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Abstract

This note shows that the inoperability input-output model (IIM) estimates only a part of only the negative wider economic impacts of disasters. This means that the IIM is not suited to prioritize industries for policy interventions that aim at reducing the negative impacts of such disasters. Besides, it shows that the application of the IIM to typical disaster situations is problematic, and tends to overestimate the subset of impacts that the model aims to quantify. Finally, we identify two approaches that much better capture the variety of different disaster impacts.

Keywords Disasters, Supply shocks, Elasticities, Inoperability, Input-Output Model

1. Introduction

The original formulation of the inoperability input-output (IO) model (Haimes & Jiang, 2001) was in physical terms and proved very hard to estimate. Its subsequent operationalization in the demand-reduction inoperability input-output model (IIM) (Santos & Haimes 2004) became very popular, in that a series of extensions have been developed and numerous applications have seen the light of day since (see Santos et al. 2014, p.62, for a brief overview). Greenberg et al. (2012), in fact, claim that the IIM is one of the ten most important accomplishments in risk analysis of the last thirty years. The early criticism as regards its limitations (Kujawski 2007) obviously did not have an impact on this proliferation. The reason may be that Kujawski limited his criticism to only questioning the IO assumptions of constant technical coefficients and excess supply, but did not discuss the more fundamental problems of estimating disaster impacts with the IIM.

The question is whether this literature is on the right track. In the next Section, I summarize the complex positive and negative, short run and long run, interregional and interindustry economic impacts of major natural and man-made disasters, and indicate that the IIM tries to estimate only a subset of only the negative effects. Unfortunately, this is not made explicit in the IIM literature. In Section 3, I summarize how the IIM tries to do that and why it is practically impossible to do that in a right way, as the predominant character of most disasters, i.e., being a supply shock to the economic system, cannot be captured by a demand-driven model like the IIM. Moreover, I show that the actual applications of the IIM tend to lead to an overestimation of the economic losses involved. In the concluding Section, I briefly discuss some alternatives and indicate why two of them, an established one and a new one, are much better able to capture the complex wider economic impacts of disasters than the IIM.

2. An overview of the wider economic impacts of disasters

Disasters, such as the recent tsunami in Japan (2011), lead to both short run and long run, and both positive and negative economic impacts. These various impacts occur, not only in the region and the industries directly hit by a disaster, but, due to the disruption of global supply chains, also in seemingly unrelated regions and industries. These wider economic impacts are caused by three types of indirect effects that all start with the direct destruction of production capacity, infrastructure and labour supply by the disaster at hand. These direct effects, essentially, represent damages to *stocks*, including human capital, whereas the indirect effects, essentially, represent damages to *flows* of production and consumption (Okuyama & Santos, 2014).

First, and foremost, the destruction of production capacity, infrastructure and labour supply will cause a differential disruption in the supply of goods and services by the various industries in the regions hit by the disaster. In its turn, this drop in supply will have forward or *downstream effects* on the production of firms in the same and in other industries, in the same and in other regions.

When the differential disruption relates to the supply of *non-replaceable* intermediate or labour inputs, these wider negative forward effects may be many times larger than the direct supply effect, and may occur in the disaster region, but also in industries in faraway regions that depend on these inputs. To estimate the directly related production losses one needs to multiply the drop in the supply of the irreplaceable inputs with the reciprocals of the corresponding technical coefficients, i.e., with working-up or *processing coefficients* (Oosterhaven 1988). Some processing coefficients, e.g., those for rare metals, may have values that are much, much larger than one, and thus result in negative forward multiplier effects that are much, much larger than the size of the direct shock to the supply of the input at hand. To estimate the further *negative forward impacts* with an IO modelling approach, an elaborate series of additional, case-specific assumptions has to be made to get a decent estimate (cf. Oosterhaven 1988, Hallegatte 2008).

Second, in the case of *replaceable* inputs, other firms will step in to replace these losses and may thus experience positive impacts due to technical and/or spatial *substitution effects* (Rose, 2004). Technical substitution occurs when, e.g., metal subparts are replaced by plastic subparts, whereas spatial substitution occurs when metal subparts from one origin region are replaced with those from another origin region. Obviously, spatial substitution is far more likely to occur, especially in the short run, than technical substitution, which was the focus of Bujawski´s (2007) critique. The increase in the demand for both types of substitutes will induce the firms supplying them to increase their output, but it may also induce them to increase their prices, especially if the increase in their own demand for intermediate inputs and labour will lead to an increase in the prices of their own inputs and labour. These secondary demand increases may lead to further *positive backward impacts* on supplying industries and on the consumption of labour supplying households.

However, even when the downstream industries hit are able to fully substitute the loss of the supply of their intermediate and labour inputs, they will most likely have to pay higher prices and wages, which may force them to increase their output prices, with a negative impact on the demand for their own products. When the downstream industries that experience these *negative forward impacts* are located in the region that is hit, while the industries that produce the replacing inputs are located elsewhere, the result will be an increase in the import coefficients. When the replacements come from the own region, a possible consequence may be a reduction in the exports of the region hit, and a subsequent reduction in the import coefficients of other regions. Moreover, damages to transport infrastructure networks will directly lead to changes in the trading patterns of firms and to spatially differentiated price and spatial substitution effects.

Obviously, the size of all the above effects will depend on the price elasticities of supply and demand, and of technical and spatial substitution (Rose & Guha 2004). None of the above described positive and negative impacts will be picked up by the IIM, as both the technical coefficients and the trade coefficients of that model are assumed to be constant, while price do not play a role.

Third, the destruction of production capacity, infrastructure and labour supply will cause a direct drop in both intermediate (firm to firm) demand and final (mainly consumer) demand in the regions hit by the disaster. These direct drops in *demand* will be due to the fall in the production of their industries and the income of their households. The backward effects of these direct drops in demand will occur in the industries and regions that directly and indirectly supply the industries and households hit by the disaster. Estimating these *negative backward impacts* is the core objective of the IIM (Santos & Haimes 2004).

Finally, aside from the wider economic impacts of the damages to economic stocks, there will also be short run and long run impacts due to *reconstruction* programs. When these programs relate to the reconstruction of buildings and infrastructure, the *positive backward* economic impacts will most likely be regionally concentrated. When the reconstruction relates to rebuilding production capacity, the *positive backward* impacts might well occur in faraway regions, as the capital goods industry is quite specialized. In conjunction, financing these programs, mainly by a mix of higher insurance premiums and higher taxes, will lead to longer run *negative forward*, spatially spread, macro-economic impacts.

Since, the IIM only tries to estimate a subset of the negative impacts, while it entirely ignores the positive impacts, its suggested use as a risk management instrument to prioritize support for industry resilience programs, first in Santos & Haimes (2004), will most certainly lead to a wrong ranking of industries and thus to wrong policy advice.[1]

3. The problematic estimates of the inoperability IO model

The IIM literature (e.g., Santos & Haimes 2004, p.1447, Lian & Haimes 2006, p.253-4, Santos 2006, p.26, Andersen et al. 2007, p.187), in fact, proposes to estimate two types of rankings of industries, namely one based on the absolute size of the projected economic losses by industry and one based on the relative (i.e. percentage) size of these losses. The latter measure is innovatively labelled as the

[1] An exception to this first general conclusion has to be made for disruptive events, such as most terrorist attacks, that involve relatively little direct damages, but have a large impact, through fear, on the spending behaviour of, especially, households (cf. Galea et al. 2002). Thus, in the rare cases where the direct supply shocks from a disaster are negligible compared to the direct demand shocks, using the IIM to assess the wider economic impacts may produce a reasonable approximation of the total impact. But also in these cases *substitution effects* need to be added to the empirical application of the IIM. If less air travel is used and fewer hotels are booked, as in Santos (2006), people and firm will most likely spend the money saved on different items. Note that not only for these types of disasters, but for all types of disasters the analyst should try to make an estimate of the so-called *net* impacts instead of the *gross* impacts (cf. Oosterhaven et al. 2003).

inoperability of the industry at hand. Both measures are calculated consistently, i.e., with exactly the same assumptions of exactly the same standard demand-driven input-output model (Leontief 1951).

Contrary to the IIM literature, I write this model for an open economy, with imports and exports, in its most complete structural form, such that the (mostly implicit) assumptions become much clearer than is usually the case:

$$\mathbf{x}^r = \mathbf{Z}^{rr}\,\mathbf{i} + \mathbf{f}^r = \mathbf{Z}^{rr}\,\mathbf{i} + \mathbf{f}^{rr} + \mathbf{e}^r \tag{1}$$

$$\mathbf{Z}^{rr}\,\mathbf{i} = \mathbf{A}^{rr}\,\mathbf{x}^r = \mathbf{T}^{rr} \otimes \mathbf{A}^{\square r}\,\mathbf{x}^r \tag{2}$$

where $\mathbf{i}$ indicates a summation vector with ones, $\square$ a summation over the index concerned, and $\otimes$ a cell-by-cell matrix multiplication. The economic interpretation of (1)-(2) is the following.

For any period t, any region or country r, and any industry *i*, equation (1) indicates that the production/output of its industries, $x_i^r \in \mathbf{x}^r$, follows the demand for its products, which equals the total of that region´s own demand for locally produced intermediate products, $\sum_j z_{ij}^{rr} \in \mathbf{Z}^{rr}\,\mathbf{i}$, plus that region´s final demand, $f_i^r \in \mathbf{f}^r$. The latter, in turn, consists of that region´s own final demand for locally produced products, $f_i^{rr} \in \mathbf{f}^{rr}$, plus the intermediate and final demand from the Rest of the World, i.e. exports, $e_i^r \in \mathbf{e}^r$. Economically, the above ´supply-follows-demand´ assumption implies that the price elasticity of supply is infinite, whereas the price elasticity of demand is zero (Oosterhaven 1996, 2012).[2]

For the same t, equation (2) indicates that the local intermediate demand for products from industry i in region r is endogenously determined, via unit *input coefficients*, $a_{ij}^{rr} \in \mathbf{A}^{rr}$, by the output of the local industries j, $x_j^r \in \mathbf{x}^r$. The a_{ij}^{rr} are usually calculated from a historic IO table by means of $\mathbf{A}^{rr} = \mathbf{Z}^{rr}\left(\hat{\mathbf{x}}^r\right)^{-1}$, where $\hat{\mathbf{x}}$ indicates a diagonal matrix of vector $\mathbf{x}$. In much of the IO and IIM literature these ´input per unit of output´ coefficients are unjustly called ´technical coefficients´.

To understand the qualification ´unjustly´, it is necessary to acknowledge that the a_{ij}^{rr} are, in fact, the product of a real *technical coefficient*, $a_{ij}^{\square r}$, and a regional purchase or domestic *trade coefficient*, t_{ij}^{rr}, which indicates the fraction of the total need for intermediate inputs from industry *i* from all over the world, $\mathbf{A}^{\square r}\mathbf{x}^r$, that is purchased domestically. Assuming the real technical coefficients to be fixed in time is more or less reasonable, at least for the short run, but assuming the domestic trade coefficients to be fixed is much less reasonable (Oosterhaven & Polenske 2009). In face of a major disaster the latter assumption, in fact, should even be considered highly implausible, as firms will most certainly adjust their regional purchase behaviour if they are confronted with a sudden drop in their usual supply of inputs.

[2] From this it follows that the IO model is an extreme case of a CGE model, which mostly uses finite elasticities (cf. Rose 2004).

Equation (1) and (2) together indicate that final demand has to be exogenously determined outside the IO model, while the production by industry is *endogenously determined* by the solution of the model, as are all variables that are linked to the production by industry, such as all intermediate inputs, value added, employment and energy use. Dropping all clarifying indices, as usual in the IO and IIM literature, the solution of (1)-(2) is simple:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f} \qquad \Rightarrow \qquad \mathbf{x} = \left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{f} \tag{3}$$

The IIM literature follows the standard IO literature when it takes the difference of (3) between period *t* and *t-1* to calculate the *absolute loss* of production by industry, $\Delta\mathbf{x}$, due to a disaster at the start of period *t*:

$$\Delta\mathbf{x} = \mathbf{A}\,\Delta\mathbf{x} + \Delta\mathbf{f} \qquad \Rightarrow \qquad \Delta\mathbf{x} = \left(\mathbf{I} - \mathbf{A}\right)^{-1}\Delta\mathbf{f} \tag{4}$$

To this, the IIM adds the normalisation of (4) with the lagged output levels, $\mathbf{x}_{-1}$, to get the *relative loss* of production by industry, $\mathbf{q} = \hat{\mathbf{x}}_{-1}^{-1}\Delta\mathbf{x}$, i.e., the *inoperability* by industry:

$$\mathbf{q} = \hat{\mathbf{x}}_{-1}^{-1}\,\mathbf{A}\,\Delta\mathbf{x} + \hat{\mathbf{x}}_{-1}^{-1}\,\Delta\mathbf{f} \qquad \Rightarrow \qquad \mathbf{q} = \left(\mathbf{I} - \hat{\mathbf{x}}_{-1}^{-1}\,\mathbf{A}\,\hat{\mathbf{x}}_{-1}\right)^{-1}\left(\hat{\mathbf{x}}_{-1}^{-1}\,\Delta\mathbf{f}\right) = \left(\mathbf{I} - \mathbf{A}^{*}\right)^{-1}\mathbf{c}^{*} \tag{5}$$

Aside from the implausibility of, especially, the assumption of fixed trade coefficients, applying (4) and (5) to calculate the wider *negative backward impacts* of a disaster is problematic for several other reasons.

First and foremost, note that a disaster manifests itself, economically, mainly in the form of a direct loss of production capacity, transport facilities and labour, which all represent a *supply shock* to the economic system, which the demand-driven IO model is incapable to handle. To nevertheless model capacity losses and limits, one might run the IO model with a cap on total output by industry or a cap on trade relations in case of infrastructure capacity limits, but this runs against its very assumptions of, respectively, infinitely elastic supply and fixed trade coefficients. This contradiction can only be solved by a series of case-specific ad hoc assumptions, as in Oosterhaven (1988) or Hallegate (2007).

In the IIM literature, however, the IO model´s inability to accommodate an exogenous change in output levels is circumvented by, mostly implicitly, transforming the production capacity loss into a supposedly equivalent exogenous drop in final demand. However, transforming the *exogenous* drop in output into an exogenous final demand drop $\Delta\mathbf{f}$ that, with equation (4), projects an *endogenous* output drop $\Delta\mathbf{x}$ that correctly and precisely incorporates the exogenous drop in output is very problematic, if not impossible. Take, for instance, the mining industry with almost zero final demand. Even assuming the full loss of this exogenous final demand will not produce an endogenous drop in total mining output that is large enough to incorporate any sizable exogenous drop in mining output.

When using (5), the problem is even a bit larger, as (5) relates *relative* changes to each other. In that case, an exogenous percentage drop in production capacity has to be transformed into a percentage drop in exogenous final demand, $\hat{\mathbf{f}}_{-1}^{-1}\Delta\mathbf{f}$, that downscaled with the final demand to total output ratio, $\hat{\mathbf{x}}_{-1}^{-1}\hat{\mathbf{f}}_{-1}$, projects an endogenous percentage drop in output, $\mathbf{q}$, that correctly and precisely incorporates the exogenous percentage drop in output. Unfortunately, nowhere in the IIM literature, one even finds the start of a discussion of this equivalence problem.

In fact, in several applications the opposite happens. When using (5), IIM applications tend to compare the total impacts of *uniform* reductions of exogenous final demand $\mathbf{c}^*$ by industry, e.g., of 10% (Santos & Haimes 2004) or 20% (Barker & Santos 2010). Alternatively, they apply uniform uncertainty distributions with, e.g., an average of 35% (Barker & Haimes 2009) to all industries. Applying a uniform $\mathbf{c}^*$ can only be based on the implicit, and sometimes explicit,[3] but incorrect assumption that $\mathbf{c}^*$ has a *uniform* upper limit of 1. Equation (5) and Santos & Haimes (2004, p.1442), however, clearly show that $\mathbf{c}^* \leq \hat{\mathbf{x}}^{-1}\mathbf{f}$, which means that $\mathbf{c}^*$ has upper limits that equal the industry-specific final demand shares in total output. Ignoring these non-uniform upper limits has two consequences.

First, applying a uniform $\mathbf{c}^*$ suggests to the potential user that the resulting ranking of industries is neutral for risk policy purposes, but it is not. A 50% reduction of the exogenous final demand $\mathbf{f}$ for the public transport, which has a large upper limit for $\mathbf{c}^*$, will result in a much larger inoperability in other sectors than a 50% reduction of demand $\mathbf{f}$ in case of mining products, which has a small upper limit for $\mathbf{c}^*$. I have not found any discussion of this problem in the IIM literature, let alone a solution. This underscores the earlier conclusion that the IIM should not be used the prioritize industries for risk policy purposes.

Second, ignoring the upper limits for $\mathbf{c}^*$ leads to a *systematic overestimation* of the backward inoperability. Take, for instance, the simple case when the average output multiplier $\mathbf{i}'(\mathbf{I}-\mathbf{A}^*)^{-1}$ is 2.0. Then, setting $\mathbf{c}^* = 1.0$ if the production capacity of all industries is totally destroyed leads to an impossible macro-economic inoperability of –200%, while setting $\mathbf{c}^* = 0.5$ if the production capacity of all industries is halved leads to a macro inoperability of –100%, instead of –50%. The reason for this systematic overestimation is the *double counting* of the endogenous drop in intermediate demand in the exogenous drop in $\mathbf{c}^*$, if the exogenous drop in output is not downscaled correctly.[4] This problem is even more prominent if the IO model is closed with regard to household consumption (see Santos & Haimes 2004), as the multipliers of the extended model are substantially larger, while the exogenous final demand ratios of the extended model are substantially smaller, than those of the standard model (Oosterhaven & Hewings 2014).

In sum, the IIM is not well suited to estimate even the subset of the negative demand effects of a disaster. This conclusion holds not only for the IIM, but also for the IO model at large (Oosterhaven et al. 2013). The main reason is that exogenous final demand is the driving force in the demand-driven IO model, while the nature of most disasters is that they generate a shock to the supply-side of the economy.

[3] For the explicit statement see Santos et al. (2014, p.63), where it is stated that $\mathbf{c}^*$, similar to the inoperability metric $\mathbf{q}$, is normalized to perturbation values between 0 and 1.

[4] With Santos (2006) it is actually possible to put numbers to this overestimation, and in that case it appears to be a minor issue. The exogenous drop in output is reported to be, respectively, 33.2% and 19.2% for air transportation and accommodation (p.26), whereas the endogenously calculated drops are reported to be 33.49% and 19.38% (p.27). This implies a double-counting of 0.29%point and 0.18%point, i.e., of only 1%. This small percentage of double-counting is due to the fact that domestic air travel and hotel bookings only represent a small share of the total of intermediate inputs of the US air travel and accommodation industries.

4. Alternative approaches to better capture the wider economic impacts

Unfortunately, the alternative of using the supply-driven version of the IO model (Ghosh 1958) to add an estimate of the forward impacts to the backward impacts estimated by the demand-driven model, is even more problematic. First, because both versions are fundamentally at odds with one another, implying that if the one version is a good representation of reality, by definition, the other version is not (Oosterhaven 1996). Only a sophisticated case-specific combination of both models may provide a solution (see Oosterhaven 1988, for the basic idea, and Rose & Wei 2013, for a recent extensive application).

The second reason is that the supply-driven IO model, even when used alone, is extremely implausible in that it assumes a single homogeneous input with zero supply elasticities and infinitely large demand elasticities, i.e., cars may drive without gasoline and factories may work without labour (see Oosterhaven 2012, for a recent account). This negative conclusion, of course, also applies to the IIM application of the supply-driven IO model in Crowther & Haimes (2005).

Ideally, modelling the impacts of natural disasters requires an interregional, interindustry computable general equilibrium (CGE) model, as in Tsuchiya et al. (2007), as CGE models are able to accommodate supply shocks as well as demand shocks, while they take price reactions into account with finite price elasticities instead of the extreme IO and IIM values of either 0 or ∞. Moreover, they often account for technical substitution possibilities, and they almost always account for trade substitution possibilities.

Unfortunately, different versions of such a model are needed to model short run impacts as opposed to the longer run impacts, because short run substitution and price elasticities are much closer to zero than their longer run equivalents (Rose & Guha 2004). Moreover, in longer run simulations, many more variables need to be modelled endogenously. Such time-varying CGE models are complex and rather costly to estimate, even if the essential data, such as interregional social accounting matrices (SAMs) and the various elasticities, are available. [5] Note that these problems of using CGE models (see also Albala-Bertrand, 2013) are of a fundamentally different nature compared to the problems of using an IO or IIM model. In the CGE case the problems essentially represent empirical difficulties with the implementation of the model, whereas in the IO and the IIM case one has to cope with fundamental theoretical problems related to the fact that demand-driven models are unsuitable to model the impacts of supply shocks to the economy.

Consequently, the question persists whether the complex problem of estimating the wider impacts of a disaster might not still have a more simple solution instead of the complex CGE solution. At first sight, the hypothetical extraction (HE) method seems to provide a way out of the impossibility to use the simple IO model to capture the downstream, forward impacts, along with the backward impacts, because the HE method extracts a complete row from the IO matrix, along with a complete column

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[5] Additionally, Okuyama & Santos (2014, p.4) seem to suggest that it is a problem that "the CGE model potentially provides lower impacts estimates than IO models, partly because "not all causations in CGE models are unidirectional, i.e., functional relationships often offset each other" (Rose 2004, p.27)". This is remarkable, as modellers should consider having included these offsetting impacts an advantage instead of a problem, as the presence of countervailing market equilibrium forces is a feature of reality, as described in Section 2.

(Paelinck et al. 1965, Strassert 1968). However, interpreting the extraction of a row of the IO matrix in the demand-driven IO model to represent the forward impacts of the extracted industry is faulty. What is really measured, are the backward impacts of the complete disappearance of the demand for an industry´s intermediate sales. What is not measured, are the forward impacts of the secession of these sales upon the purchasing industries.

Recently, Oosterhaven et al. (2013) proposed to build a non-linear programming model that combines the simplicity of the IO model with the greater plausibility of the CGE approach. Their basic idea is that both firms and households, in the short run after a disaster, try to stick as much as possible to their old pattern of sales and purchases. They operationalize this idea by minimizing the information gain (Kullback 1959, Theil 1967) of a simulated post-disaster interregional IO table compared to the actual pre-disaster table.[6] This approach, up till now, has been tested intensively on a hypothetical interregional IO table (Oosterhaven et al. 2013), and is being used to simulate the international impacts of possible Russian natural gas boycotts of different part of Europe (Bouwmeester & Oosterhaven 2015). The intensive testing on a hypothetical IO table showed that more simple versions of the non-linear program produce more plausible results. This remarkable conclusion, however, requires further testing before this approach can be accepted as a viable alternative to a real spatial CGE model.

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[6] Okuyama et al. (1999) used a comparable approach, i.e., entropy maximization, to model the impacts of an earth quake in the Midwest of the US. The goal function in their case was restricted to maximizing the entropy of the post-earthquake levels of regional final demand by commodity compared the pre-earthquake levels, whereas Oosterhaven et al. (2013) propose to minimize the information gain for all economic transactions.

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