databases for more than 100 individual countries (Lenzen et al., 2012, appx S6).

Figure 2. Regional classification used in this study.
Amongst the national IO databases, information for Venezuela deserves more attention. The most recent of financial IO table for Venezuela dates back to 1997 (Banco Central de Venezuela (BCV), 1997, Hernández-Perdomo, 2005; detailed 121- and 180-sector versions). In order to obtain an up-to-date representation of Venezuela’s economy in our MRIO tables, we collected a large amount of recent current-price data and integrated these as data feeds into the existing MRIO build pipeline (Lenzen et al., 2014). The new data include:

- 1995–2002 household consumption (BCV, 2004);
- 1995–2003 and 2012–14 GDP by industry (BCV, 2015h, BCV 2015f);
- social accounting matrices for 1997–2003 (Pedauga et al., 2012a);
- social accounting matrices for 1998–2005 (Pedauga, Sáez, et al., 2012b);
- 1997–2008 consolidated national accounts (BCV, 2009a);
- 1997–2008 basic macroeconomic interrelationships (BCV, 2009b);
- 2005 South American input–output tables including Venezuela (United Nations Economic Commission for Latin America and the Caribbean (CEPAL), 2017);
- 2012–14 consolidated national accounts (BCV, 2015a);
- 2012–14 GDP and its components (BCV, 2015g);
- 2012–14 goods and services accounts (BCV, 2015c);
- 2012–14 household consumption (BCV, 2015b);
- 2012–14 fixed capital formation (BCV, 2015e);
- 2012–14 production account (BCV, 2015d); and
- 2015–17 consolidated national accounts (BCV, 2018).

\( x, A \) and \( B \) are derived from \( S \). The concordance matrix describing input substitution was constructed as:

\[
C = \begin{bmatrix}
I_T & \ldots & I_T \\
0 & \ddots & 0 \\
0 & \ldots & I_V
\end{bmatrix},
\]

where \( I_T \) is an identity matrix fitting intermediate demand, and \( I_V \) is an identity matrix fitting value-added. We thus describe perfect substitution of any sector’s domestic input through the import of the same product from any of the other \( R - 1 \) regions (cf. the spatial substitution in Oosterhaven & Bouwmeester, 2016). We do not model the substitution of intermediate inputs with labour or capital.

**Computational implementation**

The optimization variable in equation (1), and some of the variables defining the constraints, are matrices. Most optimization algorithms do not operate with matrices, but with vectors. It is therefore necessary to rewrite the optimization problem in a vectorized form. In addition, in order to avoid runtime-intensive reshape functions, this vectorization should ideally be accomplished using computationally inexpensive matrix products. Finally, providing analytical gradients and Hessians is able to reduce runtime further. For technical details of our implementation, see Appendix A1.3–1.5 in the supplemental data online. Results documented in the following section were obtained from runs in Matlab (2020b) on a high-performance server with 112-Cores CPU and 6TB RAM. Appendix A1.6 online contains a detailed sensitivity and performance analysis of the implementation of the optimization algorithm.
RESULTS

In the following, we first present an illustrative yet representative example that can be easily understood on the basis of a handful of numbers, and that provides a proof of concept. We will then explain the results pertaining to our case study of Venezuela.

Illustrative example

Assume a low-income but resource-rich country (called ‘V’) embedded in a larger, high-income service-based supranational economy (‘R’) (see Appendix A3.1 in the supplemental data online). Trade is balanced at 150 units; however, V is an export-oriented economy: of its total output of about 300 units, V exports roughly half, whilst trade represents only 3% for R. V exports most of its agricultural, fuel and mining output to R, and imports processed food, machines and services in return. Accordingly, most of V’s value-added and employment resides in extractive export-oriented sectors. In turn, R’s manufacturing and utility sectors depend vitally on V’s exports. This situation is not untypical in the current global state of play.

We now simulate a 50% production loss in V’s crude oil production, once using the modification of Steenge and Bočkarjova’s method by Faturay et al. (2020), and once using the formalism in this method. This way we are able to demonstrate the key innovation in this work: decision weights. Accordingly, we set $S$ as in Appendix A3.1 in the supplemental data online, $\Gamma_{4,4} = 0.5$ for the production loss of V’s crude oil sector, $\Gamma_{20,20} = -0.05$ for R’s refining reserve, and $C = [I | I]$, indicating perfect substitution between domestic and imported production. We further ask that the changes in the intermediate product recipe stay below $\varepsilon = 0.1$. We allow changes in final demand patterns to be more variable by setting $\varepsilon = 0.2$. We invoke the trade balance condition to reflect sanctions such as freezing V’s assets, inhibiting V’s central bank’s

![Figure 3. Decision weights in the illustrative case study.](image)

Note: V refers to a low-income but resource-rich country; R refers to a high-income service-based supranational economy; the white-to-black colour bar represents decision weights on a log-normal scale.
foreign exchange handling, and withholding assistance and loans, thus preventing V from being able to mobilize funds for paying its import bills. All constraints were adhered to by the optimal solution (see Appendix A1.4 online).

We once set $wij = 1 \forall i, j$, and once $1 \leq wij \leq 500$ (Figure 3). In the priority-weighted scenario, the final demand of food by the high-income region R receives the highest priority ($wij = 500$), followed by R’s demand for fuels (200–300), and R’s domestic final demand and value-added (100). The remainder of inter-industry transactions in both R and V receive intermediate attention (10). In contrast, V’s value-added and final demand are assumed to be least prioritized, and hence most susceptible to change ($wij = 1$).

• **Overall losses:** when analysed using uniform weights, consumption losses are $-6.6$ (V) and $-8.3$ units (R). Using priority weights (Figure 3), these losses become $-31.6$ (V) and $-3.3$ units (R). The placing of weights has effectively shifted the disaster burden from R to V (Figure 5). In addition, overall losses have now more than doubled, which is a result of R’s high-income households now being shielded from disruption, at the cost of intermediate sectors’ loss increasing from $-76$ to $-119$ units. The overall higher losses are the consequence of the mismatched political powers of V and R, in the sense of transaction cost preventing allocative efficiency (Coase, 1960, Furubotn, 1991).

• **Petrol supply:** in the unweighted scenario, triggered by the reduction of oil exports from V into R’s refining sector, R’s residents experience significant reductions in petrol consumption: $-11$ units from domestic production and $-0.7$ from imports, whilst V’s residents lose only $-1.4$ units. In the weighted scenario, a large decision weight is placed onto crude trade from V to R and onto fuel consumption in R, so that R’s losses are now much smaller at $-5.8$ and $-2.8$, respectively. In contrast, V’s losses now stand at $-5$ units. In other words, R’s domestic refining is receiving protection from the loss, whilst V’s domestic consumption is taking the hit.

• **Power:** in this simplified model, electricity generation is indirectly affected through the decrease in crude oil, leading to shortages of refined fuel as an input into power utilities. In the unweighted scenario, V experiences power outages worth $-0.6$, whilst for R these are $-0.13$. Since R’s power takes priority over V’s power, the weighted method leads to power outages worth $-10$ in V, and none in R.

• **Food supply:** food supply is even more indirectly affected through the decrease in utility power output required for food manufacturing. In the unweighted scenario, these spillovers into food supply are relatively benign: $-1.1$ for V and none for R. Once a large weight is placed on R’s food consumption, the optimization suppresses food exports from R to V, leading to losses of $-6.1$ for V and – because of power generation being guaranteed for food manufacturing – none for R.

Summarizing, placing decision weights that are advantageous for R is a game-changer for V’s disaster outcomes: V’s residents will face severe shortages of petrol and food, as well as power blackouts. These simulation outcomes agree in principle with the actual outcomes reported by many news outlets on the situation in Venezuela (see the section ‘Computational implementation’). A disaster method not using decision weights is unable to describe these circumstances.

**Influence of the priority weight**

We scaled the priority weights $w$ non-linearly to $w^\eta$ by applying an exponent $0.2 \leq \eta \leq 3$. This has the consequence of polarizing ($\eta > 1$) or depolarizing ($\eta < 1$) the priority differences between country V and region R. Clearly, country V will be worse off for more diverging priority weights, that is, if a higher priority is placed on protecting region R (Figure 4). Conversely, a
more solidary approach to dealing with V’s disaster, in which both regions place equal priority on each other’s economies and citizens, can greatly diminish V’s pain and burden.

**Case study: Venezuela**

As mentioned in the introduction, the purpose of this case study is to establish whether the minimum-disruption approach proposed here is able to replicate the actual consequences resulting from Venezuela’s economic crises. In order to examine the consequences of oil price decline and drought on Venezuela’s economy, we subject an 11-region 15-sector MRIO system to a Venezuelan production shortfall of 73.4% of crude oil output and 26.5% of electricity generation (cf. Figure 1).

**Figure 4.** Priority weight dependence of V’s loss as a function of priority weight magnitude (represented by the mean $\bar{w} = (RS)^{-2} \sum_j w_{ij}$. The relationship is independent of multi-region input–output (MRIO) element magnitude (represented by circle size) and weight magnitude (represented by the shade of grey). ‘x’ symbols indicate the position of the results shown in Figure 4 (V’s consumption losses of 4.4% and 20.8%).

**Figure 5.** Absolute economic losses (top row) and relative economic losses (bottom row) in unweighted (left column) and weighted (right column) simulation scenarios. Note: Absolute economic losses represent $\hat{S} - S$; relative economic losses refer to $(\hat{S} - S) \odot S$ ($\odot$ denotes Hadamard division). Values in the panel titles refer to the overall consumption losses of V and R, in absolute and relative terms.
We distribute priority weights across seven groups (Figure 6, top right panel):

- 200–500: Domestic supply and imports of food, petrol, electricity for households, and intermediate imports of crude oil and petrol for refineries, power plants and vehicles, in the European Union, North America, developed Asia-Pacific and OPEC countries. This setting reflects geopolitical realities of wealthy nations securing their essential supply chains.
- 100: Venezuela’s exports to its allies; remaining final demand in the European Union, North America, developed Asia-Pacific and OPEC. This reflects Venezuela’s commitment to trading partners, with a view of supporting export earnings.
- 50: Domestic and imported intermediate demand of the European Union, North America, developed Asia-Pacific and OPEC; domestic final demand of all other regions except Venezuela.
- 10: Domestic and imported intermediate demand, and imported final demand, of all other regions.
- 5: Venezuela’s domestic and imported final demand except that of its households.
- 1: Venezuela’s households’ final consumption. The prioritization of imports to producing sectors over households reflects Venezuela’s focus of using its export earnings to secure much-needed inputs into production.
- 0.1: Venezuela’s supply of food to domestic households, and to the rest of the Americas. This setting reflects the reluctance of food suppliers to supply the domestic market after the introduction of price controls, and the selling-off of food to neighbouring Colombia (Milne & Watts, 2014; Muñoz, 2014; Garcia Rawlins, 2015).

Production recipe tolerances (Figure 6, top right) are set to $\epsilon = 0.1$ for all intermediate inputs, except net taxes and capital. The latter are allowed to vary by $\epsilon = 0.9$ because they are
not strictly required for production in a physical or engineering sense. Household consumption structure tolerances are set to $\varepsilon = 0.5$, seeing that households have a wide range of choices, even amongst food items. The remaining final demand categories (government, capital and inventories) are allowed to vary widely by $\varepsilon = 0.9$.

Our optimization run adhered to all constraints with a tolerance of less than 1% (Figure 6, bottom panels). For comparison, the run using unweighted minimum disruption also adhered to all constraints (see Appendix A4 in the supplemental data online).

**Regional relationships**

As expected, the Venezuelan economy suffers the largest losses (Figure 7) as a result of the oil revenue decline and power blackouts, distributed across value-added and final demand (about US$127 billion, about one-third of GDP) and intermediate demand (about US$233 billion). This loss fits well within the measured GDP decline between 2013 and 2017 of US$124 billion.

![Figure 7](image)

**Figure 7.** Regional relationships of Venezuela’s production shortfalls.

Note: Numbers at the top and right panel margins are row- and column-wise loss totals, with all sectors aggregated.
Intermediate exports decline by US$87 billion, again, well explained by data on Venezuela’s oil export revenue (Figure 1, left panel). Trading partners suffer negligible losses in percentage terms, and the small losses that do occur are compensated by increases in imports from other regions. Final imports decline significantly, due to a lack of export earnings to use as payments, and due to the prioritization of imports to producing sectors over households (see the weights description above). Venezuelan exports to the rest of Americas increase, as a consequence of providing a means to buffer export losses elsewhere, and enabling imports of vital commodities (Milne & Watts, 2014; Muñoz, 2014; García Rawlins, 2015). Finally, Venezuelan value-added declines noticeably (Chinea, 2017).

Compared with the unweighted scenario, transactions for the developed rest of the world – especially Venezuela’s exports to its Allies (Parraga & Ulmer, 2017) – are more preserved, which is a direct consequence of the higher priority weights placed on those other regions (Figure 6). This leads to Venezuelan losses being higher in the weighted scenario (see Appendix 4 in the supplemental data online).

**Sectoral relationships**

In absolute monetary terms, the decline of crude oil export revenues is the dominant feature of Venezuela’s losses (Figure 8), obviously leading to supply shortages for petrol refining.
(‘OilGasVen’ to ‘PetrolVen’) and to loss of government revenue (‘Ven-restVA’). Refinery inputs in the rest of the world are being compensated by increases in crude oil imports from elsewhere (‘OilGasVen’ to ‘PetrolRoW’). The reduction in Venezuelan petrol refining results in severe shortages at petrol stations (in our analysis ~51%; cf. Buitrago, 2019; Pozzebon, 2019). The worsening trade balance and job losses in the petroleum sector lead to food shortages (~38% in our analysis; cf. Benzaquen, 2017; Graham-Harrison, 2017; Otis, 2018). Finally, the drought-caused blackouts affect mostly households (~86% in our analysis; cf. with 80% of Venezuela’s power stemming from hydroelectric stations; Daniels, 2019).

**DISCUSSION AND CONCLUSIONS**

A number of features in the method proposed here deserve further discussion: (1) the nature of the objective function, (2) the magnitude of the priority weights and (3) the interpretation of the priority weights. In the following we discuss these issues in turn.

**Objective function**

Because of the squaring, the objective function does not distinguish between losses and gains when preventing disruptions. Strictly speaking, one could argue that an increase in transactions, for example, wages or turnover, does not really constitute a disruption. Especially in the situation of a disaster, increases in economic activity elsewhere must be seen as beneficial. However, such changes are being prevented by the square-form objective function, especially so in areas with large priority weights. This seemingly counterproductive feature could in principle be dealt with by re-defining the objective function so it penalizes only losses and not gains, for example, as \( \sum (S_{ij} - \tilde{S}_{ij})^2 w_{ij} \). Minimizing weighted differences would actually favour increases in \( \tilde{S} \). However, additional numerical experiments showed that this formulation has a massive drawback; it actually leads to substantial re-distribution of transactions from low- to high-priority areas, even without any exogenous losses being imposed via the \( \Gamma \) matrix. Drawbacks would also apply for any form in which losses and gains would be dealt differently via separate cases, for example, \( \sum (S_{ij} - \tilde{S}_{ij})^2 w_{ij} \) for \( S_{ij} > \tilde{S}_{ij} \), and 0 otherwise, because not only would such functionals be non-differentiable, and render gradient and Hessian functions cumbersome and runtime-consuming, but also would they not reward any gains either.

In this work we have enabled gains through the setting of the priority gains. For example, as visible in the top left panel of Figure 6, the priority weight for Venezuelan food exports to the rest of America is very low at 0.1, meaning that these transactions are allowed to change freely. Indeed, Figures 7 and 8 show that this setting has enabled the desired outcome. This means that if one deals with an area of the economy that shall take priority in the sense that one aims at increasing economic activity, the weight-setting logic does not prescribe a high value to these areas, but a low value. Whilst this sounds counter-intuitive at first, it is consistent if one interprets ‘priority’ as an attribute for preventing change, not just loss. This in turn means that priority weights will likely need to be low for any area of input substitutability as expressed by the concordance matrix \( C \), and for any area with a high substitution threshold \( \varepsilon \), because it is here where the larger changes are to be expected.

**Magnitude of priority weights**

In this work we applied priority weights in the range of 0.1 to 500, that is, spanning 3.5 orders of magnitude. The question is whether this magnitude range of priority weights is realistic, that is whether, in real-world decisions, people do place such different priorities on different economic transactions, and in turn on the agents involved in those.

To address this question, we gathered data on life insurance premiums, economic losses and deaths from Covid-19, average wages, and healthcare expenditure at a global level to
assess variability across countries (Figure 9). The rationale for examining these quantities is

(1) insurance premiums directly reflect the perceived value of the life of different people,
(2) Covid-19 statistics indicate how much economic loss a society is willing to accept to avoid
a death, (3) average wages show how much people are remunerated for in essence doing the
same job, and (4) health care expenditure is a direct measure of the societal importance of
citizen’s well-being.

When plotted against per capita gross domestic product at a country level, these measures
(Figure 9, y-axis) span a range of almost four magnitudes for insurance premiums, more than
four magnitudes for Covid-19 deaths, 170 for health expenditure and 400 for average wages.
Countries with a high per capita GDP spend more on insurance premiums, pay higher wages,
are willing to accept high economic losses to avoid Covid deaths and have a high health expen-
diture. The variation across countries could be likened to priority-weighting in an IO setting,
where countries with low per capita GDP generally represent less important trading partners,
and also are less able to highly prioritize the economic and general well-being of their citizens.

The range of 3.5 magnitudes applied in this work fits well within the observed range of pri-
ority indicators in Figure 9, which we take as justification of our chosen weight values.

Interpretation of priority weights in practice

Third, the question arises with regard to the interpretation of decision weights in practical appli-
cations. The term itself suggests decisions by stakeholders about which areas of economic activity
to prioritize in the face of disaster-caused shortages. This may be the case shortly after natural
disasters such as earthquakes or cyclones (Hooper, 2014; Chatterjee et al., 2016; Raikes et al., 2019; Tang et al., 2019). Such weights may, however, also arise out of political constellations that are not founded on individual local decisions, for example, international trade relationships that are governed by geopolitical alliances, or protected by subsidies and tariffs. Another example for such political constellations are asymmetries in resource endowments and political power that, given economic interdependencies, result in conflict over control of strategic resources (Lipschutz & Holdren, 1990), and open avenues to political influencing (Wagner, 1988), economic coercion (Olson, 1979) or even military intervention. For example, some commentators maintain that protecting crude oil supplies was the rationale of the 2003 US invasion of Iraq, and that the United States would not have engaged had there been no critical resource issue (Hinnebusch, 2007). In this sense, the term ‘decision weights’ used in this paper should be seen in a more general sense as indicating mechanisms that safeguard certain inter-industry transactions over others.

Limitations
There are a number of aspects that are not addressed in this study. First, the supply shortages accompanying most if not all disasters will invariably lead to price hikes, which will influence post-disaster outcomes. Traditionally, minimum-disruption analyses have used only quantity models. Assessing price implications is the mainstay of CGE analysis; however, here, to the knowledge of the authors, assigning decision priorities to economic transactions has not yet been realized. Another aspect is that of resolving post-disaster trajectories temporally. Future work could be directed at refining this method to incorporate prices, and to enable modelling of post-disaster recovery paths, such as in the work of Steenge and Reyes (2020).

CONCLUSIONS

This study considers the case of the economic crises in Venezuela to showcase a new disaster analysis approach – minimizing disruption. Here we present several innovations: (1) the ability to specify the intermediate and final demanders that should not be affected by a disaster (addressing the problem of negative final demand in prior work); (2) input substitution (addressing the problem of constant production recipes in prior work); (3) the ability to incorporate decision weights, using a priority-weighted optimization method to reflect decision-makers’ behaviour in response to a disaster; and (4) to include downstream effects.

The method presented in this study can be used to assess the impacts of future or current pandemics, such as Covid-19, which undoubtedly require decision-makers to prioritize the delivery of services and funds (Goswami & Chouhan, 2021). In the context of risk management, the minimizing disruption approach can inform The Sendai Framework for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction (UNDRR), 2021) in order to understand disaster risk (e.g., for forecasting the effects of climate-related events), and for informing policy and legal frameworks for coordinating and overseeing disaster risk reduction (i.e., disaster risk governance).

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NOTES

1 This method has been applied to floods in Germany (Schulte in den Bäumen et al., 2015) to severe space weather events (Schulte in den Bäumen et al., 2014), and to damage from a tropical cyclone (Lenzen et al., 2018).
2 Their equations (12), (13), (22) and (23).
3 Negative final demand can be interpreted as indicating that the disaster necessitates assistance from outside the economy under consideration. However, this assumption becomes problematic in studies where the global economy is examined. Dietzenbacher et al. (2019) write, ‘It would assume importing from Mars’ (see Appendix A1.1 in the supplemental data online).
4 In Schulte in den Bäumen et al. (2014), intermediate sectors that receive only marginal inputs from a damaged sector are assumed to be able to substitute for the reduced input, or slightly alter their production recipe otherwise, so they can keep producing at pre-disaster levels. The distinction between marginal and significant inputs is controlled by manually setting a threshold (see Appendix A1.2 in the supplemental data online).
5 Condition ii is Oosterhaven and Bouwmeester’s equation (2). For Condition iv, see Oosterhaven & Bouwmeester (2016, p. 587), but no distinction is made for subsidies and decreases in inventories. Instead of our condition i, Oosterhaven and Bouwmeester’s model specific scenarios in equations (7) and (8). Conditions iii and v do not appear in Oosterhaven & Bouwmeester (2016).
6 According to Baptista (1997), oil rent results from the remuneration paid out of ownership of non-produced means of production, therefore, this rent is not the result of the productive effort of the productive factors that participate in any capitalist society to generate the product.
7 Several studies have suggested the causes for this ‘curse of natural resources’, such as the Dutch disease, lack of human capital accumulation, corruption, rent-seeking and deficiencies in institutions (Aganani & Iza, 2011).
8 According to Monaldi (2015), along the last oil price boom, which ended in mid-2014, some oil exporter’s countries were more prudent than in the past, saving and investing more of the windfall and taking advantage of the price environment to increase oil production. Venezuela was not one of them.
9 Chávez’s government (1999–2012) used the income from high oil prices to dramatically boost domestic consumption largely sustained by cheap imports, while accumulating a profuse foreign debt without generating any significant in productive reinvestment (for further details, see Monaldi, 2015; and Bull & Rosales, 2020).
Regional groupings necessarily require compromises. For example, many ‘Former Eastern Bloc’ countries are now European Union members; however, their per capita income lies significantly below that of earlier European Union member states. On the other hand, non-European Union members, such as Switzerland and the UK, fit into the ‘EU+’ group because of their similar per capita income.

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