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DIFFERENT APPROACHES TO MODEL ECONOMIC DIMENSION OF COMMUNITY RESILIENCE

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ABSTRACT

Earthquakes and extreme events in general cause direct and indirect economic effects on every major economic sector of a given community. These effects have grown in the last years due to the increasing interdependency of the infrastructures and make the community more vulnerable to natural and human-induced disruptive events. Therefore, there is need for metrics and models which are able to describe economic resilience, defined as the ability of a community affected by a disaster to resist at the shock and bounce back to the economy in normal operating conditions. Several attempts have been made in the past to achieve a better measurement and representation of the economic resilience and to find suitable metrics to help decision planning. The most popular methodologies are based on Computable General Equilibrium models (CGE) and Inoperability Input-Output models (IIM). In this study, we analyze these methods, showing advantages and limitations. Finally, a new method is proposed to evaluate economic resilience which is based on equilibrium growth models and compared with other approaches.

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Different Approaches To Model Economic Dimension Of Community Resilience

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ABSTRACT

Earthquakes and extreme events in general cause direct and indirect economic effects on every major economic sector of a given community. These effects have grown in the last years due to the increasing interdependency of the infrastructures and make the community more vulnerable to natural and human-induced disruptive events. Therefore, there is need for metrics and models which are able to describe economic resilience, defined as the ability of a community affected by a disaster to resist at the shock and bounce back to the economy in normal operating conditions. Several attempts have been made in the past to achieve a better measurement and representation of the economic resilience and to find suitable metrics to help decision planning. The most popular methodologies are based on Computable General Equilibrium models (CGE) and Inoperability Input-Output models (IIM). In this study, we analyze these methods, showing advantages and limitations. Finally, a new method is proposed to evaluate economic resilience which is based on equilibrium growth models and compared with other approaches.

Introduction

Resilience, according to the current literature, is defined as the ability of systems to rebound after severe disturbances, disasters, or other forms of extreme events. As suggested by the work of Renschler et al. [1] seven dimensions of the resilience problem summarized within the acronym PEOPLES can be identified. In his framework, the performance indices are integrated over space and time in a landscape setting. Among these dimensions, the economic one is certainly one of the most controversial. In fact the economic aspect has been often not taken in account in the recent studies which have focused mainly in the actual applications and quantification of the other dimensions [2][3][4][5]. However, the possibility to measure the economic resilience of a community after a disaster is increasingly being seen as a crucial step towards disaster risk reduction. Recent studies focusing on the economic resilience measurement and decision planning after natural/manmade disasters mainly use two approaches: *Inoperability Input-Output models (IIM)* [6] and *Computable General Equilibrium models (CGE)* [7]. These models are able to describe the behavioral response to input shortages and changing market conditions by computing the overall changes in economic variables across sectors, and compare the changes with the economy in normal operating conditions. Both models share many common features of the classical *Leontief Input-Output Models* but they differ in some properties and characteristics.

The *IIM* models have been formulated by Haimes and Jiang (2001) to analyze the

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behavior of interconnected systems and was then expanded by Santos and Haimes (2004) [8] to model the demand reduction due to the terrorism threat of interconnected infrastructures. Later Lian and Haimes (2006) [9] have focused on the risk of terrorism through the dynamic IIM. More recently Pant et al. (2011) [10] have focused on the interdependent impacts at multimodal transportation container terminals, and offer an overview on the metrics suited to decision support [11]. They also developed a specific approach (2013) [12] for the evaluation of quantitative resilience metrics accounting for interdependencies among multiple infrastructures.

They belong to the second group of models the work by Konovalchuk [13] which developed a CGE model to analyze the economic effects of the Chernobyl nuclear disaster. Boisvert et al. [14] depicted the macroeconomic costs of the foot-and-mouth disease in the United States. Rose and Liao (2005) described a CGE methodology able to consider one of the few advantages of I-O over CGE that is the clear distinction between direct and indirect impacts. However, as stated in the work of Benjamin H. Mitra-Kahn [15] the CGE models can be a very useful policy tool, only for understanding static fixed output models, because they are not built for dynamic analyses. Resilience is a static but also a dynamic process, as affirmed, for example, by Rutter [16] in the Social field, by Stokols[17] in the Ecological field and by Rose[19] in the Economic field. Based on the considerations above, a new methodology for measuring economic resilience based on the *Structural Dynamic Growth model* described by Li [18] is presented and adapted to evaluate the economic resilience index, using the procedure described by Cimellaro et al. [20][21] where the restoration curves are the activity/output curves provided by the model.

The paper describes and compares the three approaches to evaluate economic resilience showing the advantages and limitations within the resilience framework.

The Common Origin of IIM and CGE models

Wassily Leontief [22] developed in 1966 the Input-Output model, a quantitative economic model that was capable of describing the interdependencies between systems of a national economy or different regional economies. However, extended approaches have been formulated, starting from I-O Model, in order to address the estimation and planning of economic resilience. The most popular are IIM and CGE. While the first one is more suitable for decision planning, the other is advantageous in the evaluation of economic resilience.

The Inoperability Input-Output Model (IIM)

The assumptions on which the IIM is based are the same of the classical I-O model. Therefore, it is an equilibrium, time-invariant, deterministic and linear representation subjected to all limitations of classical Leontief's formulation. The IIM formulation derive from the metrics of *Inoperability q* given in Eq. (2), a vector where each component represents the ratio of production loss with respect to the usual production level of the industry and that well applies to represent resilience metrics, and demand perturbation d* given in Eq. (3), a vector expressed in terms of normalized degraded final demand. Using the symbolism of PEOPLES we can defined the metrics as follows:

$$\boldsymbol{q} = \left[\boldsymbol{diag}\left(\widehat{\boldsymbol{Q}}\right)\right]^{-1}\left(\widehat{\boldsymbol{Q}} - \widetilde{\boldsymbol{Q}}\right) \tag{2}$$

$$\boldsymbol{d}^{*} = \left[\boldsymbol{diag}\left(\widehat{\boldsymbol{Q}}\right)\right]^{-1}\left(\widehat{\boldsymbol{d}} - \widetilde{\boldsymbol{d}}\right) \tag{3}$$

where $\widehat{\boldsymbol{Q}}$ and $\widehat{\boldsymbol{d}}$ are the equilibrium functionality and demand levels respectively while $\widetilde{\boldsymbol{Q}}$ and $\widetilde{\boldsymbol{d}}$ are the respective disrupted equilibrium levels. Combining $\boldsymbol{q}$ and $\boldsymbol{d}^*$ Santos and Haimes obtained the IIM formulation in Eq. (4), that maintains a form similar to the Leontief I-O model, and that shows how *Inoperability* is driven by perturbations in demand.

$$\boldsymbol{q} = \boldsymbol{A}^*\boldsymbol{q} + \boldsymbol{d}^* \rightarrow \boldsymbol{q} = [\boldsymbol{I} - \boldsymbol{A}^*]^{-1}\, \boldsymbol{d}^* \tag{4}$$

where $\boldsymbol{A}^*$represents the normalized interdependency matrix that indicates the degree of coupling of the industry sectors. However, since resilience needs a dynamic formulation, a dynamic extension of the IIM (DIIM) developed by Lian and Haimes (2006) is considered. It is a first-order differential equation that incorporates a rate constant into the static IIM structure, and whose analytical equation is given in Eq. (5).

$$\boldsymbol{q}(\boldsymbol{t}) = \boldsymbol{e}^{-\boldsymbol{K}(\boldsymbol{I}-\boldsymbol{A}^*)\boldsymbol{t}}\boldsymbol{q}(\boldsymbol{0}) + \int_{\boldsymbol{0}}^{\boldsymbol{t}} \boldsymbol{e}^{-\boldsymbol{K}(\boldsymbol{I}-\boldsymbol{A}^*)(\boldsymbol{t}-\boldsymbol{z})}\boldsymbol{K}\boldsymbol{d}^*(\boldsymbol{z})\boldsymbol{dz} \tag{5}$$

where $\boldsymbol{K}$ is the rate term, a matrix with elements that represent the speed at which sectors attain particular responses to disruptions in outputs or change in demands.

Pant et al. (2013) made distinction between metrics able to describe static or dynamic economic resilience. However, in their definition the static resilience value corresponds to the avoided initial loss of functionality as shown in Fig. 1. The static resilience index although very useful it is not able to consider the recovery phase in its formulation therefore the focus has shifted toward the dynamic definition of economic resilience.

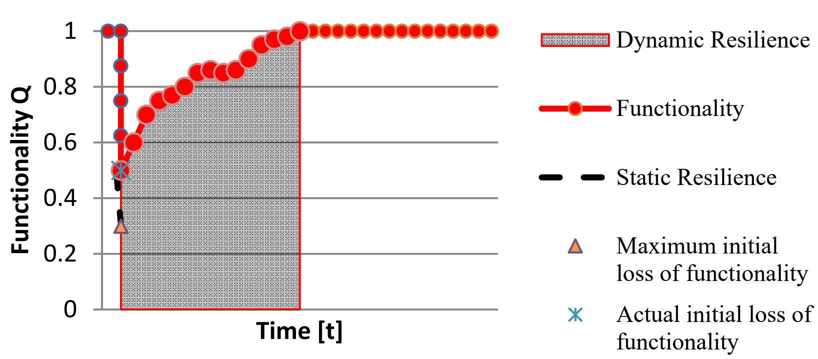


Figure 1. Comparison between static and dynamic resilience

The dynamic dimension of economic resilience can be evaluated using DIIM models. A decision space can be generated by varying the values of three resilience metrics that represent the matrix $\boldsymbol{K}$ and reflect investment options. These metrics are given in Eq. (6), Eq. (7), and Eq. (8) and are respectively: (i) *the time averaged level of operability* M_i which represents the overall level of functionality maintained by a system, (ii) *the maximum loss of sector functionality* q_i^m, and (iii) *the recovery time* τ_i which represents the time that the system implies to return to pre-disruption levels of functionality.

$$M_i = 1 - \frac{1}{T}\int_0^T q_i(t)dt \leftrightarrow \boldsymbol{M} = 1 - \frac{1}{T}\int_0^T \boldsymbol{q}(t)dt \tag{6}$$

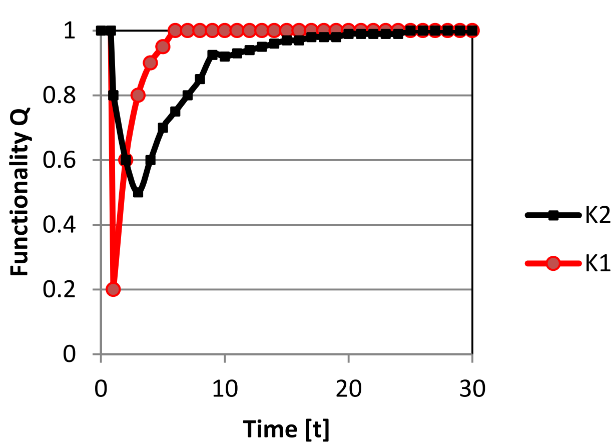
$$q_i^m = \max_{t\geq 0}[q_i(t)] \leftrightarrow \boldsymbol{q}^m = \max_{t\geq 0}[\boldsymbol{q}(t)] \tag{7}$$

$$\tau_i = \{t: t > 0, |q_i(t) - q^e{}_i(t)| \leq \varepsilon \ll 1\} \tag{8}$$

The division of the matrix $\boldsymbol{K}$ into the above metrics allow us to consider the multidimensional aspect of dynamic economic resilience, and in particular the trade-off that exists between the recovery time and the maximum loss of functionality, as shown in Fig. 2 where both lines represent the behave of the sector having no initial perturbation. The metrics are put in relation each other in Eq. (9) under specific assumptions [12]Considering that $\boldsymbol{\tau_i}$ is function of α_i a parameter which is a measure of interdependency [23] and introducing another constant $\tau_i\alpha_i = L_i$, the final dynamic decision space among F_i, q_i^m and τ_i is obtained in Eq. (10) after some mathematical manipulations.

$$\boldsymbol{M} = \mathbf{1} - \frac{\mathbf{1}}{\mathrm{T}}[\mathbf{1} - \mathbf{e}^{-\mathbf{K}[\mathbf{I}-\mathbf{A}^*]\tau}][\mathbf{K}(\mathbf{I} - \mathbf{A}^*)]^{-\mathbf{1}}\mathbf{q}^{\mathbf{m}} \tag{9}$$

$$M_i = 1 - \frac{1}{L_i T}[1 - \mathrm{e}^{-L_i}]\tau_i q_i{}^m \tag{10}$$



A*	
0.3	0.45
0.15	0.1

q(0)
0
0.5

K1	
1	0
0	1

K2	
0.4	0
0	0.4

Figure 2. Trade-off between time to recovery and maximum inoperability (adapted from Pant et al. [2013])

The equations generate a decision space through contour curves that can be used to estimate the system performance. Below is described how the method can be used as decision support tool. Considering that L_i is a measure of the amount of recovery and denoting with $r_i \in [0,1]$ the fraction of recovery from the observed maximum impact, L_i can be reformulated in Eq. (11).

$$L_i = \ln\left(\frac{q^m{}_i}{(1-r_i)q^m{}_i}\right) \tag{11}$$

Fig. 3 identifies the decision space of a representative economy where there are only two sectors. The contour curves are equal for both sectors obtained by assuming $r_i = 0.95$ in order to address the time when the system recovers the 95% of the experienced loss.

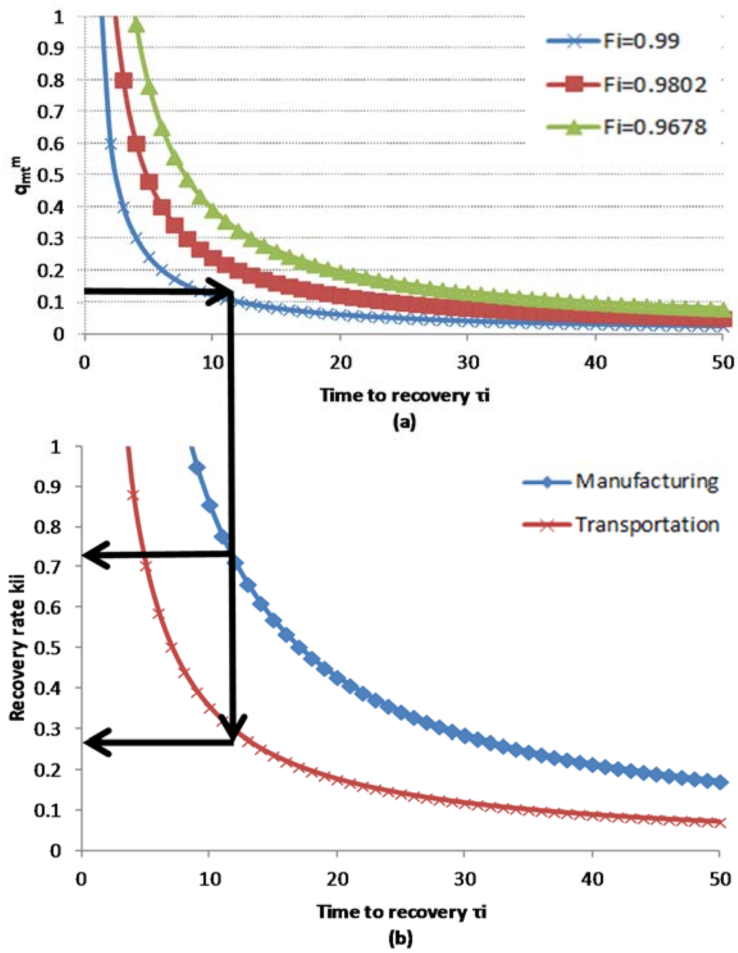


Figure 3 (a)Contour curves of decision space for dynamic economic resilience
(b)Relationship between time to recovery and recovery rate

Starting from the pair $(M_i, q^m{}_i)$ that indicates the desired level of overall operability during recovery, the recovery time is evaluated from Fig. 3a. Combining α_i and $\tau_i\alpha_i = L_i$, we can graphically represent in Fig. 3b the relationship between the recovery rate and the recovery in Eq. (12). Entering in Fig. 3b with the evaluated recovery time, the recovery rate can be estimated and can be identified the sectors that need to more investments to maintain a similar level of functionality compared to the others

$$k_{ii} = \frac{L_i}{\tau_i\left(1-\sum_{j=1}^{n} \alpha^*{}_{ij}\right)} \tag{12}$$

Computable General Equilibrium Models

CGE (i) are (usually) based on a system of non-linear equations and are more suitable to represent international and interregional competition with respect to I-O. On the other hand, they have a thin empirical base so often modelers are forced to make heroic assumptions regarding, production structure, and household behavior. The CGE set of equations adopted for the analysis of economic resilience must satisfy specific conditions as: market clearance of commodity, market clearance of factor, zero-profit and income balance. In particular, the algebraic framework can be derived distinguishing between consumers (households) and industry sectors (producers). The problem of households is to maximize their utilities subject to the constraints of their incomes, while the problem of industries is to maximize the profit subject to the constraint of the production technology. These problems are solved by using the Lagrangian equations for the household's utility and for the producer's profit, that are shown respectively in Eq. (13), and Eq. (14) for a Cobb-Douglas economy.

$$\mathcal{L}^C = p_U U - \sum_{i=1}^{N} p_i c_i + \lambda^C \left(U - A_C \coprod_{i=1}^{N} c_i^{\alpha_i} \right) \tag{13}$$

$$\mathcal{L}_j^P = p_j y_j - \sum_{i=1}^{N} p_i x_{ij} - \sum_{f=1}^{F} w_f \nu_{fj} + \lambda_j^P \left(y_j - A_j \prod_{i=1}^{N} x_{ij}^{\beta_{ij}} \prod_{f=1}^{F} \nu_{fi}^{\gamma_{fi}} \right) \tag{14}$$

where: N and F are the types of commodities and primary factors respectively; U is an utility good generated by consumption; p_U, p_i, p_j, and w_f are respectively the prices of the utility good, the intermediate goods, the outputs, and the primary factors, A_C and A_j are scaling parameters; x_{ij} and ν_{fj} are respectively the amount of intermediate good i and the amount of primary factor f for the j^{th} firm; c_i and y_j are the consumption of the commodity i and the output of the j^{th} firm; α_i are the shares of each good in expenditure on consumption while β_{ij} and γ_{fi} are the shares of each input in the cost of production.

From Eq. (13) and Eq. (14), Wing [24] demonstrated how we can infer (i) the representative consumer's demand function for the consumption of the *i*th commodity, (ii) the producer *j*'s demands for intermediate inputs of commodities, and (iii) the producer *j*'s demands for primary factor inputs. These demands are bound together by the economic assumptions of market clearance, zero-profit and income balance listed above, that once properly substituted yields two excess demand vectors that define the divergence Δ^C between supply and demand in the market for each commodity and the divergence Δ^F between supply and demand in the market for each primary factor, one excess profit vector Δ^π and one excess income vector Δ^m. The absolute values of both of these sets of differences are minimized to zero to reach the general equilibrium.

To address economic resilience estimation CGE models need to be calibrated considering data representing a benchmark economy. These data are usually taken from the SAM matrices [26] that are related to the mentioned I-O matrices. The most acknowledged methodology to compute regional economic resiliency to earthquakes or manmade disasters with CGE is the one introduced by Rose & Liao (2005), an approach able to consider one of the few advantages of I-O over CGE, that is the clear distinction between direct and indirect impacts.

The approach uses a multilayered CES (constant elasticity of substitution) production function for each sector. The initial values of the elasticities of substitution that represent how is easy is to substitute one input for the other are based on a careful synthesis of the literature. Each sectoral production function is extracted and the elasticities of substitutions are recalibrated with a numerical solution in order to match losses found by empirical estimate. Thereafter the recalibrated sectoral production functions are reinsert into the CGE model, the input supply is reduced to a level consistent with empirical estimates the total regional losses computed. Finally, subtracting direct losses from total losses the indirect losses are defined. The outcome is a measure of resilience through two indices called DRER and TRER (Direct/Total Regional Economic Resilience), given in Eq. (15), and Eq. (16).

$$DRER = \frac{\%\Delta DQ^m - \%\Delta DQ}{\%\Delta DQ^m} \quad (15)$$

$$TRER = \frac{\%\Delta TQ^m - \%\Delta TQ}{\%\Delta TQ^m} \quad (16)$$

where $\%\Delta DQ^m$ and $\%\Delta TQ^m$ are the maximum percent change in direct and total output, while $\%\Delta DQ$ and $\%\Delta TQ$are the estimated percent change in direct and total output.

The Structural Dynamic Growth Model

Li (2010) developed the structural growth model from the classical growth framework. Even if it was conceived as a *growth model,* it can also be well used to compute *general equilibrium*. The model represents the production processes in the economy through two matrices: the input and the output coefficient matrices. For example, for the economy described in Eq. (17) the two matrices are given in Eq. (18), and Eq. (19).

$$\begin{cases} 280 \text{ quarters wheat} + 12 \text{ tons iron} \rightarrow 575 \text{ quarters wheat} \\ 120 \text{ quarters wheat} + 8 \text{ tons iron} \rightarrow 20 \qquad \text{tons iron} \end{cases} \quad (17)$$

$$\boldsymbol{A} = \begin{bmatrix} 56/115 & 6 \\ 12/575 & 2/5 \end{bmatrix} \quad (18)$$

$$\boldsymbol{B} = \boldsymbol{I} \quad (19)$$

where the i^{th} column in matrix $\boldsymbol{A}$ represents the standard input bundle of agent *i*. In the classical economic growth framework, the equilibrium price vectors and equilibrium output vectors are the left and right P-F eigenvectors of A. The Structural Dynamic Growth model tries to integrate the market mechanism into the classical growth model by embedding an exchange process in it which is represented by an exchange vector, in order to reach equilibrium.

Exchange Process

The exchange process considers the economy as a discrete-time dynamic system and supposes economic activities such as price adjustment, exchange and production occur in turn in each period. With reference to the previous economic system, **S** in Eq. (20) denote the (n x m) supply matrix, and **s** in Eq. (21) denote the supply vector in the initial period.

$$\boldsymbol{S} = \begin{bmatrix} 575 & 0 \\ 0 & 20 \end{bmatrix} \quad \boldsymbol{s} = \begin{bmatrix} 575 \\ 20 \end{bmatrix} \quad (20)$$

Let **z** denote the vector consisting of purchase amounts of m agents, and z is called the purchase vector or exchange vector (of standard input bundles), **Az** is called the sales vector of goods. It's possible to derive Eq. (21) where **ŝ** represent the diagonal matrix with the vector **s** as the main diagonal and **u** the n-dimensional sales rate vector indicating the sales rates of n goods.

$$\mathbf{u} \equiv \hat{s}^{-1}\mathbf{Az} \quad (21)$$

Under the given price vector **p**, the purchase and sales values of m agents are $\boldsymbol{p}'\boldsymbol{A}\hat{z}$ and

$\boldsymbol{p}'\hat{u}\boldsymbol{S}$ respectively. We suppose that the value of each agent purchases must be equal the value it sells, as in CGE income balance, so Eq. (22) is obtained.

$$\boldsymbol{p}'\boldsymbol{A}\hat{z} = \boldsymbol{p}'\hat{u}\boldsymbol{S} \equiv \boldsymbol{p}'\hat{s}^{-1}\widehat{\boldsymbol{A}\boldsymbol{z}}\boldsymbol{S} \tag{22}$$

When Eq. (23) holds and **S'A** is indecomposable it's there exists a unique normalized exchange vector, and the unique maximal exchange vector can be found by following steps, which stands for the outcome of the exchange process:

Step 1. Compute the matrix $\boldsymbol{p}'\hat{s}^{-1}\widehat{\boldsymbol{A}\boldsymbol{z}}\boldsymbol{S}$;
Step 2. Find the normalized right P-F eigenvector of **Z**, denoted by x;
Step 3. Find the minimal component of $\widehat{\boldsymbol{A}\mathbf{x}^{-1}}\boldsymbol{s}$, denoted by ξ;
Step 4. Compute the exchange vector $\boldsymbol{z} = \xi\boldsymbol{s}$.

So, it is assumed that the state of the economic system at a period *t* is represented by the variables $\boldsymbol{p}$(t)=price vector; $\boldsymbol{S}$(t) = supply matrix; $\boldsymbol{u}$(t)=sales rate vector; **z**(t)=exchange vector and production intensity vector; **Y**(t)=Output matrix. The market mechanism is embedded considering that in period t+1 the economy runs as in Eq. (23) until the time where the system reaches the equilibrium.

$$\begin{aligned} &- \quad \boldsymbol{p}(t+1) \ = \ P(\boldsymbol{p}(t), \boldsymbol{u}(t)) \\ &- \quad \boldsymbol{S}(t+1) \ = \ \boldsymbol{B}\widehat{\boldsymbol{z}(t)} + Q(\boldsymbol{e} - \widehat{\boldsymbol{u}(t)}\boldsymbol{S}(t)) \\ &- \quad (\boldsymbol{u}(t+1), \boldsymbol{z}(t+1)) = Z(\boldsymbol{A}, \boldsymbol{p}(t+1), \boldsymbol{S}(t+1)) \end{aligned} \tag{23}$$

where P represents price adjustment process, Q is the inventory depreciation function and stands for the depreciation process of inventories and Z is the exchange function depicted above.

Application of Structural Growth Model Models to Evaluate Economic Resilience

Starting from the I-O matrices representative of the economy in normal operating condition, a shock is applied to simulate to earthquakes or other disasters, modifying the exchange vector, which is the driver of the equilibrium process.

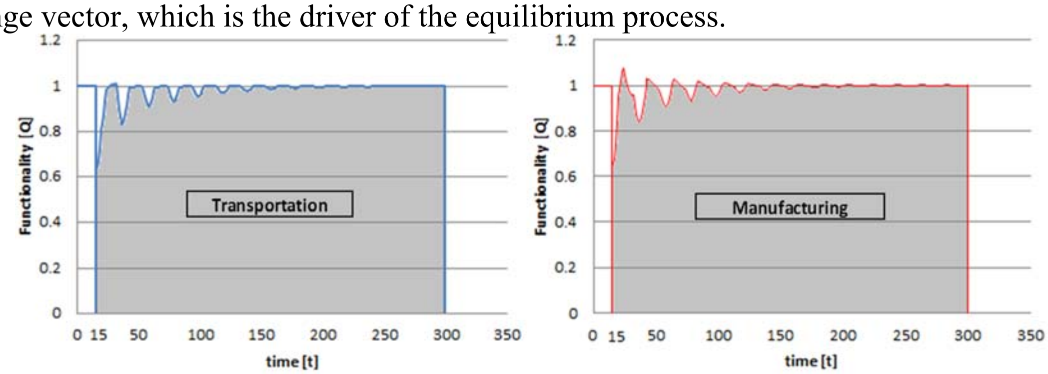


Figure 4. Restoration curves of the different economic sectors

After the application of the shock, from the restoration curves of the system obtained in Fig. 4, the values of the economic resilience of the system can be quantified using the estimation procedure explained by Cimellaro et al. [22] that describes resilience as "the normalized shaded area underneath the function describing the functionality of a system". The model is also useful because it incorporates a series of parameter that controls the converging speed in case of availability of after-disruption data. Table 1 represent the comparison between the results obtained using the static and dynamic resilience analysis with IIM with the results obtained using SGM for the same representative economy under two different scenarios: great demand disruption in manufacturing (A) and great demand disruption in transportation (B).

	SGM		IIM	
	A	B	A	B
Resilience transportation	0.96	0.87	0.99	0.87
Resilience manufacturing	0.97	0.90	0.94	0.92

Table 1. Outcomes of the IIM and SGM resilience approaches under two scenarios

The outcomes of the two methods are similar, and underline the necessity to protect the transportation sector respect to the manufacturing one, because of the lower resiliency value of the scenarios B. However, the SGM is able to identify a non-dimensional measure that captures the dynamic dimension of the resilience. On the other hand, the IIM can be used to well-address the comparison between different strategies as described above in its dynamic decision space, but it doesn't give as output a non-dimensional value for the economic resilience.

Conclusion

This paper summarizes and compares the methods adopted in modeling economic resilience. Two different approaches for the evaluation of the economic resilience have been described: the Inoperability Input-Output Model, and the CGE model. A new promising model, called the Structural Growth Model has been proposed to be used to evaluate the economic resilience index. Critical comparison among the models is presented and applied to a specific case study to highlight differences, advantages and limitations of all approaches.

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