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On input-output economic models in disaster impact assessment

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ABSTRACT

During the last decades, input-output (I/O) economic models have assumed a prominent role in disaster impact analysis and resilience assessment. Rooted in general equilibrium theory and economic production theory, they catalyse attention on the distinction between direct economic losses and ripple effects that may be generated inside a multi-industry system as a consequence of perturbations. Empowering the I/O analysis framework and overcoming some of its inherent limitations is crucial in order to successfully approach emerging disaster assessment challenges, such as multi-regional loss quantification and the investigation of shock responses in global supply chains. In this paper, we review and discuss how different disaster modeling aspects have been incorporated in recent contributions exploiting I/O techniques, taking into account both demand- and supply-sided perturbation triggers, static and dynamic representations, as well as the assessment of economic resilience.

1. Introduction

In [1], disaster has been defined as the set of *"consequences of a natural or man made hazard"*. Considering the multi-faceted nature of primary triggers and outcomes encompassed by this definition, today one of the core research areas in disaster analysis is related to the assessment of resulting spillover effects in networked systems and societies. A critical review of the nature of cascading disasters and their fallouts was proposed in [2], pointing out elements of interest such as *"interdependencies, vulnerability, amplification, secondary disasters and critical infrastructure"*. [3] introduces a magnitude scale for classifying incidents, disasters and catastrophic events. Dominoes are sometimes subtle to forecast and unexpected in magnitude and extent, when compared with causing factors. This is also the case as far as economic losses associated to disasters are concerned. In this domain, a quantitatively precise evaluation of indirect losses remains a challenge so far, considering the complexity of many economic environments, the diverse nature of disaster contingencies, data constraints (e.g. information availability, accuracy, resolution) and restrictions intrinsic to the analytic tools in use, which are often tailored to specific hazard types, geographical areas and/or historical moments.

In spite of that, economic theory has an ancient interest in the discipline of disaster impact assessment [4] and a number of principles have been determined towards sound economic loss estimation [5–10], whereas many aspects remain open for debate and further inquiry. For instance, [11] observes that even the way of counting economic losses over time has been addressed quite variably in the literature. Clearly, different analysis frameworks can be more or less adequate to assess disaster consequences at the micro-, meso-, and macroeconomic scale. At the same time, objectives in their application can include both an *ex post* loss quantification and an *ex ante* risk evaluation, which in turn modulates the validity and effectiveness of specific techniques.

Three dominant classes of economic models are mentioned in [12] and a handful of other references towards disaster loss analysis: simultaneous equation econometric models; input-output (I/O) models; computable general equilibrium (CGE) models. These families of methods are gaining interest in time as within modern, strongly intertwined economies, indirect losses may outclass direct ones. Analyses and evidences about this aspect have been recently provided for a series of highly-disruptive events in terms of disaster impact multipliers, see for instance [13,14] for discussion. An extended body of literature deals with comparative advantages and disadvantages of the three above-enumerated approaches in the context of disaster analysis [15,7]. Also, [16] adds to the comparison Social Accounting Matrix (SAM) methods, while [11] considers cost-benefit analysis.

Many recent contributions primarily focus on I/O and CGE techniques, which [17] qualifies as *"the most commonly used and well-documented approaches in disaster impact analysis"*. On one side, I/O models offer linearity as well as a neat way of outlining inter-industry linkages and demand structure, achieved by imposing specific structural constraints. On the other side, the CGE framework introduces higher flexibility and the possibility to represent a large spectrum of demand- and supply-side elasticities and behavioral responses, typically at the cost of more elaborated assumptions needed to describe the mutual adjustment

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of prices and quantities. In disaster analysis, I/O models are often regarded as overestimators of economic losses, while CGE models as underestimators [17,12]. As far as the analysis time horizon is concerned, I/O models are often preferred for short-horizon estimation, whilst CGE models for long-horizon estimation [17,18]. Besides, complexity considerations tend to promote the use of CGE on a narrower set of sectors than in the I/O case. See [19] for a review of CGE applications to the analysis of economic impacts of disasters and [20,21,15,4,22–24] for a broader comparison between the two approaches.

In this paper, we specifically focus on I/O techniques, which have been gaining attention as instruments for rapid assessment of the cascading economic effects of disasters. The representation of backward and forward linkages allowed by I/O models (see [25], Chapter 12) can serve towards the identification of key sectors, the appreciation of different sources of change and of the system's sensitivity, the comparison of economies. Moreover, the I/O approach has inherent affinities with methodologies for the analysis of cascading events from other domains, which facilitates their integration. As for the operational use of I/O technques, a set of useful observations can be found in Ref. [26], while [27] addresses the estimation of some catastrophe-relevant quantities such as production capacities.

In itself, the empirical construction of I/O datasets (e.g. product-by-product, industry-by-industry tables) underlying I/O models involves a number of different practices and procedures [28]. However, the exploitation of I/O approaches in disaster analysis is facilitated by the increasing availability of I/O databases [29], the support provided by statistical accounting frameworks such as the System of National Accounts [30–32][1], and the development of industry classification standards such as ISIC, JSIC, NACE, SIC and NAICS.[2] Some significant instances of publicly available I/O data sources are listed in Table 1. Observe that the data coverage today at disposal goes beyond the pure monetary accounting. An example is provided by the physical input-output tables, that constitute key instruments in enviromental-economic analysis [44–47]. Moreover, a number of initiatives are in place to collect information on disasters and associated losses, e.g. the OFDA/CRED International Disaster Database EM-DAT[3] [48].

The International Input-Output Association[4] (IIOA) manifests raising interest in the correlation of disaster impact analysis and I/O techniques, as well as in opportunities and solutions to address some of the shortcomings pointed out in the above-mentioned references. In the last years, two special issues of journal *Economic Systems Research* have been specifically devoted to this subject. Opening the first of them, dated 2007, [49] witnesses the emergence of integrative approaches, *"in which IO models are combined with engineering models and/or data, in order to estimate higher-order effects that are more sensitive to the changes in physical destruction"*. The author also acknowledges time horizons, geographical space and in-built counteractions among the current issues in I/O-based disaster analysis. Introducing the 2014 special issue, [1] expands over the latter reference by reflecting on the role of disaster impact analysis in terms of both post-hazard impact estimation and pre-hazard assessment. I/O methods are compared with CGE and SAM approaches. The difficulty of evaluating impacts in the long run is recognized. Finally, empirical data availability and reliability, modeling

Table 1
Examples of open data sources for supply-use/input-output tables.

Name	Source	Literature references
EORA-MRIO	http://worldmrio.com/	[33,34]
EU-Eurostat	http://ec.europa.eu/eurostat/web/esa-supply-use-input-tables	[35]
EXIOBASE	http://www.exiobase.eu	[36,37]
JP-IDE-JETRO	http://www.ide.go.jp/English/Data/Io	[38]
OECD-ICIO	http://www.oecd.org/sti/ind/inter-country-input-output-tables.htm	[39]
OECD-IOTs	http://www.oecd.org/trade/input-outputtables.htm	[40]
US-BEA	https://www.bea.gov/industry/io_annual.htm	[41]
WIOD	http://www.wiod.org/home	[42,43]

for decision making and impacts on economic structures are pointed out as key categories in current research on disaster impact analysis.

In continuity with these contributions, in this paper we aim at providing an overview and some discussion on the recent developments of I/O analysis techniques for the study of disaster repercussions on an economy, putting an emphasis on cascading effect modeling and resilience assessment. At the outset of our discussion, we will overview two core classes of I/O models developed in the literature, namely demand- and supply-driven formulations. While the first one starts from an exogenous assignment of demand and assumes fixed production functions characterized by constant proportions of inputs, in the second case supply is assigned together with fixed allocation functions.

The two approaches, jointly with their extensions, provide a reference frame for mapping a number of practically relevant disaster descriptors. A key aspect is the expression of exogenous perturbations in terms of either demand or supply shock. In addition to that, recent works highlighted further non marginal features of disaster analysis, including mixed impact localization, short- and long-term impact accounting issues, import/export re-balancing, substitution effects, capacity constraints, adaptation. Such a variety of aspects challenges traditional I/O formulations, and lately the scientific community has tackled the integration of some of these factors in a framework of one or the other type. Also, hybrid techniques have been proposed to combine demand- and supply-oriented approaches in addressing the peculiarities of disaster impact analysis.

Finally, some studies also delve into the notion of economic resilience and its relationships with the I/O formalism. The property, as outlined in recent literature, depends on structural factors as well as behavioral responses to critical events; it is affected by conjunctural circumstances; it can be sensitive to different drivers such as the action of a single regulator, a polycentric governance and the market. As such, it opens interesting research perspectives and challenges for the I/O modeling community.

2. Demand- and supply-driven I/O models

2.1. Demand-driven (Leontief) model

Based on general equilibrium theory, the standard I/O model proposed by Leontief [50] gained spread recognition as one of the cardinal contributions to the study of multi-sector economies, the latter being described in terms of the static balance between demand and supply at the level of both intermediate and final exchanges.

Considering a set of n single-commodity industries, the model construction starts from the definition of an *inter-industry transaction matrix* $Z = [z_{ij}] \in \mathbb{R}_{\geq 0}^{n \times n}$ where $z_{ij} = q_{ij} p_i$ specifies sales from sector i to sector j as a function of quantities q_{ij} and prices p_i at equilibrium. In addition to internal demand, each sector i is also subject to a final demand $f_i \geq 0$ by end consumers. Assuming perfect equilibrium between

[1] https://unstats.un.org/unsd/nationalaccount/.

[2] ISIC (International Standard Industrial Classification of All Economic Activities): https://unstats.un.org/unsd/cr/registry/isic-4.asp (rev. 4). JSIC (Japan Standard Industrial Classification): http://www.soumu.go.jp/english/dgpp_ss/seido/sangyo/index.htm. NACE (Nomenclature statistique des activités économiques dans la Communauté européenne): https://publications.europa.eu/en/publication-detail/-/publication/cefc43bb-b336-4ff2-ad71-a21e92cc7614/. SIC (Standard Industrial Classification): https://www.osha.gov/pls/imis/sic_manual.html. NAICS (North American Industry Classification System): https://www.census.gov/eos/www/naics/. Correspondence tables are available at http://ec.europa.eu/eurostat/ramon/relations/index.cfm.

[3] http://www.emdat.be.

[4] https://www.iioa.org.

demand and supply for each sector, we have the following balance equation, describing the distribution of each sector's output across the economy:

$$x = Z\mathbb{1}_n + f \tag{1}$$

where $x = [x_1, \ldots, x_n]'$ collects the total output $x_i > 0$ of each sector, $f = [f_1, \ldots, f_n]'$ and $\mathbb{1}_n$ is the all-ones column vector of size *n*. Equivalently, we can write

$$x = Ax + f \tag{2}$$

where $A = [a_{ij}] \in \mathbb{R}^{n\times n}_{\geq 0}$ is the *technical coefficients matrix*, with $a_{ij} = \frac{z_{ij}}{x_j}$ so that $A = Z\ diag(x)^{-1}$. Finally, assuming that $(I - A)$ is non-singular and introducing the *Leontief inverse* (or *total requirements matrix*) $L = (I - A)^{-1}$, we have the *standard demand-driven (Leontief quantity) I/O model*

$$x = Lf \tag{3}$$

The Hawkins-Simon theorem guarantees that there exists $x \geq 0$ such that $(I - A)x > 0$ if and only if all principal minors of $(I - A)$ are positive [51]. Observe that we can express the Leontief matrix as $L = \sum_{i=0}^{\infty} A^i$, where each term A^i captures dependencies at different levels of depth, starting from final demand and following internal demand-to-supply chains. A price model corresponding to quantity model (3) also exists [25].

Model (3) is linear and is referred to as open since, in its operational use, f is considered as a completely exogenous variable. Two significant aspects of the representation have to be considered, in particular:

- the model is *demand-driven*, since it leads to defining production levels needed for each industry through backward propagation from exogenously assigned values of final demand. It assumes infinite elasticity of supply with respect to demand, neglecting potential supply capacity constraints;
- the representation assumes *fixed technical (input) coefficients*, i.e. that each sector fulfils its productive task by exploiting inputs in fixed proportions. More specifically, see for instance [25], the production function inherent to the model can be expressed as

$$x_j = \min_{i\in\{1,\ldots,n\}} \left(\frac{z_{ij}}{a_{ij}}\right), \quad \forall\ j \in \{1, \ldots, n\} \tag{4}$$

and is based on an assumption of constant returns to scale. Most importantly, the latter formula embeds the concept of *irreplaceability* (or *non-substitution*), i.e. *"Leontief production functions require inputs in fixed proportions where a fixed amount of each input is required to produce one unit of output"* [25].

See also [7] for further discussion on limitations of the approach.

One of the key uses of the model is multiplier based analysis, whose objective is *"to assess the effect on an economy of changes in the elements that are exogenous to the model of that economy"* [25]. Anyhow, multiplier analysis has limitations in that a sector's importance to the economy is not necessarily pointed out comprehensively by the score of a given multiplier, and import/export may affect it considerably.

To conclude, observe that the I/O representation allows to incorporate empirical data specific to an economic area and its exchanges with other regions through import and export information. These features considerably contributed to the success of the I/O approach in the last decades.

2.2. Supply-driven (Ghosh) model

Developed on the basis of the Leontief multi-industry approach, the Ghosh model [52] introduces the concept of a supply-driven economy as a possible descriptor of productive systems dominated by scarce resources, central planning and monopolistic market structure. Starting from the same definition of matrix Z as in (1), the supply-demand equilibrium is now expressed in terms of equation

$$x' = \mathbb{1}'_n Z + v' \tag{5}$$

where $v = [v_1, \ldots, v_n]'$ specifies sectoral value-added. Through steps analogous to the case of the standard Leontief model, we then obtain

$$x' = x'E + v' \tag{6}$$

where $E = [e_{ij}] \in \mathbb{R}^{n\times n}_{\geq 0}$, $e_{ij} = \frac{z_{ij}}{x_i}$ is the *allocation coefficients matrix*. Assuming $(I - E)$ non-singular, we formulate the *standard supply-driven (Ghosh) model*

$$x' = v'H \tag{7}$$

where $H = (I - E)^{-1}$ is the *Ghosh inverse*. It has been observed that the presented Leontief and Ghosh models are not dual. In particular, they cannot generally be solved simultaneously, since f and v are both exogenous quantities [53,54].

Conversely to the case of the standard Leontief model, in (7)

- the formulation is *supply-driven*, i.e. it *"calculates changes in gross sectoral outputs for exogenously specified changes in the sectoral inputs of primary factors"* [55];
- in contrast to the production function approach inherent to the Leontief model, here an allocation function is implied instead, which assumes the form

$$x_i = \min_{j\in\{1,\ldots,n\}} \left(\frac{z_{ij}}{e_{ij}}\right), \quad \forall\ i \in \{1, \ldots, n\} \tag{8}$$

Therefore, the model has *fixed allocation (output) coefficients*, implying *"fixed output, or sales, distribution across sectors"* [56].

The rationale of such approach can be found observing that *"in a competitive market and with fairly plentiful resources, allocation functions will play a minor role and special conditions can be formulated under which production will determine the equilibrium. But in a monopolistic market with scarce resources, allocation functions will determine which of many alternative processes and combinations will be chosen by any particular industry; that is, production functions will play a minor role"* [57].

After its introduction, the Ghosh model underwent huge questioning as of its plausibility. Early criticism, in particular, disputed over the assumption of perfect demand elasticity to changes in supply and some improper handling of value-added terms, while alternative formulations were proposed as well [58]. Ref. [59] further criticizes the perfect input substitutability implied by the model, while it suggests the supply-driven formulation as reasonable in case of small perturbations. These aspects are taken into account in Ref. [60] to further endorse the implausibility argument. Work was done to validate the role of the Ghosh model in I/O analysis in its interpretation as a price model, with a corresponding quantity model [55]. See the latter reference and [25] for discussion on the relationships between quantity and price models of the two classes. In Ref. [61], a re-interpretation and extension of supply-based approaches suggests the joint usefulness of the two methodologies in order to tackle non-stationary conditions occurring in-between two successive market equilibria. Still, [62] questions various aspects of Ghosh's model and its overall interest. See [54] for a more extended account of recent debate on the topic of supply-driven I/O formulations.

2.3. Extensions

The elaborations proposed in the literature over the two standard frameworks presented above offer quite a vast landscape of options. Next we provide a short overview of some of the most important developments and pointers to related literature. See also [63] for a list of extensions and applications.

2.3.1. Closed models

In the standard Leontief model presented in Section 2.1, final demand represents an ‘exogenous sector’ with respect to the economy. However, the possibility to formulate a closed model has been explored, too. A typical way to perform this operation is based on taking into account the feedback effect introduced by households, considering their purchase power as a function of the amount of labor requested by the productive sector [25]. Closing the model can be considered, anyway, a subtle operation, since it requires cautious estimation of the characteristics of the mentioned feedback mechanism. Similar considerations hold also for the case of the Ghosh model. The possibility of higher plausibility has been identified for the Ghosh model in the closed version [64,65].

2.3.2. Dynamic formulations

While the standard Leontief model and the Ghosh model presented above are static representations, dynamic extensions have been introduced, as well. Focusing on the Leontief case, the base formulation was elaborated to take into account the connection between investments and output prices, leading to the idea of multi-sectoral balancing over time [66]. For instance, in the continuous time case, from representation (2) we can pass to the following dynamic model:

$$x(t) = A(t)x(t) + B(t)\dot{x}(t) + f(t) \tag{9}$$

where technical coefficients are expressed in $A(t)$ as a function of time and $B(t)$ is the (possibly singular) capital matrix function. Structural attributes of dynamic I/O models such as stability have been investigated extensively in the literature. See also [67] for a recent report on dynamic I/O analysis.

2.3.3. Other aspects

The two above-mentioned aspects are just some of the most relevant ones found in the literature. Among other notable variants, there are nonlinear I/O formulations taking into account the complexities of many real production processes [68–70], stochastic models [71], and multi-commodity-per-industry representations [72,25]. Generalized theories have also been laid down to bring together salient aspects of both demand- and supply-driven frameworks and overcome some of their limitations. For instance, this is the case of the mixed I/O model proposed in Ref. [30], which aims at taking into account supply constraints more extensively with respect to traditional Leontief techniques by exploiting the concept of purchasing coefficients. [73] observes the demand-sided nature of this type of model, which exploits a partitioning of supply into constrained and unconstrained sectors. See also [74] for some discussion.

3. Disaster representation in the I/O framework

As observed in Ref. [75], *“of the various applications of IO models, impact analysis is undoubtedly the most widely used”*. In this section, we will focus on some of the major aspects related to the representation of disasters and resulting economic impacts in the I/O framework. Our presentation builds on a developing corpus of literature devoted to both general principles and particular applications of disaster economics. This includes the already mentioned [7] and survey [76], which points out initial costs, and both short-and long-run growth effects among the main features of the problem. Some recent references in the field specifically address advantages and limitations of I/O-based disaster impact representations. An account is provided in [77] about indirect effects of critical events, not always adequately captured by some of the I/O techniques in use. These include: the forward propagation of supply perturbations; the different role and effects of replaceable and irreplaceable components, with potential substitution coefficients; the possible presence of both negative and positive economic impacts resulting from a critical event (e.g. reconstruction activities that may induce positive economic swing). See also [17,26] for further discussion on general equilibrium effects of perturbations and on I/O modeling limitations.

In continuity with the articulation of previous section into demand-driven and supply-driven I/O approaches, here we will especially discuss the interpretation of disasters in terms of perturbations to demand, supply or their ensemble. Furthermore, we will concisely address other aspects of I/O based disaster representation that have attracted interest in the literature, notably the unfolding of cascading effects in time and space and the treatment of non-market and behavioral effects. This will set the ground for our review of recent I/O disaster analysis methods, which often try to overcome some of the key limitations seen in traditional I/O modeling assumptions and practices.

3.1. Equilibrium modeling and disaster-induced imbalances

A major point of debate is related to the adequacy of the I/O framework and other equilibrium representations to assess the inherently disequilibrium economic setting that can be induced by a large disaster [78]. An aspect of interest concerns, in particular, the relationships between post-disaster economic actions and economic growth. Criticism has been raised in the literature against the traditional Von Newmann growth theory assertions that separate the two moments consisting in post-disaster return to equilibrium and subsequent normal growth [79,22]. In particular, the latter reference, aside from observing the incorrectness of separation in practical cases, claims potential interaction also in the pre-event phases, as the risk of future shocks may influence pre-crisis growth patterns, as well.

The plausibility that adverse events may have negligible macroeconomic impacts or trigger positive economic counter effects is also under theoretical and empirical investigation. [80] refers to the possibility that disasters of even consistent magnitude may lead to minor macroeconomic consequences. In Ref. [81], technological development speed-up following crisis is considered, together with the potential that it may induce long-run growth of the economy. [82] sets on scale the building-back-better opportunities and poverty traps that may emerge, for instance, from the handling of the post-disaster decisions and the availability of spare production capacity. Additionally, with respect to long-run losses stemming from natural disasters, [83] refers to the concept of *creative destruction*. Finally, some studies have statistically investigated the plausibility issue by mining disaster databases such as EM-DAT and relating the resulting losses to different economic indicators [84,85].

3.2. Direct/indirect and stock/flow losses, double counting

In the literature, we find different definitions of direct/indirect losses and stock/flow losses. For instance, in Ref. [17] direct losses are associated to stock input losses and indirect losses to flow output losses, wherein *“stock input losses refer to material damages and include the existing level of capital, facilities, and inventories”*, while *“flow output losses refer to outputs and services of stocks over time”*. In Ref. [7], *“stocks refer to a quantity at a single point in time”* and *“flows refer to the services or outputs of stocks over time”*. On the other side, *“direct flow losses pertain to production in businesses damaged by the hazard itself”*, whereas a terminological improvement is proposed to overcome the ambiguity in qualifying *“indirect effects”* as either *“all economic impacts beyond direct (including intangibles)”* or, according to I/O parlance, *“interactions between businesses”* alone. See also [74] for further discussion.

Related to the distinctions made above is the issue of double counting of losses [86]. For instance, [82] emphasizes the importance of evaluating indirect costs in terms of value added. [87] warns against the issue of double-counting in exogeneization procedures. Furthermore, [7] argues that damages should not be included in the estimation of losses. As observed in latter reference (see also [88]), a correct interpretation of stock and flow losses should lead to avoid double counting issues deriving from simply computing the total impact as the sum of those belonging to the two types. Moreover, flow losses should be further articulated into those components directly deriving from stock losses and those induced by linkages.

3.3. Shock types

Loss assessment in the I/O disaster analysis literature tends to polarize around the two aspects of shock impact localisation and propagation paths. The first, typically associated to the assignment of exogenous variables (demand-, supply- or mixed-type), is discussed next. The second, mediated by the structure of I/O tables used for analysis and by other factors such as time and space, will be scrutinized in the next subsection.

Demand-side perturbation. In continuity with the demand-driven nature of the standard Leontief model, a large portion of the literature on I/O-based disaster impact analysis concentrates on demand perturbations, which finds justification in a number of applications. In Ref. [89], for instance, consumption alteration is qualified as a consequence of *"security concerns of the general public"*, such as in the case of a terrorist event. A topic of debate in the scientific community is related to the issue of persistence of demand-side perturbations depending on the type of triggering circumstance. The relevance of this aspect is corroborated when considering that demand shock may introduce demand redirection, as well [90]. The estimation of impacts of demand perturbation through demand-driven models is not free from risks. As observed in [77,14], in fact, even estimating the economic consequences of a negative demand shock through standard I/O models may induce some issues related to double counting of impacts on total output and labor income.

Supply-side perturbation. Representing and analyzing impacts in terms of demand is not always exhaustive. In Ref. [17], for instance, it is observed that *"a disruption caused by a (natural) disaster is most often a disruption in the supply side of the production chain"*. In the context of I/O models, a supply shock should also be considered as a perturbation to internal demand to properly assess its propagating consequences. [91] observes that supply alteration can be further articulated in terms of internally constrained (e.g. physical damage, loss of inventory) and externally constrained (e.g. limited input availability for production) supply. Notably, changes in the I/O structure of specific regions throughout a post-catastrophe time horizon have been assessed in specific empirical analyses. For instance, in Ref. [92] homogeneity of sectoral recovery in the aftermath of the 2011 Tōhoku earthquake is studied in conjunction with trade and demand changes. Many complexities underlying the modeling of supply-side shocks have been well outlined in Ref. [18]. In particular, the reference discusses some inconsistencies deriving from the use of demand-driven formulations to estimate supply-side impacts on top of demand impact estimation. Supply-driven perturbations are particularly in contrast with the fixed allocation logic pertaining to the standard Leontief model. Furthermore, supply-driven perturbations can allow overcoming the assumption that the economy proportionally shrinks in all sectors [22].

Mixed-sided perturbations. Since the early days of the I/O application to disaster analysis, methods to blend demand- and supply-side perturbations were searched for. Notable examples are provided by [93] and related literature, which introduce a partitioning of the standard I/O model and an exhogeneization procedure for supply-constrained sectors. Also [94], applies a mixed I/O model to better account for supply constraints. Recently, a connection has been found between the simultaneous effect of demand- and supply-driven perturbations and the articulation of impact assessment into short- and long-term components. In Ref. [18], the possibility of widespread negative impacts along supply chains is addressed, considering them as *"caused by the backward effect of the direct drop in demand in the region at hand, and by the forward effect of the direct drop in the supply of its output"*.

3.4. Causal paths and cascades

The analysis of backward and forward linkages and propagation through Leontief and Ghosh type models leads to an issue related to the nature of the impact, notably the joint stability of Leontief and Ghosh matrices. In particular, in terms of the standard Leontief model, sectoral output perturbation is obtained as $\Delta x = L\Delta f$, where Δf is demand perturbation. This formulation, based on the assumption of fixed A, implies that the corresponding E (and H) in the Ghosh formulation cannot in general remain unmodified. A symmetric problem is found when considering the Ghosh case. As a result, joint stability is conditional [25].

Moreover, two major aspects of interest related to the analysis of causal paths associated to shocks are about the description of cascading effects in time and space.

3.4.1. Time horizon considerations

The application of I/O techniques for loss assessment over different time horizons (short- and long-run impacts) is a controversial. A primary criticism is related to the impossibility of standard I/O models to incorporate substitution effects, which may be relevant particularly in long term and may induce loss overestimation issues [7]. This may also be substantial to an enhanced estimation of the recovery phase duration. Related aspects are about production simultaneity and synchronization.

In addition to that, time horizon concerns emerging in recent discussion include the following topics:

- *time resolution*: an important consideration related to the use of I/O models is that *"unexpected events often generate the bulk of their impacts within time periods that are shorter than the time interval of the model's observation or solution"* [95]. This aspect often differentiates between economic and, for instance, engineering impact assessment datasets and methods [96];
- *time disaggregation and economic cycle*: work has been done, notably, in order to disaggregate I/O tables in time and provide a more detailed and dynamic view of factors such as trends and seasonal effects, see for instance [91] and related references. The literature also focuses on the topic of time disaggregation of recovery processes [95];
- *interaction of disaster impacts and long-run economic trends*: this aspect has been taken into account in a number of case studies; in [1], for instance, it is observed that the superimposition of structural economic trends and disaster impacts can result in complex responses of economies under the action of critical stressors;
- *time compression*: [97] points out that, following the disruption of an economic equilibrium, recovery actions may induce a non-gradual, accelerated progression towards the next steady state.

3.4.2. Space localization and impacts

A comprehensive discussion of methodologies for regional and interregional analysis can be found for instance in Refs. [98,99,25,100,101]. Notable case studies include the nonsurvey approach proposed in Ref. [102], and the hybrid method found in [103]. The aggregation error resulting from performing regionalizations was studied, for instance, in [104]. The literature also includes models tuned to cover the absence of regional data, such as the Leontief-Strout gravity model [105].

The coupling of disaster space localization and geographical resolution of available I/O tables is among the core research issues today. An emerging concern is related to the role of globalization in determining disaster impacts and the challenge of analyzing global supply chains [88]. Also, the topic should be put in the broader context of the development of joint regional tools supporting a global assessment of damage impacts [106].

Additional geographical considerations pertain to the qualification

Table 2
I/O literature mapping of recent large disasters. See also [111], Table 2.1 for further information on some of them, including economic damages estimation.

Popular name	Date of event	Type of event	I/O literature references
Great Hanshin-Awaji (Kobe) Earthquake	17 January 1995	Earthquake	[16,112,27,113]
9/11 attacks	11 September 2001	Terrorism	[114–117]
2003 Northeast blackout	14 August 2003	Power outage	[118]
2003 European heat wave	July-August 2003	Extreme heat	[110]
2004 Indian Ocean earthquake and tsunami	26 December 2004	Earthquake and tsunami	[16,119]
Hurricane Katrina	August 2005	Tropical cyclone	[120,82,121]
2008 Sichuan earthquake	12 May 2008	Earthquake	[122]
2009 H1N1 pandemic	2009–2010	Pandemic	[123]
Typhoons Ketsana and Parma	September-October 2009	Flood	[124]
Haiti earthquake	12 January 2010	Earthquake	[125]
2010 eruptions of Eyjafjallajökull volcano	14–20 April 2010	Eruption and ash cloud	[126]
2011 Tōhoku earthquake and tsunami	11 March 2011	Earthquake and tsunami	[127–131]
Hurricane Sandy	October-November 2012	Hurricane	[132,133]
2013 European floods	May-June 2013	Flood	[134,14]

and quantification of import/export perturbations, which may assume the double role of

- a consequence of the impacting threat affecting the import/export activity itself;
- a result of regional demand perturbation, inducing the need to compensate demand imbalances or to fulfil reconstruction needs [17].

The necessity for both a temporal and a geographical articulation of imports/exports disruptions was emphasized, for instance, in Ref. [107]. In addressing interregional and international spillover effects through I/O models, one of today's research branches aims at including the analysis of feedback effects observed in multi-regional studies [108].

3.5. Non-market and behavioral effects

An issue related to the use of I/O models in the context of disaster analysis is about the presence and significance of non-market effects. [7], in particular, refers in this sense to losses due to the lack of provision of public services, e.g. public infrastructures. Further discussion on the topic is found for instance in [109], referring to damages that do not respond to market purchases in recovery. Furthermore, [110] reflects on the fact that focusing on flow losses in the analysis of non-market effects can be primary, as stock losses may be difficult to quantify. [26] offers further observations on the non-negligible role of individual behaviors in determining the overall economic response to stress. Finally, among the most relevant behavioral aspects to be taken into account, we have to consider the in-built disaster counteraction mechanisms of societies, as illustrated for instance in Ref. [49].

4. I/O methods for disaster impact analysis

In the last decades, huge progresses have been registered both in I/O methodologies for disaster impact analysis and in their empirical application. A number of major recent events have been studied by means of this class of techniques, see Table 2 for a (non-exhaustive) literature mapping. The relevance of these developments is also gauged by the integration of I/O modules in some reference disaster analysis and decision support tools in use. Our review of pivotal I/O methods for disaster impact analysis will be structured around the static and dynamic categories.

4.1. Static methods

4.1.1. Structural analysis and network-theoretical methods

Despite the fixed-structure limitations found in traditional I/O analysis, successive developments such as exogenous superimposition of structural changes and enhanced structural analysis methods helped to deal with a number of aspects related to disaster representation. Interestingly, structural analysis is also one of the key tools used today for industrial performance monitoring of productive sectors and of countries, see for instance the OECD STructural ANalysis (STAN) Database.[5] As discussed in Section 2, multiplier analysis stands very much at the core of I/O techniques [135]. Research on multipliers is documented, for instance, in [25], and one of the aspects of interest is the breakdown of economic consequences into direct and indirect effects. Moreover, the reality of demand- and supply-sided factors led the literature to the investigation of both backward and forward linkages of economic sectors in I/O models, which can be helpful in assessing the results of demand-driven supply-side alterations and vice versa. The application of structural analysis techniques led to significant achievements in recent disaster impact analysis literature. For instance, [27,113] were able to detect tangible structural changes in time due to a disaster and subsequent reconstruction activities. In the domain of key sector analysis, another fundamental reference technique is the hypothetical extraction method, see [25] for attribution information. [136] discusses the role of both the classical multiplier method and the hypothetical extraction method in evaluating internal and external impacts, while it proposes a hybrid approach allowing to disaggregate external and internal effects. Among the recent results, [137] introduces a generalized hypothetical extraction method together with a mixed exogenous/endogenous I/O model as an alternative to the standard IIM (vide infra) to analyze losses by imposing the structural change determined by disasters. However, [18] observes that the algorithm indeed estimates backward effects resulting from the removal of demand on a particular sector, while forward effects are not properly captured.

In recent years, research in I/O modeling is displaying a fertile interaction with econophysics and complex network theory, in particular. This connection finds a poivotal point in interpreting I/O tables as weighted, directed networks with boundary conditions [138–140]. Studies in this domain are shedding light into the bonds between underlying topologies of I/O tables and emerging performance, including response to shocks. In the first place, this entails a characterization of I/O structures in terms of each sector's systemic importance, centrality or other metrics, often with a multi-regional outlook [141–145]. Moreover, as far as perturbation analysis is concerned, areas of investigation include the fundamental relationships between network metrics and shock propagation, the development of shock-diffusion models, the assessment of economic stability properties [142,146,147]. Along the same lines, we can observe a surging attention towards the vertical trade perspective and the analysis of spillovers in global value chains.

[5] http://www.oecd.org/sti/ind/stanstructuralanalysisdatabase.htm.

This activity is supported by the emergence of inter-country I/O databases endowed with increasing levels of detail on bilateral transactions. In this sense, data have been exploited in various ways, e.g. to identify trends based on value chain decomposition [148], to assess the role of industries and countries in the global perspective [149] and to investigate competition and collaboration [150]. Some of the metrics proposed in the domain are apt to account for both demand and supply shock transmission, such as in the case of output upstreamness and input downstreamness [151–153]. Network analysis has also been applied in order to relate the probability of spillover effects to the existence of global hub sectors playing a primary role in shock transmission [154].

Finally, one may observe that some of the recent literature on multi-sector real business cycle modeling investigates cascading effects under the lens of I/O network layouts and structural properties. Notably, a conceptual framework for the study of cascading effects is proposed in Ref. [155], which examines the relationships between low-/high-order interconnections and aggregate volatility. Moreover, questioning the assumption that idiosyncratic shocks to individual firms cancel out in the aggregated perspective [156], Ref. [157] connects the asymmetries in the I/O structure of economies to the possibility that microeconomic shocks may induce macroeconomic fluctuations. See also [158] and related references for further discussion.

4.1.2. Optimization techniques

The connection between I/O analysis and optimization techniques is deeply rooted. For instance, as discussed in Ref. [159], the pioneering work on linear programming by George Dantzig led to the formulation of a Leontief substitution model, both in a static and a dynamic version [160]. This achievement allows the evaluation of different ways of aggregating final products starting from inputs based on the simplex method. Linear and nonlinear programming techniques matched with I/O models have also found use in disaster impact analysis, especially in order to allow specific degrees of flexibility useful in this type of applications. Among the recent contributions, [161] proposes a nonlinear programming formulation based on Leontief's model and including the representation of production bottlenecks. The impact assessment model presented in Ref. [17] combines demand-driven I/O modeling with linear programming in a multi-regional perspective, implementing a constrained production costs minimization principle that takes into account demand, technological restrictions and maximum production capacities. A key advantage of the method is its ability to describe inefficiencies associated to the presence of those constraints, which is particularly relevant towards disaster impact analysis. In Ref. [18], nonlinear programming is employed to describe the short-run response of an inter-regional, inter-industry economy to shock, formalizing the effort to re-establish pre-event transaction levels. To this end, the authors assume *"fixed technical coefficients, flexible trade coefficients, partial import and export substitution, and minimum information gain with endogenous totals"*. Both regional production shocks and inter-regional trade shocks can be accommodated in this representation.

4.1.3. IIM and extensions

The I/O Inoperability Model (IIM) was introduced in its theoretical foundations in Ref. [162], wherein it is expressed in physical terms, and [114], through a demand-reduction formulation that allows to exploit standard I/O tables towards parameterization. Inheriting the demand-driven nature of the standard Leontief model, the IIM translates critical events into demand perturbations and assumes infinite elasticity of supply. In time, the IIM has gained attention as a tool useful to jointly assess inoperability (normalized difference between as-planned output and actual output of different sectors) and economic losses (consequence of lacking output) that result from critical events. For instance, in a post-disaster analysis perspective, [116,117] associate IIM representations to different successive post-event regimes. Notable applications of IIM in disaster analysis include the cases of terrorism [163], electrical blackouts [118] and shocks in transportation systems [164].

Moreover, extensions and integrations of the basic model are numerous in the literature. One such case is the IIM formulation in Ref. [165], which exploits a fields of influence approach for mapping the most relevant technological sectors, see also [166]. [167] presents an IIM taking into account international trade inoperability. In Ref. [168], a methodology was introduced for IIM parameters assessment in the context of critical infrastructures, exploiting technical and operational data. A supply-driven IIM (SIIM) was proposed in Ref. [169] on the basis of the Ghosh I/O representation; the technique was applied in Ref. [170] for risk analysis in manufacturing systems. Optimization techniques have also been combined with IIM models. For instance, within a risk management perspective, [171] applies linear programming to determine the optimal distribution of initial inoperability leading to minimum total losses.

In Ref. [137], the IIM was criticized as *"a straightforward application of the standard input-output method"*, while the relevance of the modeling work enriching the basic framework was acknowledged. Limited usability was attributed to the IIM in Ref. [77], observing that the model *"tries to estimate only a subset of mainly the negative impacts"*. See both references for further discussion.

4.1.4. Extended, integrated models

The research community developed an interest in I/O analysis frameworks able to cope with complex perturbation types and constraints. For instance, on the basis of [93], [87] introduces a technique to impose supply-side output constraints to selected sectors. [128] exploits a mixed multi-regional input-output (MRIO) model to evaluate the global effects of a supply chain perturbation induced by a disaster. A generalized (shared-responsibility) I/O model is proposed in Ref. [172] starting from a comparison of Leontief and Ghosh approaches and applying ideas elaborated on top of the total flow concept. Impacts on production are attributed to an ensemble of agents, e.g. *"consumers, producers, workers, and investors"*, to better reflect the role of different stakeholders in the supply chain. In this way, both supply-driven and demand-driven perturbation propagation factors can be simultaneously captured.

A number of recent initiatives are related to the exploitation of I/O modeling in the construction of analysis and decision support tools, which in time have been expanded and integrated with other disaster assessment techniques, even beyond a purely static analysis framework. A notable example is HAZUS (Hazard US), a multi-hazard analysis tool proposed by the US Federal Emergency Management Agency,[6] see [173] for an overview of its development. As part of the portfolio of risk estimation methodologies proposed therein, the evaluation of both direct and indirect economic losses is included. While the direct component involves capital stock losses and income losses, indirect losses are evaluated by means of an I/O model [174]. [175] explains that the method is based on the concept of rebalancing of demand and supply in a standard Leontief I/O model based on adjustments in imports and exports, see also [176]. The technique also takes into account supply constraints and factors such as the presence of inventories. In the recent literature, we can find an extensive set of case studies involving HAZUS-aided economic loss estimation, see for instance [177,178,86]. Another case of interest is represented by the National Interstate Economic Model (NIEMO), an operational MRIO focusing on the United States [179,180] and which has allowed, in time, the introduction of extensions and refinements such as TransNIEMO [181,182] (introducing the representation of the transportation network) and FlexNIEMO [183,184] (addressing the stability of economic multipliers).

[6] https://www.fema.gov/hazus.

4.2. Dynamic methods

4.2.1. Temporal analysis, dynamic and lagged I/O models, SIM

A number of studies proposed in recent years are investigating the time evolution of I/O economic networks through the comparison of I/O tables referring to different years. Examples include temporal inverse analysis techniques [185] and methods based on network theory [186]. This research direction has strong ties with the discussion on structure analysis methods proposed above in this section.

According to [96], while the theoretical characterization of Leontief's dynamic I/O model was extensively addressed in the literature, its empirical application brought up a number of issues. One of the ways found in research to address this problem was by the introduction of techniques enriching static I/O methods with dynamical features, obtained for instance by exploiting series expansions of the Leontief inverse. This is the case of lagged I/O models, see for instance [187,188]. A somehow affine approach to the formulation of dynamic I/O representations is based on the use of the Sequential Interindustry Model (SIM), see for instance [95]. Introduced in Ref. [189], the method aims at describing the inter-industry production web dynamically, by integrating the Leontief I/O framework with technological aspects related to the way production is performed. *"In the SIM, production is not simultaneous as in the static input-output model, but rather occurs sequentially over a period of time"* [95]. This leads to the definition of an industry time interval internally articulated to include production and shipment time frames. The SIM allows to compare differences in production modes, notably anticipatory and responsive production as well as their combination. It is also employed in Ref. [95] as a tool for temporal disaggregation towards impact analysis in regional economies. Interesting applications of the SIM to disaster impact analysis can also be found, for instance, in [112,96]. In the latter reference, in particular, a discussion is proposed about the applicability of the SIM to economic impact quantification of unscheduled events.

4.2.2. Basic equation, dynamic inequalities

It has to be mentioned that the I/O equilibrium framework has opened the doors for the formulation of dynamic disequilibrium characterizations, for instance through supply-demand disequilibrium models [190] and equilibrium-disequilibrium switching [191]. Further relevant observations on imbalance in terms of partial versus general equilibrium effects, as well as micro-/meso-/macroeconomic effects, can be found in Ref. [192] in the context of computable general disequilibrium analysis. See also [26] for further considerations about recovery processes and disequilibrium.

Recent contributions in this direction include [193,79], wherein post-disaster recovery is represented as a two-step process: the first stage aims at re-establishing the pre-disaster relationships between outputs, while the second one aims at returning to the pre-event output levels. The modeling objective is met by combining an I/O table with an event accounting matrix. At the core of the method is the construction of the "basic equation", an I/O equation depicting the imbalances of the system resulting from a disaster. Imbalanced economic recovery has instead been considered explicitly in Ref. [22] by means of dynamic inequalities. The idea is to express the contributions of post-crisis drivers such as labor, capital and final demand in terms of constraints affecting the dynamics of recovery between consecutive equilibrium conditions, formulated in terms of Leontief models. The method can be used to trace the temporal progress of an economy and to perform sensitivity analysis.

4.2.3. DIIM and extensions

In time, the IIM underwent dynamic extensions, notably through the Dynamic Input-Output Inoperability Model (DIIM) [194], wherein a resilience matrix is used to specify the inoperability dynamics. A comparison of the DIIM and the dynamic Leontief I/O model can be found in [137]. See also [195] for an analysis of (demand- and supply-sided) IIM and DIIM and the proposal of an alternative approach based on systems dynamics principles. Similarly to the case of IIM, a number of applications of DIIM appeared in the literature, including the cases of terrorism [194], natural events [196] and epidemics [197,123].

Elaborations of the basic DIIM were meant to include different features of the recovery processes [198] and mitigating factors such as inventories [199,200], as well as to incorporate recovery strategies based for instance on sector prioritization logics [201]. A hybrid DIIM and event tree analysis was introduced in Ref. [202] to specify time-varying recovery models. Also, [203] proposed a fuzzy DIIM for the analysis of global supply chains. While, in principle, the DIIM approach is based on the concept of demand-side shocks, other possibilities have been considered, too. For instance, in Ref. [204] a time-varying perturbation on workforce availability has been taken into account. Based on the above-mentioned SIIM, [205] presented a dynamic extension of the SIIM (SDIIM), related to the DIIM.

4.2.4. ARIO model and extensions

The Adaptive Regional Input-Output (ARIO) model has been introduced in Ref. [82] to the purpose of disaster modeling and is based on a Leontief model plus additional features to cover limitations of the basic technique in the context. In particular, the methodology considers demand perturbation, while it adds constraints on supply capabilities, expressed in terms of production bottlenecks, and proposes a rationing scheme determining priorities associated to the demands to be served. Furthermore, price dynamics are evaluated as a function of underproduction, whereas adaptation capabilities are modeled at the levels of final demand, intermediate consumption and production. The formulation described in the reference above, in particular, focuses on the following behavioral parameters: overproduction, by the exploitation of spare production capacity; adaptation, which obeys the principle of reconfiguring demand if possible and bringing it back when possible; demand and price response. [206], building on the ARIO model, introduces a disaggregated view for the production system as a web of producers-consumers specified on the basis on assigned degree distribution configurations. Disaster response characteristics, particularly robustness, are then studied as a function of network features such as concentration, clustering, subregions connectedness. The role of inventories is also taken into account. [207] extends ARIO by including expanded categories of supply (taking into account their essentiality and ability to be stocked). Inventories are consequently introduced in the model, together with their filling and depletion dynamics, while production bottlenecks and input scarcity are also allowed by the representation. In the proposed case study, two phases are identified for the recovery period: an initial stage, dominated by production bottlenecks; the rest of the reconstruction period.

4.2.5. Extended, integrated dynamic models

Also in the domain of dynamic I/O-based analysis, some of the recent contributions focus on the integration of I/O techniques with other economic models such as the ones mentioned in the introduction of this paper. Notable is the concept of merging I/O and CGE principles, that can be found for instance in some of the already mentioned models such as ARIO. Moreover, the combination of I/O models and econometric models has been considered in the literature [208,209]. Instances include INFORUM models [210] and FIDELIO 2, a fully interregional dynamic econometric long-term I/O model for the EU and beyond [211]. In some cases, analysis frameworks have also been constructed by involving multiple techniques among those reviewed above in this section. Such is the case of the multistep procedure proposed in Ref. [212], which addresses direct loss assessment, economic shock, pre-recovery period, recovery period and total consequences. The method contemplates the exploitation of the basic equation and of the ARIO model at specific analysis stages. A generalized dynamic I/O framework is proposed in Ref. [213] by combining intertemporal dynamic modeling principles with the intratemporal representation of production and market clearing. The approach allows to consider both demand and supply constraints and has a strong nexus with static and dynamic Leontief models as well as with SIMs.

Another interesting trend in dynamic analysis is that of merging the advantages of the I/O-based economic representation with that of heterogeneous modeling components, able to track more specifically dynamical features of systems involved in the disaster scenarios under consideration. Examples of matchings with technological models can be found for instance in Ref. [214] (transportation network) and [215] (electrical transmission grid). Other recent references include [212], integrating of the I/O framework with a biophysical model for flood risk assessment, and [216], proposing a combined I/O technique and system dynamics ecological model.

5. I/O models and resilience assessment

Resilience in economic systems is a central topic in today's research in disaster impacts assessment and mitigation. Aspects of great interest include the definition and measurement of this property [217] as well as the associated policy implications [218]. Recently, a number of characterizations of economic resilience relevant to multi-industry representations have been provided in [219,220]. The latter reference, in particular, qualifies this notion as focusing more on flow losses than on stock losses. Additionally, it defines static economic resilience as *"the ability of a system to maintain function when shocked"*, while dynamic economic resilience in terms of *"hastening the speed of recovery from a shock"*. Moreover, it is possible to distinguish between inherent (built-in) and adaptive (arising out of ingenuity under stress) aspects of a resilient economic behavior, as well as between final customer-side and business-side resilience measures. In turn, the latter ones can be broken up as follows, taking into account the double nature of businesses as customers of intermediate goods and suppliers:

- customer-side measures: these represent ways for the different industries to effectively exploit available input resources in order to minimize impacts on their own activity;
- supplier-side measures: here the focus is on the ability of businesses to keep delivering service.

For both cases, the reference discusses a categorized series of resilience options. Micro-, meso- and macroeconomic levels are taken into account in this study. Finally, resilience indicators and indexes from the literature are assessed.

Traditional approaches to impact analysis based on I/O models are challenged in providing resilience-oriented interpretations of economic systems and applications, as resilience *"places greater emphasis on flexibility and responding effectively to the realities of disequilibria, as opposed to unrealistically smooth equilibrium time-paths"* [221]. In recent years, remarkable efforts have been made by the scientific community in the use of I/O techniques to address various aspects of resilience analysis.

In the first place, I/O structures are being studied in the literature as possible determinants of shock response and resilience attributes of economies. This topic is inherent, for instance, to a number of works on structural analysis and on network-theoretical methods. Moreover, empirical validation has been performed in recent works, especially in a regional perspective. For instance, I/O methods are employed in Ref. [222] to assess regional labor market resilience. Adopting an evolutionary approach, the two phases of shock and recovery are considered. Key factors of regional resilience are identified in embeddedness, relatedness and connectivity, where the first reflects the dependency of shock propagation on the I/O structure of the region, while the other two are associated to intersectoral and interregional labor mobility. Another case can be found in Ref. [223], combining I/O modeling and shift-share analysis to assess regional resilience to economic crisis.

Furthermore, resilience concepts, factors and metrics have been integrated in some of the models illustrated above in this paper, especially with reference to some of the dynamic frameworks. For instance, as mentioned, the DIIM was complemented in Ref. [199] with the representation of the buffering capabilities provided by inventories, while in [198] the inventory DIIM was also enriched considering different types of recovery paths. The DIIM is also studied in Ref. [224] through the concepts of static and dynamic economic resilience and the related resilience triangle representation, see [225]. Attributes such as robustness, rapidity, redundancy and resourcefulness allow the formulation of resilience metrics, including the time-averaged level of inoperability, the maximum loss of sector functionality and the time to recovery. A combined demand- and supply-driven I/O analysis framework for resilience assessment was introduced in Ref. [107]; in the considered port disruption application, resilience measures were identified in terms of: ship re-routing; export diversion; use of inventories; conservation; unused capacity; input substitution; import substitution; production recapture (rescheduling).

A risk management perspective has also been adopted in proposing the exploitation of I/O models for resource allocation and prioritization. For instance, the IIM has been exploited in Ref. [226] to address preparedness considerations in a multi-regional perspective. Also, in Ref. [200] inventory resources allocation has been considered in the DIIM by means of an optimization technique taking into account inoperability, inventory costs and technical constraints. Resilience metrics and aspects of the failure and recovery processes reverberate in a number of recent formulations of optimization problems for I/O systems. One such example is [227], wherein an extended Leontief I/O model is embedded into an energy-economic resilience optimization problem. This relates to the determination of *"the minimum level of extrinsic resource recovery investments required to restore the production levels sufficiently, such that the total economic impacts do not exceed a stipulated level over a stipulated post-disruption duration"*. Finally, decision theory has also benefited from the assimilation of I/O techniques and datasets towards the formulation of resilience assessment methods, see for instance [228].

6. Conclusions

In Ref. [229], some reflections are proposed on the emerging challenges and opportunities for I/O analysis: exploiting increasing volumes of data available and fostering estimation capabilities; integrating the I/O analysis framework with other techniques; tackling the study of global supply chains, emerging economies and global cities; expanding regional accounting systems; exploiting multipliers; favor supply chain literacy in conjunction with the evolution of Internet of Things; increasing the frequency of I/O tables computation, taking into consideration both the national and inter-country dimensions.

In this paper, in particular, we addressed the relationships between I/O modeling and the assessment of economic losses associated to disasters resulting from both natural and man made hazards. The relevance of I/O models in the context finds a huge plus in their moderate data requirements and their ability to combine with other analysis techniques, such as technological models or market behavioral descriptors. In this sense, they could maintain a relevant role in policy support, especially for large scale impact analysis, and in determining a cost-effective use of resources [230].

We documented the recent evolution of the discipline to support a better understanding, measuring and counteracting of complex disasters scenarios affecting societies and economies. Theoretical problems and practical case studies explored in research often involve complementary views of rippling phenomena, including both backward and forward aspects of propagation. The literature has considerably expanded and extended classical demand- and supply-driven I/O formulations to take into account the dynamics of critical events and crisis response. The interaction with other disciplines, such as complex network theory, also aims at addressing some of the emerging problems, such as the large-scale behavior of interacting economies and supply chains. Resilience analysis of economic systems also represents an opportunity for an evolved approach to I/O modeling, involving a continuous dialog with complementary analysis frameworks.

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