Agnani *et al. Journal of Economic Structures* (2024) 13:7
https://doi.org/10.1186/s40008-024-00327-0

Journal of Economic Structures

RESEARCH

Open Access

An index of static resilience in interindustry economics

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Abstract
We introduce a novel static indicator of economy-wide resilience that assesses an economy's ability to adapt and recover from negative shocks originating from either the demand or supply side. This metric is counterfactual and, through simulation, reveals the extent of adjustments required to maintain total income at or above the initial pre-shock level while preserving the initial economic structure. The larger the scale of adjustments needed in response to the shock, the lower the resilience of the economic system. The methodology we propose for this assessment relies on the concept of constrained input–output multipliers embedded within a linear programming problem. We demonstrate the applicability of our approach by calculating and comparing demand and supply resilience indices for a group of ten large OECD economies. In all these economies, the results indicate that manufacturing industries exhibit higher resilience to demand shocks than service sectors and that economic resilience regarding negative supply shocks is higher than that of demand shocks.

Keywords: Demand resilience, Supply resilience, Static economic resilience, Constrained input–output multipliers, Endogenous scaling

1 Introduction

In recent years, any analysis of the impact of the COVID-19 pandemic has highlighted the importance of economic resilience and its measurement (among others, OECD 2021b; Linkov et al. 2021a, 2021b; Hynes et al. 2022; Trump et al 2020). The analysis of economic resilience dates back to the 1970s and was initially used in the study of ecological systems (Holling 1973). In this regard, resilience is a concept that transcends economics, describing the ability of physical, biological, or social systems to withstand external negative shocks (Haimes 2009; Serfilippi and Ramnath 2018). Nowadays, the concept of resilience is applied in a broad range of interdisciplinary studies concerned with the interactions between people and nature. Furthermore, resilience is often used in conjunction with the concept of 'adaptive capacity', another term with multiple meanings (Carpenter et al. 2001).

Generally speaking, resilience can be defined in several ways (Cumming et al. 2005) including: the system's capacity to undergo change while maintaining the same controls on structure and function, its ability to self-organize, and the degree of learning and adaptation within the system. As pointed out by Béné et al. (2012), resilience is associated with three distinct types of capacities: absorptive, adaptive, and transformative capacity (OECD 2014).

More specifically, in the field of economics, various definitions of economic resilience exist in the literature. These definitions strongly depend on the context of each analysis. For example, economic resilience can be derived from the response and recovery from earthquakes (Tierney 1997) or from the analysis of society's behavior and disaster hazards (Rose 2004, 2009), among others. While the definition of economic resilience still requires some refinement (Rose 2009), it is usually defined as the capacity of households, institutions, regions, and countries to absorb and recover from shocks while positively adapting and transforming their structures and means of living in the face of short- or long-term stresses, changes, and uncertainties (Mitchell 2013). For instance, Pant et al. (2014) define economic resilience as the capacity of the economic system to recover economic productivity from a disruptive event within a specific period and with appropriate costs. On the other hand, following Rose and Liao (2005), economic resilience refers to the inherent ability and adaptive response that enables firms and regions to minimize potential losses.

Based on these general conceptualizations, we can succinctly define economic resilience as the economy's capacity to adapt and recover from external shocks. These shocks may result from the normal course of events, such as a decrease in demand for exports, or from disruptions following unexpected events, like a decline in demand due to a pandemic. In both scenarios, we associate resilience with what Rose (2004, 2007) terms 'static resilience'. This concept is related to the inherent ability of the economic system to mitigate the negative impact of a shock through the reallocation of economic resources. It is closely aligned with the well-known economic problem of efficiently allocating resources. According to Rose (2007), this interpretation is considered 'static' because it can be achieved without fundamentally reconstructing economic activities. In other words, there are no changes in terms of technology and factor endowments.

On the other hand, 'dynamic resilience' pertains to disruptions affecting physical or human capital stocks, often observed after major unexpected disasters, such as earthquakes or terrorist attacks Rose (2007) and Pant et al (2014) identify common characteristics of dynamic economic resilience, focusing on the speed and stability of a system's ability to recover from a severe shock. In summary, resilience can be categorized as static, measuring a system's capacity or robustness to offset maximum impacts, and dynamic which relates to the speed at which the system can recover from a shock.

The transition from defining resilience to measuring it is no small feat. There exists a notable lack of consensus regarding the quantitative dimension of this measurement, as highlighted by Winderl (2014). One of the challenges lies in the multidimensional nature of resilience. Defining a synthetic measure becomes difficult when considering the myriad parameters involved, as discussed by Cumming et al. (2005). The complexity is compounded by the fact that resilience spans beyond mere economic factors, encompassing aspects such as environmental management and social cohesion policies, among others.

These conceptual and computational challenges make it difficult to provide a coherent comparison among various resilience indices. Moreover, the computation of these indices is contingent upon aspects that may prove elusive to measure, such as the maximum impact and expected impact of an external shock, a recognition explicitly made by Pant et al (2014). The uncertainty associated with estimating these effects should not be underestimated, as, one way or another, it influences the quantification of resilience. Another limitation present in some of the presently available measurements of resilience, particularly those utilizing input–output (I-O) analysis as discussed in Rose (2004), is the reliance on the standard multiplier technique as an estimator for the effects of shocks on the economy. Standard multipliers make sense under the assumption of excess capacity and supply flexibility. However, this assumption may not hold true when, for example, a shock occurs that impacts the supply chains within the economy.

The existence of a tradeoff between complex indices, which incorporate a multitude of aspects, and specific indices, which focus on determining a particular dimension, appears evident. The former, owing to their structure, are subject to greater uncertainty and variability, while the latter are more precise, albeit covering less background information.

In our case, as we aim to measure economic resilience, our approach will focus on specific indices. Particularly, we will emphasize both the macro and micro aspects that influence the degree of resilience. In the macro aspect, we introduce a measure of gross domestic product (GDP) as an objective function, while in the micro aspect, we incorporate elements of productive interdependence characteristic of a modern economy, all under the umbrella of static or short-term resilience.

Our approach, therefore, aims to uncover the intrinsic properties of the economic system within its usual course of events. This has the advantage of enabling a more straightforward conceptualization and potential planning of standard mitigation policies by the government, as noted by Briguglio et al. (2009). The extent of the government's mitigation or intervention would reveal the system's response requirements to counteract the negative shock. In fact, what we need is the counterfactual response, regardless of the actual feasibility of its policy implementation. The magnitude of this counterfactual response indicates the state of the system when confronted with the shock.

High system fragility measured in terms of acute reactions to shocks would therefore suggest low system resilience. Therefore, one possible and simple way of revealing the economic resilience of the system when facing a negative shock would be measuring the minimal countervailing needs that, outside the subsystem receiving the shock, would eliminate its detrimental effects. The larger the compensation needs, the more fragile would be the economy in the face of a shock and the lower would be its resilience and, thus, the higher its vulnerability. In this regard, as in Klein et al. (2004), we assume that "a system is vulnerable because it is not resilient, and it is not resilient because it is vulnerable". In fact, existing empirical evidence reveals that an economy's vulnerability is linked to its structural fragility (Díaz 2020).

In summary, our approach associates the degree of resilience or vulnerability of economic systems with the volume of resources required to restore, in our case, the pre-shock income level generated by the economy. This restoration assumes that technology remains unchanged, and the sectoral structure of demand (supply) remains similar to the pre-shock equilibrium. It is true that economic resilience, as mentioned earlier, is a multifaceted concept. Therefore, relying solely on single metrics that address one aspect of resilience provides only limited information (Haimes 2009). However, limited information is always better than no information and any metric, no matter its simplicity, helps to reveal part of the underlying structure that is not directly and easily observable. This always contributes to a better understanding of the system's ability to adjust to changes.

Unlike major disaster disruptions, which can have substantial but discontinuous effects, we can model economic flows using continuous functions. This approach provides a computational procedure that allows us to measure intrinsic economic resilience, specifically in its static form. Resilience, being both sector-specific and network-related, has led to the use of various general equilibrium models for analyzing the effects of disruptions. The choice of the general equilibrium approach is based on its convenient modeling platform, as it integrates the receipt and transmission of external shocks and feedback. We can broadly classify these approaches into two groups: computable general equilibrium (CGE) models (Shoven and Whalley 1984) and I-O models (Leontief 1986).

In this regard, within the group of CGE models, it is worth mentioning the recent works of Wu et al. (2021) and Walmsley et al. (2023). The former uses a static CGE model to assess the impact of the COVID-19 pandemic on both the demand and supply sides of the Chinese economy. The latter, on the other hand, utilizes a dynamic CGE model to estimate the impact of the recent pandemic and its recovery in the case of the USA economy. Within the second group (I-O models), Han (2022) explores the structural changes in the Chinese economy resulting from the COVID-19 pandemic using information from the technical I-O coefficient matrix, while Pichler and Farmer (2022) use I-O data for the German, Italian, and Spanish economies to evaluate domestic demand and supply shocks. In a different methodological approach, Temel and Phumpiu (2021) employ a novel graph-theoretical method to study a group of developed and developing economies, helping identify the top-priority sectors that should be targeted to mitigate the effects of COVID-19 on unemployment.

The possibilities and limitations of the interindustry I-O model are well-known. On the one hand, the model is transparent in terms of its network interdependencies, computationally operational, easily interpretable, and last but not least, we usually have the necessary data available (Miller and Blair 2009). In this regard, it offers the possibility of measuring what we can call total static economic resilience or economy-wide resilience, as I-O models allow the capture of existing direct and indirect interdependencies between production activities. On the other hand, the classical interindustry model has limited behavioral reactions, and we should interpret its results as short- or medium-term responses before price adjustments (Rose and Liao 2005). Additionally, in contrast to CGE models and nonlinear macroeconometric approaches, I-O models only capture either quantity effects or price effects, but not both simultaneously (Rose 2004). However, the linearity of the model makes it amenable to easy integration into a linear programming (LP) framework (Intriligator 2002; Graham 2016).

Therefore, our approach uses a computational LP mechanism that helps us identify the minimum changes required for the system to recover. These changes involve minimal adjustments in the initial demand or supply structure, as well as the computation of the minimum volume of economy-wide resources needed to respond to negative shocks received by economic sectors. As mentioned earlier, the greater the volume of resources mobilized, the lower the degree of resilience (and the higher the vulnerability) of the economic system.

The paper is organized as follows: Sect. 2 introduces the economic framework used to incorporate the measurement of intrinsic static economic resilience, laying out the basic properties of the interindustry model. In Sect. 3, we extend the concept of constrained multipliers to develop a static economic resilience index based on I-O relationships. In Sect. 4, we apply the proposed methodology using domestic industry-by-industry I-O data from a group of OECD economies for the year 2018 and present the numerical results related to both demand and supply resilience indicators. Finally, Sect. 5 concludes the paper.

2 Economic framework: a generalization of the demand-driven total multiplier model

A modern economy operates through a network of interconnected industries. When an external shock affects a certain industry, the effects that directly impact that industry will have repercussions in the form of a cascade through the network of industrial interconnections and will ultimately affect the functioning of the entire economy. Interindustry economics (Leontief 1986; Miller and Blair 2009) provides an adequate framework for quantitatively measuring these ripple effects.

An interindustry economy is composed of n distinguished industries. Each industry, labeled as $j = 1, 2, \ldots, n$, acts as both a demander and a supplier of goods. Industry j demands goods from the rest of the industries, which it then uses as inputs in its production process. These intermediate demand flows are utilized by industry j in fixed proportions. In turn, the industry's output satisfies the intermediate demand of other industries that use good j as input in their production activities, as well as final demand from households, the public sector, the external sector, and so on. The economy is in balance when the total supply equals the total demand in each and all of the n industries.

In its simplest possible form, the balance condition in an I-O Leontief system is given by the expression:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{y}, \tag{1}$$

with $\mathbf{x} = (x_i)$ being a column vector representing total production or industries' gross output, $\mathbf{y} = (y_i)$ being the non-negative column vector of final demand. The non-negative matrix $\mathbf{A} = (a_{ij})$ describes the technical I-O coefficients. Each coefficient a_{ij} indicates the quantity of the output of industry i needed as input in the production of one unit of the output of industry j. The model in expression (1) is solvable under some regularity conditions[1] with non-negative solution given by:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{y} = \mathbf{M} \cdot \mathbf{y}, \tag{2}$$

with the inverse matrix $\mathbf{M}$ denoting the so-called Leontief inverse of total (direct plus indirect) multipliers. We can also write the equilibrium system of Eqs. (2) in differential terms. In this regard, we can either consider exogenous changes in final demand that lead to direct and indirect variations in industries' gross output:

[1] If matrix $\mathbf{A}$ is non-negative, constant and its maximal eigenvalue is less than 1, the system of Eqs. (1) is non-negatively solvable. See Nikaido (1972).

$$\Delta\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \Delta\mathbf{y} = \mathbf{M} \cdot \Delta\mathbf{y}. \tag{3}$$

Alternatively, we can also consider exogenous changes in industries' gross output that lead to endogenous variations in final demand:

$$\Delta\mathbf{y} = (\mathbf{I} - \mathbf{A}) \cdot \Delta\mathbf{x} = \mathbf{M}^{-1} \cdot \Delta\mathbf{x}. \tag{4}$$

A vector $\Delta\mathbf{x}$ endogenously calculated from (3) will indicate the required changes in the production of all industries that are necessary to accommodate the exogenous change $\Delta\mathbf{y}$ in the final demand originated in a specific industry k or, more generally, in a subset of industries. Focusing first on the effects originated from a unitary change in the final demand of industry k, $\Delta\mathbf{y}'_{(k)} = (0,\ 0,\ \ldots,\ 1, \ldots, 0)$, with a 1 in the kth position,[2] we can quickly calculate the total demand-induced change using the multiplier matrix $\mathbf{M}$ as:

$$\mu_k^y = \sum_{i=1}^{n} m_{ik}. \tag{5}$$

We can easily extend the quantification of the multiplier effects defined in (5) to non-unitary changes of any sign in final demand, say $\Delta\mathbf{y}'_{(k)} = (0,\ 0,\ ...,\ \delta_k^y, ..., 0)$ with δ_k^y being positive or negative in the vector's kth position. In this case, and by the linearity implied by the constancy of matrix $\mathbf{A}$, the aggregate output multiplier value associated to a δ_k^y change in final demand of industry k would turn out to be:

$$\mu_k^y(\delta_k^y) = \sum_{i=1}^{n} \delta_k^y \cdot m_{ik} = \delta_k^y \cdot \sum_{i=1}^{n} m_{ik}. \tag{6}$$

The k demand-induced multiplier $\mu_k^y(\delta_k^y)$ in (6) will be positive if $\delta_k^y > 0$ or negative if $\delta_k^y < 0$. In the first case, we have positive demand shocks, in the second one negative demand shocks.

Similarly, vector $\Delta\mathbf{y}$ in (4) captures the direct and indirect endogenous variations in final demand of all industries when there are exogenous changes in the gross output of industry k or in a subset of industries. In this case, the supply-induced effects of a change $\Delta\mathbf{x}'_{(k)} = (0,\ 0,\ ...,\ \delta_k^x, ..., 0)$ in the output of industry k on final demand would be:

$$\mu_k^x(\delta_k^x) = \delta_k^x - \sum_{i=1}^{n} \delta_k^x \cdot a_{ik} = \delta_k^x \cdot \left(1 - \sum_{i=1}^{n} a_{ik}\right). \tag{7}$$

Therefore, the k supply-induced multiplier $\mu_k^x(\delta_k^x)$ in (7) will identify a positive supply shock if $\delta_k^x > 0$ or a negative one if $\delta_k^x < 0$.

3 A measure of demand and supply static economic resilience within the input–output framework

The multiplier matrix $\mathbf{M}$ measures the unrestricted effects of external unitary shocks affecting the economy via its final demand. In the same vein, the information contained in matrix $\mathbf{M}^{-1}$ provides the unrestricted effects in final demand derived from

[2] For notational convenience, $\Delta y'_{(k)}$ is the row vector version of the corresponding column vector.

external unitary supply shocks. When a negative demand shock, such as a decline in investment flows, falls on industry k the ripple effects expand over the network and reduce overall production by a magnitude that we can approximate using the multiplier matrix $\mathbf{M}$ and the accounting from expression (6). Similarly, if the shock takes place constraining the supply, as would be the case under the scarcity or unavailability of some specific input, matrix $\mathbf{M}^{-1}$ working through expression (7) would provide now an evaluation of the implications on final demand. Consequently, one possible way to estimate the ability of the economy to recover from a negative demand or supply shock falling on industry k would be to calculate the minimal volume of resources that should be mobilized to the remaining industries $i \neq k$ that would countervail the shock on k and keep the economy at least at the initial GDP level.

Therefore, what we propose here is to use Leontief's I-O model, although adapted to a restricted version of the multipliers that is capable of capturing the level of compensatory changes required after a shock. In calculating these economy-wide resilience indices for the economy, we isolate and measure the economic strength in the non-impacted industries that offsets the shock in impacted industry k. Taken together, this simulation would provide us with a quantification of the economy's ability to withstand the shock (falling on industry k) and adjust to it (from counterfactual changes in all $i \neq k$). Since we can sequentially simulate the shock and counterfactuals across all industries, this strategy would identify the strength associated with unaffected industries that, together with the initial negative shock, would offset total GDP in aggregate terms.

We begin, firstly, by describing the method used to construct the resilience indicator induced by shocks on the demand side. One way to implement this approach is through the concept of restricted multipliers developed by Guerra and Sancho (2011) to examine the spending policies of governments under budget constraints.

Suppose a shock of magnitude $\mathrm{d}_k^y < 0$ falls on final demand in industry k. We can calculate the countervailing values $\delta_i^y > 0$ for $i \neq k$ that would keep aggregate GDP constant and do so with the least deviation from the initial final demand structure:

$$\begin{cases} \delta_i^y = \delta_k^y & (i = k) \\ \delta_i^y = -\delta_k^y \cdot \dfrac{y_i}{\sum\limits_{j \neq k} y_j} (i \neq k) \cdot \end{cases} \tag{8}$$

The changes in final demand from vector $\boldsymbol{\delta}^y = (\delta_i^y)$ have two properties. Firstly, from the definition in expression (8) we verify:

$$\sum_{i=1}^{n} \delta_i^y = \delta_k^y + \sum_{i \neq k} \left(-\delta_k^y \cdot \frac{y_i}{\sum\limits_{j \neq k} y_j} \right) = \delta_k^y - \delta_k^y \cdot \left(\frac{\sum\limits_{i \neq k} y_i}{\sum\limits_{j \neq k} y_j} \right) = 0. \tag{9}$$

Thus, total aggregate final demand remains unchanged (i.e., neutral scaling). Secondly, the changes in the non-shocked industries $i \neq k$ are set to be proportional to initial demand levels to keep the final demand structure in the non-shocked industries as close as possible to the initial one or pre-shock structure. As stated in the introduction, the later condition is in line with static or short-term economic resilience.

Consequently, the negative shock δ_k^y reduces gross output according to (6) and thus, GDP. The n-1 positive shocks would counteract this fall through its aggregation over the n-1 industries. The overall result takes both forces, negative and positive, into account and thus the restricted multiplier associated to the neutral shift in final demand takes value:

$$\hat{\mu}_k^y(\delta_k^y) = \mu_k^y(\delta_k^y) + \sum_{i=1}^{n} \sum_{j \neq k} \delta_i^y \cdot m_{ij}. \tag{10}$$

Under the type of negative shock and positive countervailing compensation we examine, the first term of this summation is always negative and captures the standard unrestricted multiplier $\mu_k^y(\delta_k^y)$ from expression (6), whereas the second one is always positive. The composite result is that the restricted multipliers $\hat{\mu}_k^y(\delta_k^y)$ defined in expression (10), unlike the always-negative standard multipliers $\mu_k^y(\delta_k^y)$ stemming from a negative shock $\delta_k^y < 0$, can now have any sign.

The neutral scaling that we define in expression (8) would change "post-shock" final demands from y_i to $\tilde{y}_i = y_i + \delta_i^y$. This scaling, however, does not guarantee that total output in the economy is going to be preserved. In fact, in general, total output $\mathbf{x}$ under demand scheme $\mathbf{y}$ will be different from total output $\tilde{\mathbf{x}}$ under demand scheme $\tilde{\mathbf{y}}$ both industry wise and economy wide (Guerra and Sancho 2011).

The same type of discrepancy occurs in regard to GDP. If the nth vector $\mathbf{v} = (v_j)$ denotes value-added per unit of jth industrial output, income GDP can be calculated as the dot product:

$$\text{GDP} = \mathbf{v}' \cdot \mathbf{x} = \sum_{j=1}^{n} v_j \cdot x_j. \tag{11}$$

As before, GDP under demand scheme $\mathbf{y}$ will be different from $\widetilde{\text{GDP}}$ under demand scheme $\tilde{\mathbf{y}}$ through the changes taking place from $\mathbf{x}$ to $\tilde{\mathbf{x}}$. Nonetheless, for any demand shock δ_k^y we can readjust the scaling in (8) to determine the minimal value ρ_k^y that would rescale the neutral coefficients δ_i^y for $i \neq k$ and has the additional property that GDP remains at least at the initial level after the shock δ_k^y, i.e.,$\text{GDP} = \widetilde{\text{GDP}}$. With this adjustment, we guarantee that the economy would recover from the external shock, at least in terms of GDP measured by its total aggregate value-added, i.e., the adjustment would be costless for the economy.

In other words, given a demand shock δ_k^y on industry k find the re-scaling value ρ_k^y that solves the LP problem:

$$\text{Min } \rho_k^y \text{ subject to}$$

$$\begin{cases} (12.1) \quad \tilde{\delta}_i^y = \delta_k^y \text{ if } i = k \text{ and } \tilde{\delta}_i^y = \rho_k^y \cdot -\delta_k^y \cdot \dfrac{y_i}{\sum\limits_{j \neq k} y_j} \text{ if } i \neq k \\ (12.2) \quad \tilde{y}_i = y_i + \tilde{\delta}_i^y \\ (12.3) \quad \tilde{x}_i = \sum\limits_{j=1}^{n} a_{ij} \cdot \tilde{x}_j + \tilde{y}_i \\ (12.4) \quad \sum\limits_{i=1}^{n} v_i \cdot x_i \leq \sum\limits_{i=1}^{n} v_i \cdot \tilde{x}_i \end{cases} \tag{12}$$

Equation (12.1) indicates the re-scaling adjustment over the neutral one. Equation (12.2) indicates the new level of final demand after the re-scaling, whereas Eq. (12.3) is the Leontief equilibrium condition between total output and total demand. Finally, Eq. (12.4) is the recovery provision for total value-added, i.e., GDP.

The optimal solution ρ_k^y of system (12) is the magnitude that proxies the system-wide economic resilience associated to industry k facing a negative demand shock δ_k^y. The smaller the re-scaling value, the smaller the compensatory adjustment needed in the economy and, therefore, the more resilient the economy's response to the negative shock. A small value of ρ_k^y implies that the productive technology and final demand structure of the economy prior to the shock are capable of offering a better adaptive response to counteract the shock.

If the solution of (12) yields $\rho_k^y = 1$, the neutral scaling defined in (8) would be sufficient to counteract the losses in GDP from the negative shock. In other words, a unitary decline in the domestic final demand of sector k is automatically counteracted by increases in the domestic final demand in the remaining $i \neq k$ sectors that at the aggregate would keep the initial level of final demand. On the other hand, whenever $\rho_k^y > 1$ the neutral adjustment would be insufficient to counteract the induced losses in GDP. Hence, the larger the negative distance $1 - \rho_k^y$, the larger the recovery effort and the smaller the adaptability or resilience, in our terminology. Then, we define $1 - \rho_k^y$ as the net demand resilience coefficient. Lastly, if $\rho_k^y < 1$, the neutral adjustment would be more than sufficient to compensate the economic losses from the negative shock in sector k. As a result, the volume of resources that should be mobilized to offset the perverse effects of the shock would be lower, which means a high degree of resilience in sector k.

Similarly, we can also construct supply-induced resilience coefficients and indices. In this case, the negative shocks on supply generate shocks in final demand according to expression (4). Using the supply-induced multiplier defined in Eq. (7), we can replicate the analysis and obtain the resilience indices from a supply perspective. We omit the details here, but they can be looked up in Appendix A at the end of the paper.

4 Calibration, results and discussion

For the calculation of the demand and supply resilience indices, we have used the industry-by-industry domestic I-O tables regularly compiled by the OECD statistical database (OECD 2021a). From this data set, we have selected the domestic I-O tables that correspond to ten of the largest OECD economies. It is important to note that our country selection is not all-encompassing. Our aim is not to conduct an exhaustive study of all

OECD member countries, but rather to focus on economies characterized by significant GDP and a stable yet diversified productive structure. Thus, we eliminate the variability that could exist when comparing large economies with small economies, which are subject to more restrictive or specialized production conditions.

We consider Australia, Canada, Colombia, Germany, France, Italy, Mexico, Spain, the United Kingdom, and the United States of America. The industry breakdown includes 44 industries (see details in Appendix C, Table 7). The monetary flows of the domestic I-O tables are expressed in US millions of dollars and refer to the year 2018 which is the last version available at the moment.

We have evaluated both the demand and supply resilience indicators solving the demand and supply LP problems specified in (12) and in (A.4) in Appendix A, respectively, using the LP solver BDMLP available in GAMS (2021). We introduce a negative shock in each of the 44 industries in each economy and solve the 44 LP problems sequentially via a loop. In order to ease the interpretation of the results, the negative shock refers to a unitary decline in the domestic demand (supply) of a specific industry.[3] Once the negative shock is introduced within the LP problem in (12) (and in supply system (A.4) in Appendix A), the domestic demand (supply) flows of the remaining industries optimally adjust to compensate the decline in GDP. Consequently, if the net demand resilience coefficient $1-\rho_k^y$ is positive and large, the degree of resilience of the economy to a potential unexpected shock in industry k will be high: less public resource mobilization is necessary to counteract the negative effect in sector k. On the other side of the spectrum, if the net demand resilience coefficient turns out to be negative and large, the degree of resilience of the economy regarding industry k will be low. The interpretation for the net supply resilience coefficient $1 - \rho_k^x$ is similar (see Appendix A for details).

4.1 Static demand-induced resilience indices

In order to have a general overview of the degree of demand resilience by country, we have calculated the average demand resilience index for each of the ten selected OECD countries. We also provide the range and the standard deviation to summarize their distribution. In Table 1, we review the stylized facts by country sorted from the highest to the lowest average net demand resilience coefficient.

Notice that the minimum index value is mostly concentrated in industry N_37, *Real Estate activities*, which identifies that this industry would induce the largest cost of recovery when facing a shock. This probably reflects that this industry has low upstream and downstream links, and adjustment changes would therefore be harder to implement. In contrast, the maximum index of net static demand resilience is frequently represented by industry N_10, *Coke and Refined Petroleum Products*, an industry that has high capital density and provides essential inputs to the rest of industries. This industry has relevant upstream interdependences, which eases the adjustment mechanisms we

[3] Recall that under the standard I-O approach with constant returns to scale and zero substitution elasticities average multipliers equal marginal multipliers. Hence, the magnitude of the evaluated shock does not affect the evaluated resilience indexes (Guerra and Sancho 2014).

Table 1 Net demand-induced resilience indices by country: distribution parameters

Country	Average index	Maximum index value		Minimum index value		St. deviation
		Sectors' code*	Value	Sectors' code*	Value	
United Kingdom	0.0763	N_10	0.7314	N_37	− 0.1687	0.9773
France	0.0752	N_10	0.6538	N_37	− 0.2193	1.3497
Canada	0.0596	N_20	0.5032	N_37	− 0.1790	0.9149
Spain	0.0593	N_10	0.7193	N_37	− 0.2195	1.3147
Australia	0.0518	N_20	0.2444	N_37	− 0.0968	0.3143
Italy	0.0483	N_10	0.6083	N_37	− 0.2256	1.1612
Colombia	0.0463	N_21	0.3911	N_37	− 0.1529	0.6880
Germany	0.0455	N_10	0.5680	N_41	− 0.2057	1.0319
United States	0.0347	N_10	0.2633	N_37	− 0.0631	0.2352
Mexico	-0.0049	N_17	0.5017	N_37	− 0.2585	1.2404

* See Table 7 in Appendix C for the sector description according with the sector code

Source: our model using OECD I-O data for 2018

study. In fact, this finding is compatible with the classical contribution of Hirschman (1958) to I-O analysis.[4]

In Appendix B, Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 offer a visual representation of the results for all 44 industries within each of the ten OECD selected economies. These figures display the industries' net demand resilience coefficients $1-\rho_k^y$ sorted by size, ranging from the least resilient industry to the most resilient one. To enhance the clarity of the presentation, we have chosen to highlight the net demand resilience index for the ten most resilient sectors (indicated by green bars), as well as the ten least resilient sectors (indicated by yellow bars) among the total of 44 sectors included in the database. The net demand resilience indices of the rest of industries are indicated by blue bars. Additionally, each figure includes the average index value (represented by an orange bar), along with the corresponding standard deviation, which is also reported in the last column of Table 1.

In line with the definition of the static demand resilience coefficient in (12), the United Kingdom (Fig. 6) turns out to be the most demand resilient economy with an average net demand resilience coefficient of 0.0763 among the ten selected OECD countries. An alternative interpretation of this net demand resilience index is the following: in the United Kingdom, on average, the volume of resources needed to compensate the negative demand shock in sector k to restore the initial GDP is less than proportional to the initial negative shock, i.e., –1 US millions of dollars, thus 7.63 percent below the initial negative shock. On these grounds, United Kingdom is closely followed by France, which has an average net demand resilience coefficient of 0.0752.

Despite the average similarity between these two OECD economies, it is important to note that France (Fig. 4) exhibits the highest standard deviation among these ten selected OECD economies, with a value of 1.3143. In stark contrast to the United States

[4] In his work, Hirschman (1958) highlighted the relevance of the strength of both backward and forward I-O interdependences to increase the efficiency of economic policies and thus of economic development. In this regard, our approach is linked to Hirschman's contributions since the highest the degree of interdependences that a sector has with other sectors, the higher its degree of resilience and thus, the lowest the volume of resources used to counteract a potential negative economic shock occurring in that sector.

(Fig. 7) or Australia (Fig. 1), which have the lowest standard deviation, France shows a significant variation in demand resilience from one sector to another.

At the other end of the ranking, we find Mexico (Fig. 10) followed by the United States (Fig. 7). According to our criteria, Mexico turns out to be the least resilient economy with an average net demand resilience coefficient of -0.0049. This figure, though quite close to zero, i.e., close to the neutral adjustment mentioned in Sect. 3, is negative. Hence, this figure informs that, on average and in that economy, the volume of resources necessary to restore the initial GDP level after receiving a negative demand shock is more than proportional to that initial shock. In other words, in the case of the Mexican economy, on average, the volume of mobilized resources to counteract the negative final demand shocks account to 0.49 per cent above the negative shock.

If we now focus on the most demand resilient economy among the ones considered in our analysis, the United Kingdom, the ten industries that present the highest net demand resilience coefficient are the following (sectors on the right-hand side of Fig. 6 indicated by green bars): *Coke and refined petroleum products* industry (N_10), *Air transport* industry (N_29), *motor vehicles, trailers and semi-trailers* industry (N_20), *basic metals* industry (N_15), *electricity, gas, steam and air conditioning* industry (N_23), *chemical and chemical products* industry (N_11), *rubber and plastic products* industry (N_13), *other transport equipment* industry (N_21), *electrical equipment* industry (N_18) and *wood and products of wood and cork* (N_8) industry.

According to the interpretation of this coefficient, this implies that if any of these industries undergoes a negative final demand shock, i.e., a decline in exports, a sharp reduction in final consumption or investment flows, little mobilization of alternative resources should be necessary in order to counteract the derived decline in income.

Do the remaining countries present common patterns in terms of the most demand resilient industries identified in United Kingdom? The high average net demand resilience in the UK results from several of its industries having high resilience values. Table 2 provides sector-specific data, showing which countries in the sample have a sector ranked among the top ten most resilient. Table 2 lists which countries share top resilience industries. For example, industry N_10 is one of the top ten resilient sectors in all ten countries in the sample, while industry N_1 does not hold a top resilience position in any of them.

We also notice in Table 2 that for most of the ten selected OECD economies the majority of the industries that are classified as having high demand resilient coefficients pertain to the manufacturing sector, i.e., *motor vehicles, trailers, and semi-trailers* industry (N_20) and the *other transport equipment* (N_21) and some energy-related sectors such as *coke and refined petroleum products* industry (N_10). The same occurs in the case of *electrical equipment* industry (N_18) with the exception of the United States. The *rubber and plastic products* industry (N_13) and the *basic metal* industry (N_15) are also quite common high demand resilient sectors. They are so classified as in seven out of the ten OECD economies analyzed here. Within the service industries, it is worth mentioning the case of the *air transport service* industry (N_29).

Table 3 provides a similar interpretation as in Table 2, but now focusing on the resilience values for the ten lowest-ranked industries. When examining the country with the lowest resilience index, Mexico, we find that the industries with the lowest net demand

Table 2 Country frequency of the first ten highest demand resilient industries

Sector code*	Country ISO 3166–1 alfa-3 code**	Sector code*	Country ISO 3166–1 alfa-3 code**
N_1		N_23	UK
N_2		N_24	
N_3	GER	N_25	
N_4		N_26	
N_5		N_27	
N_6	GER	N_28	FRA,GER,ITA
N_7	CAN,FRA,GER,USA	N_29	AUS,COL,FRA,GER,UK,ITA
N_8	UK,USA	N_30	
N_9	COL,MEX	N_31	
N_10	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX	N_32	
N_11	AUS,CAN,COL,FRA,GER,UK,ITA,SPA,MEX	N_33	
N_12		N_34	
N_13	AUS,CAN,COL,UK,USA,ITA,SPA	N_35	
N_14		N_36	
N_15	CAN,FRA,GER,UK,USA,ITA,SPA	N_37	
N_16	USA,SPA,MEX	N_38	
N_17	AUS,CAN,COL,ITA,SPA,MEX	N_39	
N_18	AUS,CAN,COL,FRA,UK,USA,ITA,SPA,MEX	N_40	
N_19	AUS,CAN,COL,FRA,USA,SPA,MEX	N_41	
N_20	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX	N_42	
N_21	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX	N_43	
N_22	AUS,MEX	N_44	

These codes are the three-letter codes published by the International Organization for Standardization, to represent countries, dependent territories, and special areas of geographical interest.

*See Table 7 in Appendix C for the sector description according with the sector code

**See Table 8 in Appendix C for the country description according with the country ISO 3166-1 alfa-3 Code

resilience coefficients are as follows (sectors on the left-hand side of Fig. 10 indicated by yellow bars): *real estate services* industry (N_37), *education services* industry (N_41), *wholesale and retail trade, repair of motor vehicles* industry (N_26), *financial and insurance activities* industry (N_36), *other service activities* industry (N_44), *administrative and support services* industry (N_39), *professional, scientific and technical activities* industry (N_38), *public administration and defense, compulsory social security* industry (N_40), *arts, entertainment and recreation* activities industry (N_43) and *accommodation and food services* activities industry (N_32).

In replicating the previous exercise (Table 3), the bulk of industries that are common low demand resilient industries belong, in this case, to the service sectors. This is, for instance, the case of the *real estate activities* industry (N_37) and *education service* industry (N_41) that stand out as low demand resilient industries in all ten OECD selected economies. In the same vein, it is worth mentioning the case of the *other service activities* (N_44) that are identified as "key" low demand resilient industries in nine out of ten economies (with the exception of Canada). The *public administration and defense, compulsory social security* service industry (N_40) and *professional, scientific and technical activities* service industry (N_38) are low demand resilient service industries in eight out of the ten OECD economies selected for this analysis. *The financial and insurance activities* industry (N_37) is also a common low demand resilient sector across these

Table 3 Country frequency of the first ten lowest demand resilient industries

Sector code*	Country ISO 3166–1 alfa-3 code**	Sector code*	Country ISO 3166–1 alfa-3 code**
N_1		N_23	CAN
N_2		N_24	UK
N_3	AUS, FRA, SPA	N_25	
N_4	COL, ITA	N_26	CAN,GER, USA, ITA,SPA, MEX
N_5	FRA,GER,ITA	N_27	
N_6		N_28	
N_7		N_29	
N_8		N_30	AUS
N_9		N_31	FRA,UK,ITA, SPA
N_10		N_32	MEX
N_11		N_33	
N_12		N_34	UK
N_13		N_35	AUS,CAN,COL,FRA, UK,USA
N_14		N_36	AUS, CAN, COL,USA,ITA, SPA, MEX
N_15		N_37	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX
N_16		N_38	AUS, CAN, COL,GER, UK,USA, ITA, MEX
N_17		N_39	CAN,COL,FRA, GER,USA,MEX
N_18		N_40	AUS,CAN,COL,FRA,GER, ITA,SPA, MEX
N_19		N_41	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX
N_20		N_42	AUS,CAN,FRA, GER,UK,USA,SPA
N_21		N_43	COL,GER,UK,USA,SPA,MEX
N_22		N_44	AUS,COL,FRA,GER,UK,USA,ITA,SPA,MEX

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*See 7 in Appendix C for the sector description and codes

**See Table 8 in Appendix C for the country description according with the country ISO 3166-1 alfa-3 Code

countries. It is identified as such in seven out of the ten selected economies. Lastly, outside the service sectors, we can highlight the extractive industries: *mining and quarrying, energy producing products* industry (N_3), *mining and quarrying, non-energy producing products* industry (N_4) and *mining support service activities* industry (N_5).

The similarities in resilience levels, whether high or low, among the industries in the sample countries, as shown in Table 2 and 3, reveal to some extent the degree of similarity in their production structures. Despite variations in numerical resilience coefficients, these countries' production structures share several significant aggregate properties. Notably, the highest resilience is concentrated in the manufacturing sectors, while the services sectors exhibit the lowest resilience. The rapid diffusion of technology that we observe in our times entails a certain degree of convergence in the adoption of productive techniques, resulting in common structural characteristics across countries, with the natural differences that we should nevertheless expect in the numerical estimates.

4.2 Static supply-induced resilience indices

In Table 4 we report, for each of the ten selected OECD countries, the resilience coefficients induced from the supply side sorted again from highest to lowest average index. In this case, none of the ten economies presents a negative index. Notice that when we

Table 4 Net supply-induced resilience indices by country: distribution parameters

Country	Average index	Maximum index value		Minimum index value		St. deviation
		Sectors' code*	Value	Sectors' code*	Value	
Australia	0.1342	N_15	0.7813	N_37	− 0.4664	3.8833
United Kingdom	0.1303	N_10	0.8258	N_37	− 0.6051	3.8848
France	0.1192	N_28	0.8140	N_5	− 0.7867	6.9363
Spain	0.1125	N_10	0.8384	N_37	− 0.7756	6.2033
Canada	0.1053	N_15	0.6786	N_41	− 0.5133	3.5557
Germany	0.0931	N_10	0.8419	N_41	− 0.6082	4.7160
United States	0.0930	N_20	0.6230	N_2	− 0.3994	2.7599
Mexico	0.0910	N_10	0.7144	N_37	− 0.6830	6.3113
Colombia	0.0884	N_19	0.7070	N_37	− 0.8148	4.7663
Italy	0.0789	N_10	0.8731	N_37	− 0.9929	8.0682

*See Table 7 in Appendix C for the sector description according with the sector code

Source: our model using OECD I-O data for 2018

compare the results in Table 4 with those depicted in Table 1, on average, the supply resilience indices are higher compared with the demand resilience indices. This informs us that, at short-term and according to the assumptions of our approach, the volume of resources that have to be mobilized to compensate negative supply shocks are much lower compared to negative demand shocks. In addition, some economies stand out as being resilient both from the demand and supply sides. This is the case of the United Kingdom and France. At the other end, among the least demand and supply resilient economies, we find the case of Mexico. Lastly, as in the face of a negative demand shock, at least in half of the countries in our sample, the minimum net supply resilience index value is concentrated in industry N_37, *real estate activities*, whereas the maximum index of net static supply resilience is represented by industry N_10, *coke and refined petroleum products.*

Coming back to the results reported in Table 4, Australia (Fig. 11 in Appendix B) with an average coefficient of 0.1342 ranks first as having the most resilient economy to negative supply shocks, while Italy (Fig. 18 in Appendix B) with 0.0789 ranks last. Furthermore, notice that Italy presents the highest sectorial variability as measured by the standard deviation. Hence, in the case of Italy, there exists a great heterogeneity in the negative effects of supply shocks across industries. We can also observe that the United Kingdom (Fig. 16 in Appendix B), in the second position of the ranking with a coefficient of 0.1303, is quite similar in results to Australia both in average and standard deviation values. France (Fig. 14 in Appendix B) with a value of 0.1192 takes the third place in the ranking but, unlike Australia and the United Kingdom, the variability in France is almost twice as large and is the second largest one after Italy. Recall that we already detected that France had the largest variability when we examined the demand-induced resilience indices. Germany, the United States and Mexico, on the other hand, present quite similar average indices but, again, their variability turns out to be quite dissimilar.

In Appendix B, Figs. 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 show the detail of the results by industry sorted by size from the lowest to the highest supply resilience index. As before, we highlight the ten most supply resilient sectors (the length of the bars in green) as well as the ten least supply resilient sectors (the length of the bars in yellow) in each of the Figures.

For the economy with the highest supply resilience index, Australia, the top ten supply resilient sectors, in descending order, are (Fig. 11 in Appendix B): *basic metals* industry (N_15), *coke and refined petroleum products* industry (N_10), *food products, beverages and tobacco* industry (N_6), *other transport equipment* industry (N_21), *construction* industry (N_25), *chemical products* industry (N_11*), rubber and plastic products* industry (N_13), *motor vehicles, trailers and semi-trailers* industry (N_20), *Paper products and printing* industry (N_9), and wood *and products of wood and cork* industry (N_8). Any supply shock falling on one of these sectors would require smaller positive supply adjustments in the rest of the industries to compensate for the negative shock. Notice that all these sectors belong mostly to the set of industrial sectors.

In Table 5, we report the frequency of the shared most resilient-supply industries of Australia with the rest of countries. We can observe that with the exception of *construction* (N_25) and for most countries, there is a strong similarity in the subset of industrial sectors across countries. In all of the ten countries, *coke and refined petroleum products* industry (N_10) and *motor vehicles, trailers and semi-trailers* industry (N_20) are in the top ten supply resilient sectors, followed by *food products, beverages and tobacco* industry (N_6), *chemical products* industry (N_11), and *basic metals* industry (N_15) with nine shared industries altogether. Furthermore, some of these manufacturing industries are also classified as being high demand resilient industries (see Sect. 4.1), i.e., *coke and refined petroleum products* industry (N_10) and *motor vehicles, trailers and semi-trailers* industry (N_20).

At the other side of the classification, we find that the least ten supply resilient industries in the least supply resilient economy, Italy (Fig. 18 in Appendix B) as mentioned before, happen to be: *real estate activities* industry (N_37), *mining support services* industry (N_5), *mining and quarrying* (N_4), *education* industry (N_41), *other services activities* industry (N_44), *professional, scientific, and technical activities* industry (N_38), *human health and social work activities* industry (N_42), *agriculture* industry (N_1), and *financial and insurance activities* industry (N_36). As in the case of the demand resilience, most of the least supply resilient industries belong to the general services category, with the exception of agriculture activities and two of the mining activities.

When we look at Table 6, we find the frequency of the shared least supply resilient industries. *Agriculture* (N_1) seems to be an outlier since only Colombia shares the classification for this sector. All ten countries share *Real Estate activities* industry (N_37) and *Education services industry* (N_41) in the subset of least resilient industries followed by *Human health and social work activities* (N_42) and *Other services activities* (N_44) with eight shared industries. As was the case with the least demand resilient industries, we find once again a majority of industries belonging to the services sector in this classification of least supply resilient industries. Notice that, some sectors such as *real estate activities* industry (N_37), *education service* industry (N_41) and *other services* industry (N_44) are also identified as being low demand resilient industries (see Sect. 4.1).

Table 5 Country frequency of the first ten highest supply resilient industries

Sector code*	Country ISO 3166–1 alfa-3 code**	Sector code*	Country ISO 3166–1 alfa-3 code**
N_1		N_23	UK,ITA
N_2	FRA,UK	N_24	
N_3	GER	N_25	AUS
N_4	UK	N_26	
N_5	UK	N_27	
N_6	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA	N_28	CAN,FRA,GER,USA
N_7	FRA,USA	N_29	GER,UK,ITA,SPA,MEX
N_8	AUS,CAN,FRA,GER,USA,SPA	N_30	
N_9	AUS,CAN,COL,GER,USA,MEX	N_31	
N_10	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX	N_32	
N_11	AUS,CAN,COL,FRA,UK,USA,ITA,SPA,MEX	N_33	
N_12	MEX	N_34	
N_13	AUS,CAN,COL,USA,ITA,SPA	N_35	
N_14	CAN,MEX	N_36	
N_15	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA	N_37	
N_16	MEX	N_38	
N_17	COL,MEX	N_39	
N_18	ITA,SPA,MEX	N_40	
N_19	COL	N_41	
N_20	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX	N_42	
N_21	AUS,COL,FRA,GER,ITA,SPA	N_43	
N_22		N_44	

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*See Table 7 in Appendix C for the sector description and codes.

**See Table 8 in Appendix C for the country description according with the country ISO 3166-1 alfa-3 Code

5 Conclusions

This work has a double objective: methodological and empirical. On the one hand, we introduce a new methodological criterion of static resilience that can be calculated from the available I-O data of an economy. In previous research, the degree of resilience of an economy has been approximated through the size of the economic consequences of negative shocks, whether on the demand side, the supply side, or both simultaneously (Wu et al. 2021; Pichler and Farmer 2022; Han 2022). Our work differs from previous ones in that we offer an alternative criterion of economic resilience based on the concept of restricted multipliers. This allows a numerical estimate of the degree of adjustment to a negative external shock in terms of the volume of resources that should be mobilized to restore the initial levels of GDP. Our proposed indicators are counterfactual, reveal intrinsic properties of the economy and provide information previous to the presence of an actual shock. To this effect, they take into account that the production structure should remain constant, whereas the adjustments in demand, or in supply, should respect as much as possible their initial structure. From here, the larger the efforts in terms or resources needed to counteract a shock and recover GDP levels, the lower the degree of resilience.

Table 6 Country frequency of the first ten lowest supply resilient industries

Sector code*	Country ISO 3166–1 alfa-3 code**	Sector code*	Country ISO 3166–1 alfa-3 code**
N_1	COL,ITA	N_23	CAN
N_2	COL,USA	N_24	
N_3	AUS,FRA,UK,SPA,MEX	N_25	
N_4	AUS,CAN,COL,GER,ITA,MEX	N_26	CAN,GER,SPA,MEX
N_5	CAN,FRA,GER,ITA	N_27	
N_6		N_28	
N_7		N_29	
N_8		N_30	AUS,USA
N_9		N_31	FRA,UK
N_10		N_32	MEX
N_11		N_33	
N_12		N_34	UK
N_13		N_35	CAN,COL,FRA,UK,USA
N_14		N_36	AUS,ITA,SPA,MEX
N_15		N_37	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX
N_16		N_38	CAN,COL,USA,ITA,MEX
N_17		N_39	CAN,COL,FRA,GER, SPA,MEX
N_18	UK,USA	N_40	AUS,FRA,GER,USA,ITA,SPA
N_19		N_41	AUS,CAN,COL,FRA,GER,UK,USA,ITA,SPA,MEX
N_20		N_42	AUS,CAN,FRA,GER,UK,USA,ITA,SPA
N_21		N_43	AUS,COL,GER,UK,USA,SPA
N_22		N_44	AUS,COL,FRA,GER,UK,ITA,SPA,MEX

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Therefore, in our view, our criterion is more compatible with a genuine definition of total static economic resilience (Rose 2004, 2007) since we are able to capture general equilibrium effects from the quantity side of the economy.

We will now outline the advantages of our approach: Firstly, our metric is policy relevant as it allows for the anticipation of disruption effects before they occur, facilitating the design and implementation of mitigation policies. For example, efforts can be directed toward increasing the digitalization of specific service sectors, which is closely linked to economic resilience (Copestake et al 2022). Secondly, our novel approach enables the ranking of economies and sectors based not on the size of the derived effects from negative shocks, but on the size of the mobilized resources that would offset those effects. Thirdly, we do not need to rely on estimates of the maximum and expected distortions induced by a shock (Pant et al 2014), simplifying the calculations. In the fourth place, our methodology works equally well for both demand and supply shocks. Lastly, it is relevant to emphasize the operational advantage of our approach regarding the required data. We only need access to I-O data, which is readily available from various periodically published statistical sources.

We should also acknowledge, on the other hand, the limitations of our approach to provide a better context for its scope. Firstly, it relies on linear estimates. Secondly, the metric is numerically one-dimensional and focuses on a specific aspect within the broader spectrum that defines resilience, extending beyond the purely economic dimension we measure. Finally, the I-O analysis framework only enables us to capture either quantity or price effects but not both simultaneously.

Some of these limitations can be overcome expanding the modeling range and we plan to do so in our future research. As an example, in our calculations we impose the condition that the adjustments must preserve initial GDP, the target that we select as the measuring yardstick. Other and different restrictions than GDP preservation are of course possible, take for instance employment levels, factors income levels, or environmental damage. All these alternative objective functions can be modeled within our methodology. Another example of possible extensions is that we only control for domestic demand and supply shocks. However, external supply chain constraints also affect economic performance, and we could incorporate them and examine their role in defining the value of resilience indicators for industries and for economies as a whole.

On the empirical side, we use our conceptual proposal to generate an empirical evaluation of demand and supply resilience for a set of ten OECD countries. We use the homogenized I-O dataset elaborated in the OECD using the most recent available data for 2018. This data has the advantage of distinguishing I-O intermediate data separating domestic inputs from imported inputs. The numerical results show, in general terms, that high demand and supply resilience tend to be associated with industrial sectors. This is specially the case of the *motor vehicles, trailers and semi-trailers* industry (N_20) and *coke and refined petroleum products* industry (N_10). In contrast, the least demand and supply resilience sectors are mostly associated with the general services sectors. *Real estate activities* industry (N_37) along with *education services* industry (N_41) and *other services* industries (N_44) are common low demand and supply resilient sectors across countries. This is the type of characteristic that we observe it in all of the ten selected OECD countries. In addition, and in line with our results, these economies appear to be less resilient regarding negative demand shocks compared to those originated in the supply side of the economy. The United Kingdom and France present the most resilient economic structures to demand shocks; with The United States and Mexico being the least resilient of the ten countries. On the supply side, Australia and the United Kingdom are the most resilient economies, whereas Colombia and Italy take the bottom places in the ranking.

Appendix A: supply-induced resilience indicators

Suppose a shock of magnitude $\delta_k^x < 0$ falls on the gross output of industry k. We can calculate the countervailing values $\delta_i^x > 0$ for $i \neq k$ that would keep aggregate value-added, or GDP, at least at the initial level with the least deviation from the initial final demand pattern. We first define the neutral scaling:

$$\begin{cases} \delta_i^x = \delta_k^x & (i = k) \\ \delta_i^x = -\delta_k^x \cdot \dfrac{x_i}{\sum\limits_{j \neq k} x_j} (i \neq k) \cdot \end{cases} \tag{13}$$

As in the case of the demand-induced resilience indicator, the changes in gross output also fulfill the following condition:

$$\sum_{i=1}^{n} \delta_i^x = \delta_k^x + \sum_{i \neq k} \left(-\delta_k^x \cdot \frac{x_i}{\sum_{j \neq k} x_j} \right) = \delta_k^x - \delta_k^x \cdot \left(\frac{\sum_{i \neq k} x_i}{\sum_{j \neq k} x_j} \right) = 0. \tag{14}$$

Hence, the restricted output induced multiplier reads as:

$$\hat{\mu}_k^x(\delta_k^x) = \mu_k^x(\delta_k^x) + \sum_{i=1}^{n} \sum_{j \neq k} \delta_i^x \cdot (1 - a_{ij}). \tag{15}$$

For the case of the supply-induced resilience index, given a negative shock δ_k^x find the re-scaling value ρ_k^x that solves the LP problem:

$$\text{Min } \rho_k^x \text{ subject to}$$

$$\begin{cases} \tilde{x}_i = x_i + \tilde{\delta}_i^x \\ \tilde{y}_i = \tilde{x}_i - \sum_{j=1}^{n} a_{ij} \cdot \tilde{x}_j \\ \sum_{i=1}^{n} y_i = \sum_{i=1}^{n} v_i \cdot x_i \leq \sum_{i=1}^{n} v_i \cdot \tilde{x}_i = \sum_{i=1}^{n} \tilde{y}_i \\ \tilde{\delta}_i^x = \delta_k^x \text{ if } i = k \text{ and } \tilde{\delta}_i^x = \rho_k^x \cdot -\delta_k^x \cdot \frac{x_i}{\sum_{j \neq k} x_j} \text{ if } i \neq k \end{cases} . \tag{16}$$

Therefore, similarly to the interpretation of the net demand resilience coefficient, the most resilient industry sector from a supply side perspective would be then the one that presents the highest positive net supply resilience coefficient $1 - \rho_k^x$.

Appendix B

See Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20.

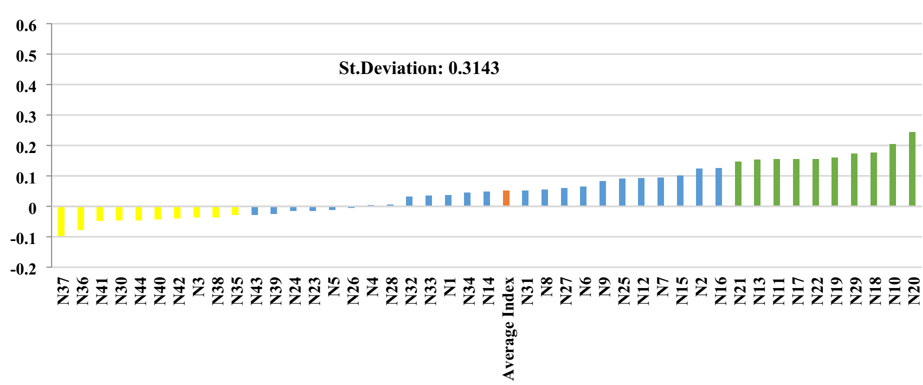

Fig. 1 Net demand resilience coefficient. Domestic I-O Table Australia. 2018

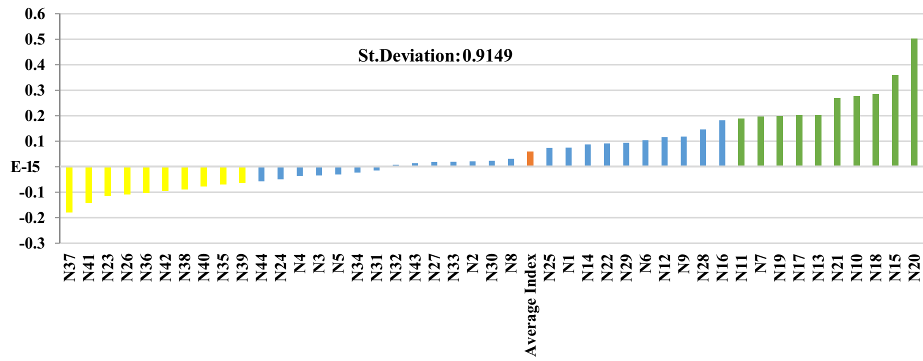

Fig. 2 Net demand resilience coefficient. Domestic I-O Table Canada. 2018

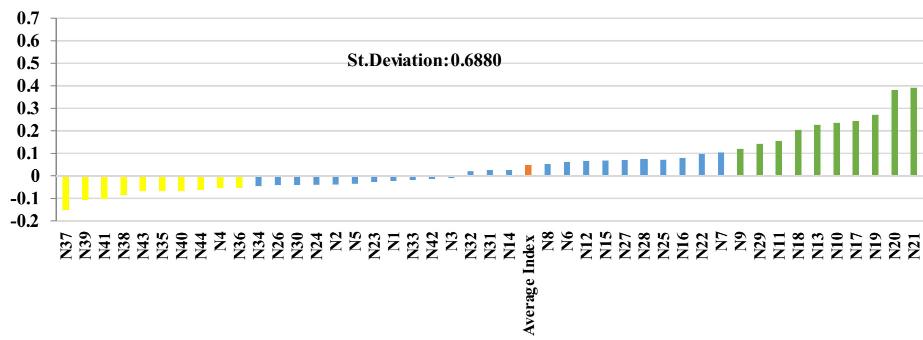

Fig. 3 Net demand resilience coefficient. Domestic I-O Table Colombia. 2018

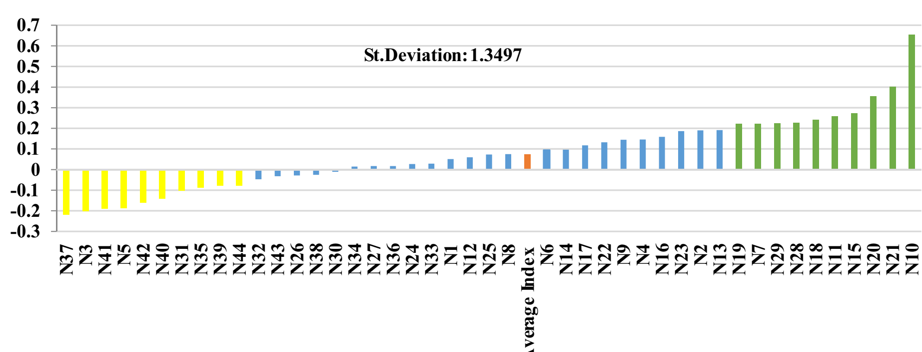

Fig. 4 Net demand resilience coefficient. Domestic I-O Table France. 2018

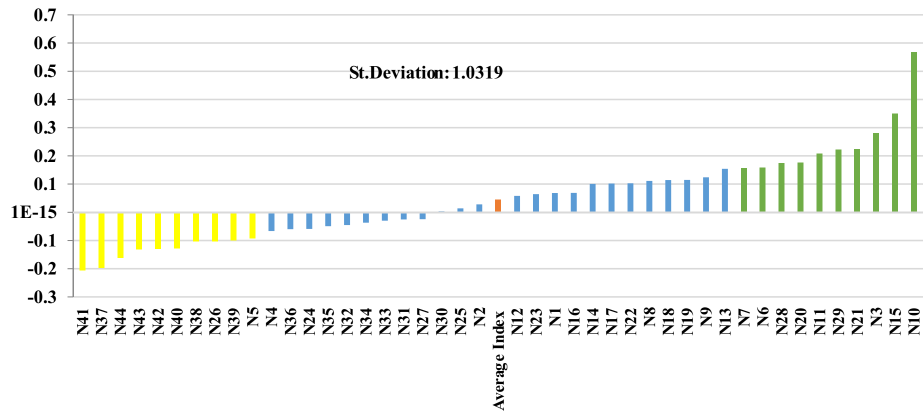

Fig. 5 Net demand resilience coefficient. Domestic I-O Table Germany. 2018

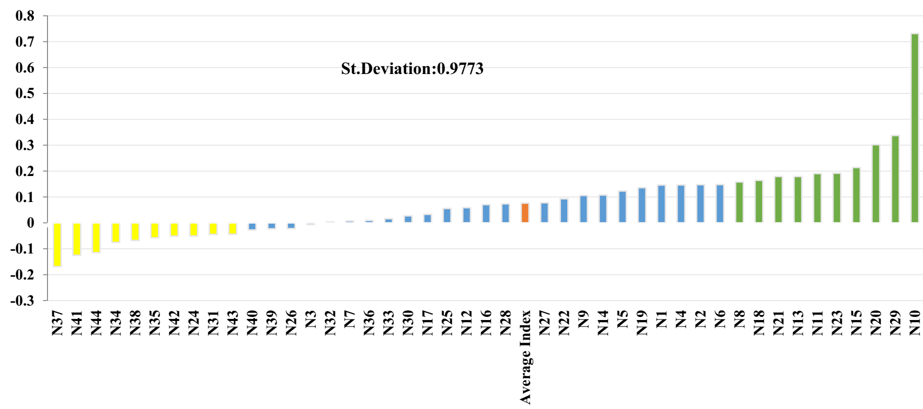

Fig. 6 Resilience coefficient in absolute values. Domestic I-O Table United Kingdom. 2018

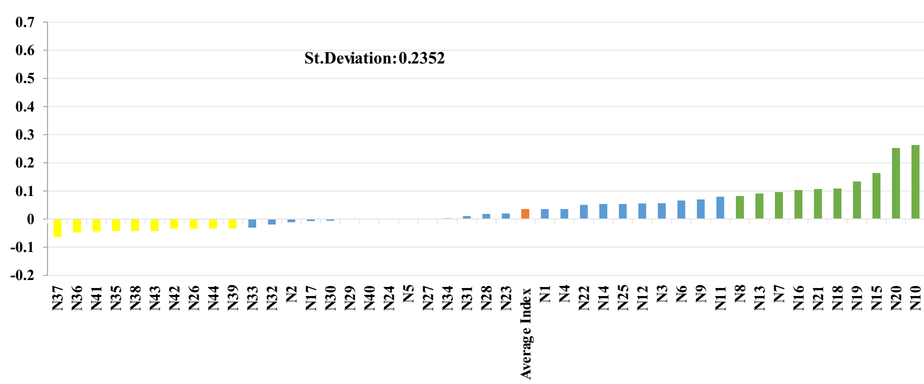

Fig. 7 Net demand resilience coefficient. Domestic I-O Table United States. 2018

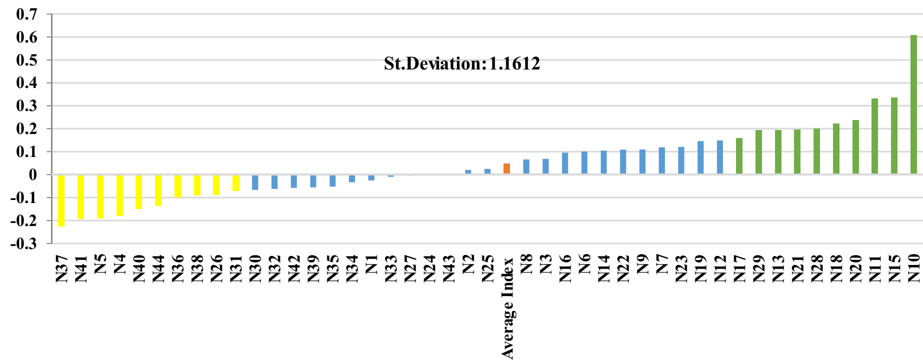

Fig. 8 Net demand resilience coefficient. Domestic I-O Table Italy 2018

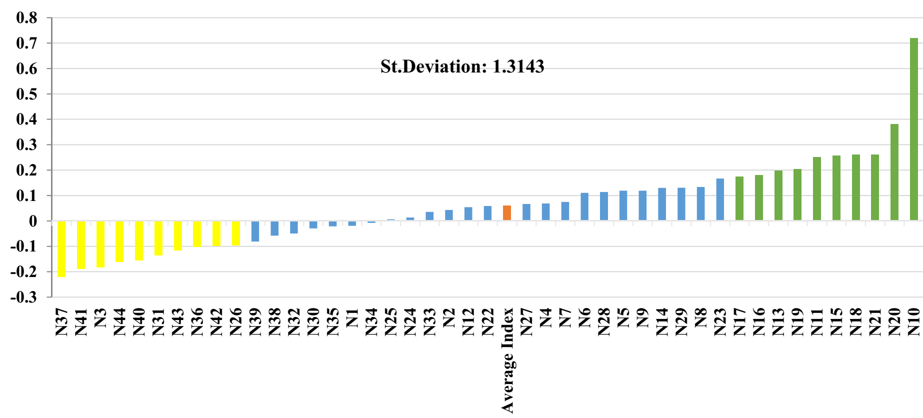

Fig. 9 Net demand resilience coefficient. Domestic I-O Table Spain. 2018

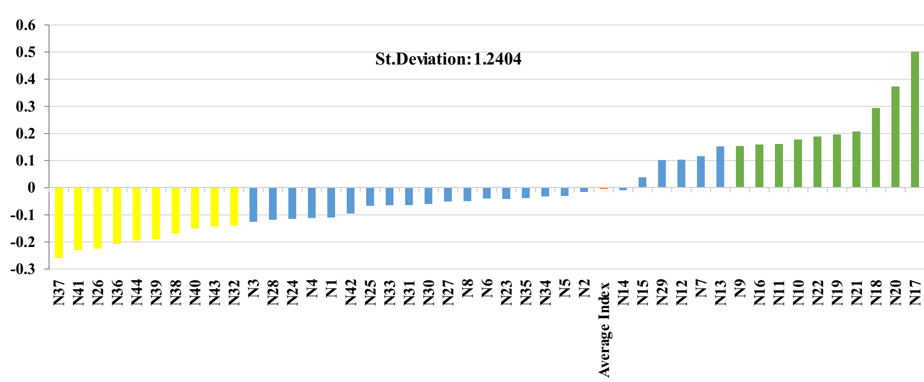

Fig. 10 Net demand resilience coefficient. Domestic I-O Table Table Mexico. 2018

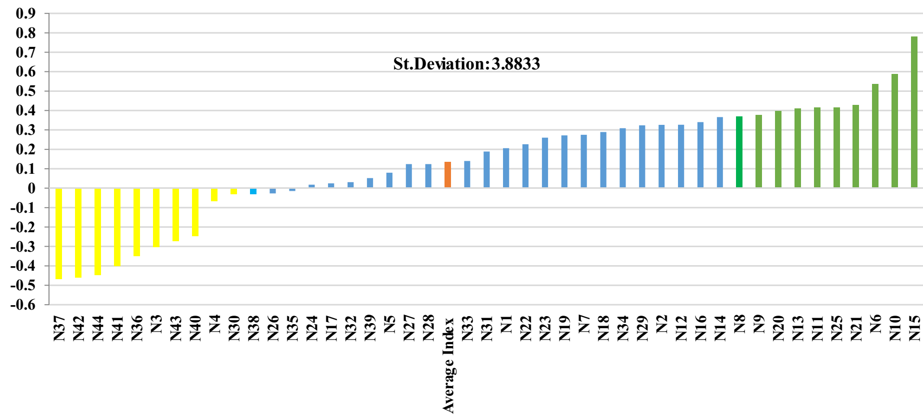

Fig. 11 Net supply resilience coefficient. Domestic I-O Table Australia. 2018

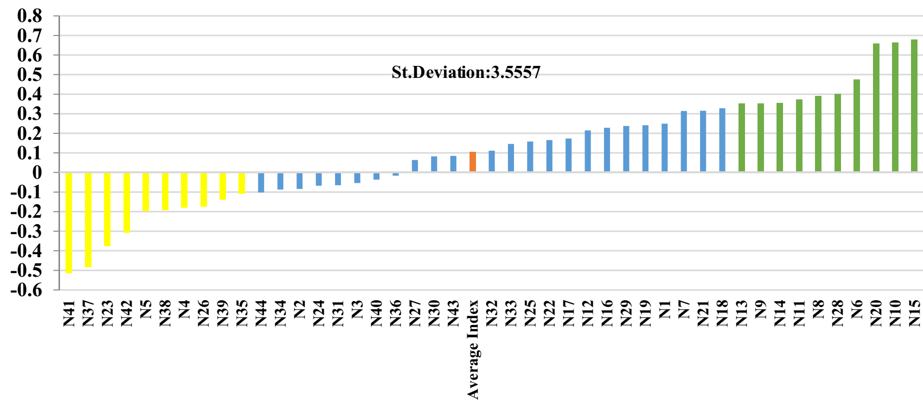

Fig. 12 Net supply resilience coefficient. Domestic I-O Table Canada. 2018

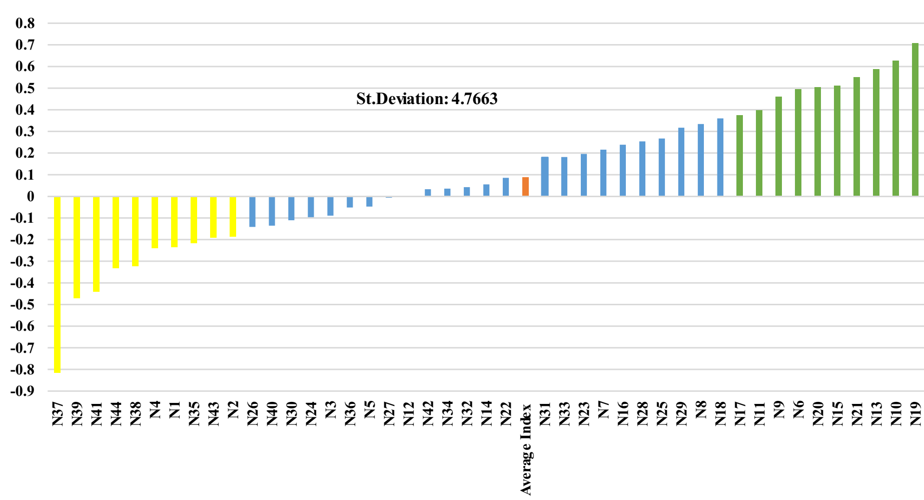

Fig. 13 Net supply resilience coefficient. Domestic I-O Table Colombia. 2018

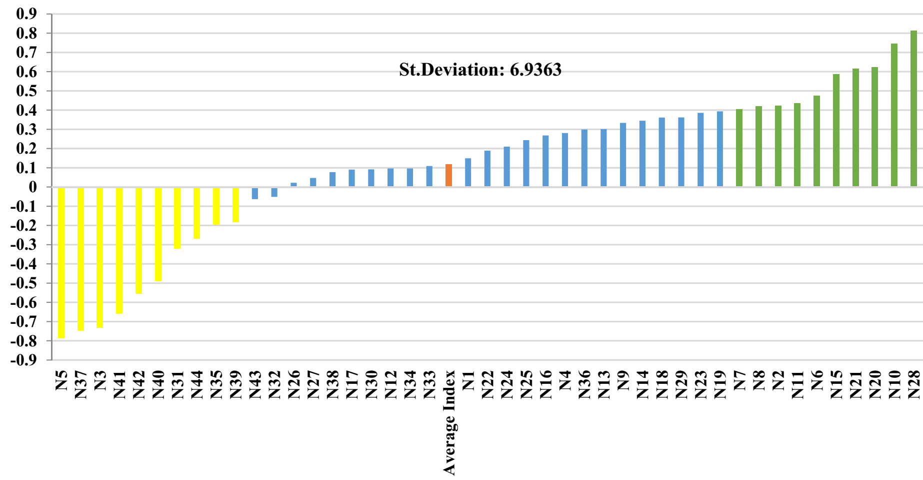

Fig. 14 Net supply resilience coefficient. Domestic I-O Table France. 2018

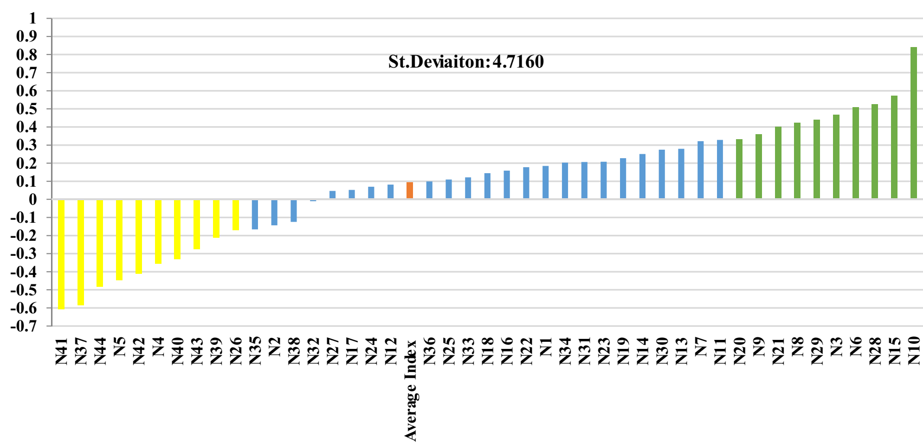

Fig. 15 Net supply coefficient. Domestic I-O Table Germany. 2018

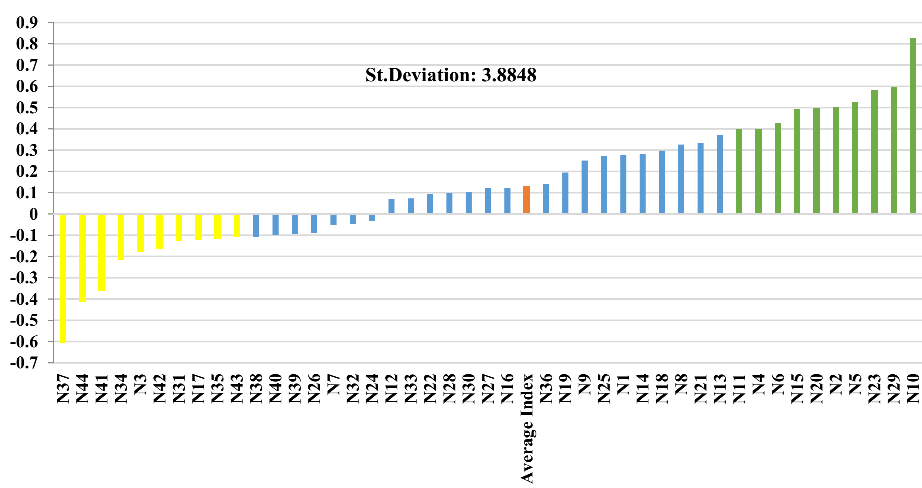

Fig. 16 Net supply resilience coefficient. Domestic I-O Table United Kingdom. 2018

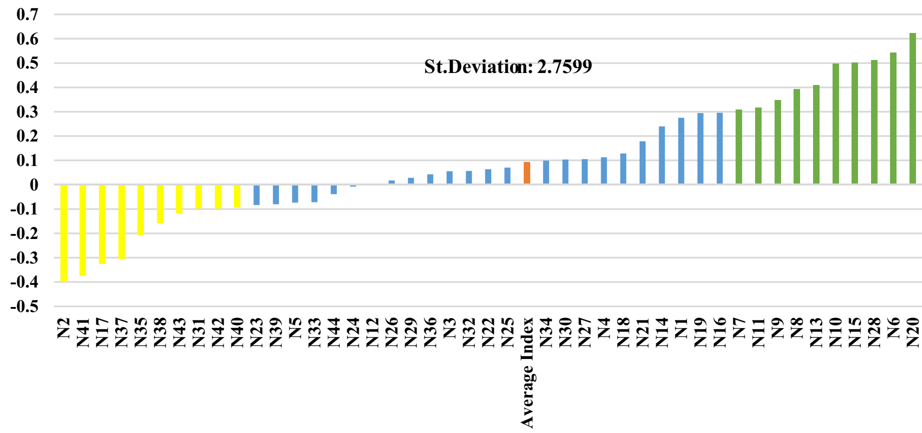

Fig. 17 Net supply resilience coefficient. Domestic I-O Table United States 2018

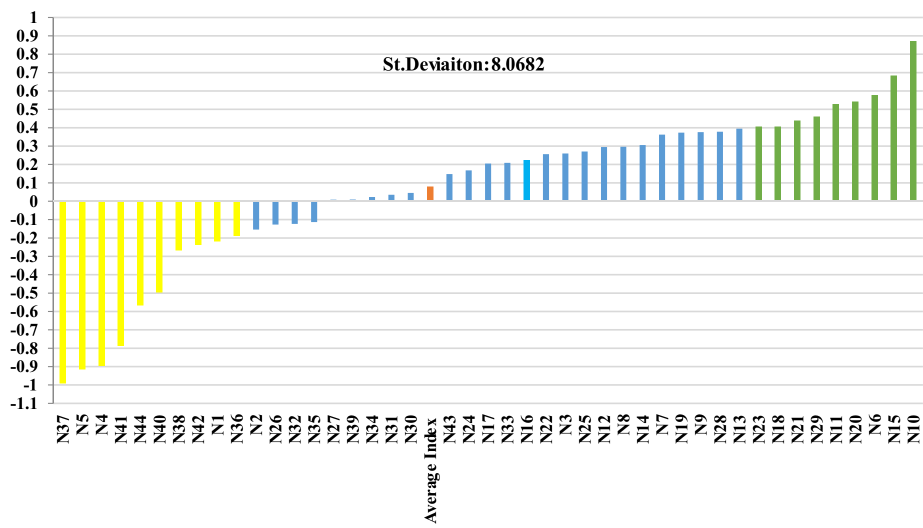

Fig. 18 Net supply resilience coefficient. Domestic I-O Table Italy. 2018

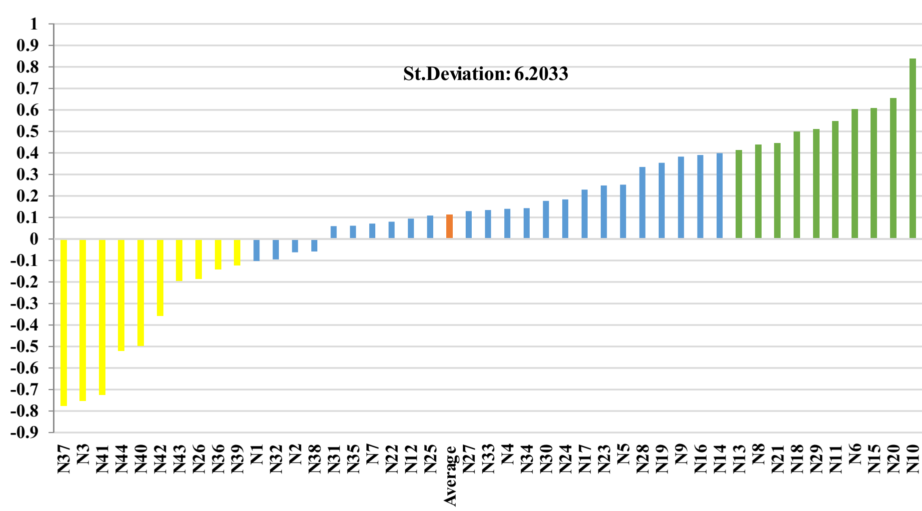

Fig. 19 Net supply resilience coefficient. Domestic I-O Table Spain. 2018

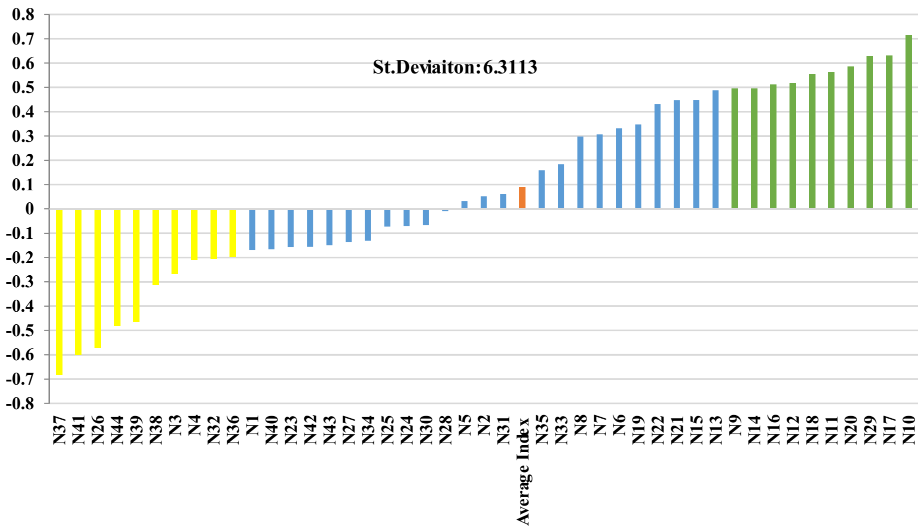

Fig. 20 Net supply resilience coefficient. Domestic I-O Table Mexico. 2018

Appendix C

See Tables 7, 8

Table 7 Industry classification OECD input–output tables

Industry-code	ISIC 4 division	Industry description
N_1	01, 02	Agriculture, hunting, forestry
N_2	3	Fishing and aquaculture
N_3	05, 06	Mining and quarrying, energy producing products
N_4	07, 08	Mining and quarrying, non-energy producing products
N_5	9	Mining support service activities
N_6	10, 11, 12	Food products, beverages and tobacco
N_7	13, 14, 15	Textiles, textile products, leather and footwear
N_8	16	Wood and products of wood and cork
N_9	17, 18	Paper products and printing
N_10	19	Coke and refined petroleum products
N_11	20	Chemical and chemical products
N_12	21	Pharmaceuticals, medicinal chemical and botanical products
N_13	22	Rubber and plastics products
N_14	23	Other non-metallic mineral products
N_15	24	Basic metals
N_16	25	Fabricated metal products
N_17	26	Computer, electronic and optical equipment
N_18	27	Electrical equipment
N_19	28	Machinery and equipment, nec
N_20	29	Motor vehicles, trailers and semi-trailers
N_21	30	Other transport equipment
N_22	31, 32, 33	Manufacturing nec; repair and installation of machinery and equipment
N_23	35	Electricity, gas, steam and air conditioning supply
N_24	36, 37, 38, 39	Water supply; sewerage, waste management and remediation activities
N_25	41, 42, 43	Construction
N_26	45, 46, 47	Wholesale and retail trade; repair of motor vehicles
N_27	49	Land transport and transport via pipelines
N_28	50	Water transport
N_29	51	Air transport
N_30	52	Warehousing and support activities for transportation
N_31	53	Postal and courier activities
N_32	55, 56	Accommodation and food service activities
N_33	58, 59, 60	Publishing, audiovisual and broadcasting activities
N_34	61	Telecommunications
N_35	62, 63	IT and other information services
N_36	64, 65, 66	Financial and insurance activities
N_37	68	Real estate activities
N_38	69 to 75	Professional, scientific and technical activities
N_39	77 to 82	Administrative and support services
N_40	84	Public administration and defense; compulsory social security
N_41	85	Education
N_42	86, 87, 88	Human health and social work activities
N_43	90, 91, 92, 93	Arts, entertainment and recreation
N_44	94, 95, 96, 97, 98	Other services activities, activities of households as employers; undifferentiated goods and services production activities of households for own use

Table 8 OECD country classification

Country ISO 3166–1 alfa-3 code	Country name
AUS	Australia Canad
CAN	Canada
COL	Colombia
FRA	France
GER	Germany
UK	United Kingdom
USA	United States
ITA SPA	Italy
SPA	Spain
MEX	Mexico

Acknowledgements
Earlier versions of this paper were presented at the first Workshop on Environmental Economics and Policy in Granada, Spain, and at the 29th International I-O Conference in Alguer, Italy. We appreciate the comments and suggestions from the participants of these events. Additionally, we extend our gratitude to two anonymous referees for their valuable feedback.

Author contributions
BA: literature review, empirical background, and results assessments. FS: language review, theoretical background, and methodology. AIG: methodology, programming, calibration and data compilation and calculations.

Funding
The second and third authors gratefully acknowledge the support from grant PID2020-116771 GB-100 funded by MCIN/AEI/10..13039/501100011033. The first and second authors also thank the financial support of the Junta de Andalucía (PAIDI 2020, Grant number P20.00691) and the Programa Operativo FEDER de Andalucía 2014–2020 (Grant number B-SEJ-544-UGR20). The third author also thanks the support of the Severo Ochoa Program for Centres of Excellence in R&D grant CEX2019-00915-S to the Barcelona School of Economics.

Availability of data and materials
The datasets generated and/or analyzed during the current study are available in the following link: https://stats.oecd.org/Index.aspx?DataSetCode=IOTS_2021

Declarations

Competing interests
The authors declare no potential competing interests.

Received: 16 August 2023 Revised: 17 November 2023 Accepted: 21 February 2024
Published online: 26 March 2024

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