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A NEW APPROACH TO MODELING THE IMPACT OF DISRUPTIVE EVENTS*

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ABSTRACT. This paper develops a new methodology to predict the interregional and interindustry impacts of disruptive events. We model the reactions of economic agents by minimizing the information gain between the pre- and postevent pattern of economic transactions. The resulting nonlinear program reproduces, as it should, the pre-event market equilibrium. The methodology is tested further by means of a comparison of this base scenario with two regional production shock scenarios and two interregional trade shock scenarios. The outcomes show a plausible combination of partially compensating demand, supply, and spatial substitution effects, which justifies the further development, testing, and application of this new approach.

1. INTRODUCTION

Disruptive events, such as the tsunamis in Indonesia (2004) and Japan (2011), have both short-run and long-run economic impacts. Negative short-run impacts occur, in not only the region and the industries directly hit by a disaster, but due to the disruption of supply chains also in seemingly unrelated regions and industries. These wider, negative impacts are 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 outputs. In rare cases, when the supply of irreplaceable production inputs is hampered, the negative forward effect may, in fact, be many times larger than the direct effect. Simultaneously, industries and regions that step in to replace these supply losses will experience positive instead of negative short-run impacts.

Modeling these impacts is possible by means of an interregional, interindustry computable general equilibrium (CGE) model, as in Tsuchiya, Tatana, and Okada (2007). In fact, different versions of such a model are needed to model these short-run as opposed to the longer run impacts, because short-run substitution elasticities are much closer to

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zero than their longer run equivalents (Rose and Guha, 2004). Moreover, in longer run simulations, many more variables need to be modeled endogenously. Such CGE models are difficult and rather costly to estimate, even if the essential data, such as interregional social accounting matrices and all kind of elasticities, are available (see Albala-Bertrand, 2013).

The much simpler interregional input-output (IRIO) model, with its point-estimated zero demand price elasticities and infinite supply price elasticities, is often used as an alternative, especially for estimating short-run economic impacts. In the context of disruptive events, the main IRIO assumption of fixed technical coefficients may be more or less acceptable, but that is not the case for the equally important, additional IRIO assumption of fixed trade origin coefficients. With this last assumption, imbalances between demand and capacity limited supply occur, which are mostly solved, iteratively, by means of additional equations with arbitrary rationing schemes, as in Hallegatte (2008) and Li et al. (2013). In reality, however, increased imports and reduced exports will prevent most imbalances to occur.

A second problem of the IRIO model is that it is only suited to estimate the impacts of the exogenous drop in the *final* demand of the regions hit, and that answers only part of the short-run question. The impact of an exogenous drop in *intermediate* demand may also be estimated with the IRIO model. That, however, requires *ad hoc* provisions to avoid double counting, as in MacKenzie, Santos, and Barker (2012), because intermediate demand is the core endogenous variable of the IRIO model, instead of an exogenous variable. This problem further deepens when household consumption demand is also endogenous, as in Okuyama, Hewings, and Sonis (1996) and Steenge and Bočkarjova (2007).

Third, the possibly far more important forward or downstream impacts of the drop in supply cannot be estimated with the standard, demand-driven IRIO model at all (see Crowther and Haimes, 2005, for a recent attempt). Unfortunately, using the supply-driven version of the IRIO model (Bon, 1988), to add an estimate of the forward, supply impacts on top of the backward, demand impacts, is unacceptable for two reasons. First, both versions of the IO model are fundamentally at odds with one another, implying that if one version is a good representation of reality, the other version is faulty by definition (Oosterhaven, 1996). Second, the supply-driven IO model itself is highly implausible, since it assumes a single homogeneous input with supply price elasticities of zero. This implies that, for example, cars may drive without gasoline and factories may work without labor (see Oosterhaven, 2012, for the extended case with supply-driven consumption).

The inoperability IO model (Santos and Haimes, 2004), which is another IO-based approach toward disaster modeling, does not capture the forward, supply impacts of disasters either. This holds for both the static and the dynamic variant (Lian and Haimes, 2006) of this model, as both represent a simple transformation of the demand-driven IO model, which expresses the IO model in relative changes (cf. Dietzenbacher and Miller, 2015, and see Jonkeren and Giannopoulos, 2014, for further extensions). Thus, the inoperability IO model suffers from the same problems as the standard IO model.¹

Historically, the hypothetical extraction (HE) method was thought to provide a way to include the forward economic importance of a certain industry, as the standard HE

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¹Additionally, expressing the IRIO model in relative changes requires that exogenous shocks to final demand are expressed as relative reductions of the total output by industry, by region. Consequently, exogenous shocks to the production capacity of an industry need to be scaled down by its final demand share to avoid double counting the endogenous decrease in intermediate demand. Forgetting this, as in Santos et al. (2014, p. 63), results in overestimation of the inoperability by industry, and a wrong rank order of the severity of the backward, demand impacts.

application extracts a complete column as well as a complete row from the IO matrix (Paelinck, de Caemel, and Degueldre, 1965; Strassert, 1968). Recently, the HE method was also recommended to estimate the impact of the (partial) shutdown of one or more industries in case of a serious economic disruption (Dietzenbacher and Miller, 2015). However, the mostly implicit interpretation of the extraction of an IO row to represent the forward impacts of the extracted industry is faulty. What are really measured are the backward impacts of the complete disappearance of the demand for an industry's intermediate sales, not the forward impacts of the secession of these sales upon the purchasing industries.

A further restriction of the HE method is that it is only applicable to smaller, open economies, because it relies on the assumption that the extraction of a row of the domestic IO matrix can be compensated by an increase in the corresponding row of the matrix with imports. This, mostly implicitly made, assumption is needed to maintain the fixed technical coefficients' assumption of the IO model. This restriction, however, at the same time, represents an advantage in that it implies that a well-defined HE method combines the assumption of fixed technical coefficients with fully flexible trade coefficients.

Oosterhaven (1988) uses part of these ideas in his method to measure both the supply and the demand effects of an exogenous drop in primary inputs (labor, capital, and natural resources) in a demand-driven IO model. He, in fact, uses the HE combination of fixed technical coefficients and flexible trade coefficients, but adds inverted technical (i.e., processing) coefficients, which need to be multiplied with the supply shock, to capture the forward impact on purchasing industries. In addition, he allows for partial import substitution, as in MacKenzie et al. (2012), along with partial export substitution (i.e., reduction), to supply part of the lacking intermediate inputs. The disadvantage of his method is that it requires a series of case-specific assumptions about the reactions of the upstream and downstream industries, as in Hallegatte (2008).

Instead of this case-specific introduction of flexible trade relations, Batten (1983, chapter 5) uses the principle of minimum information gain (cf. Theil, 1967) to more systematically estimate intraregional and interregional trade flows in various IRIO settings. When no prior information is given, simple contingency table analysis provides a solution. The maximum entropy method (cf. Wilson, 1970) is suitable when the maximum capacity of each regional transport node is given, while minimizing information gain is suitable when a base year IRIO table is known (cf. Bacharach, 1970). The latter principle is also applicable when a shock to an IRIO system results in exogenously lower production and transport capacities. What is additionally required is the possibility of endogenous changes in the production levels of the indirectly impacted industries and regions.

In this paper, we present a new model that incorporates the above-mentioned building blocks and ideas (i.e., fixed technical coefficients, flexible trade coefficients, partial import and export substitution, and minimum information gain with endogenous totals). We do that in such a way that the outcome gives a reasonable estimate of the short-run economic impacts of a disruptive event, without having to fall back on a series of case-specific assumptions or having to build a full-fledged disaggregate CGE model. In fact, we propose to build a model that combines the simplicity of the IRIO model with the plausibility of the CGE approach. Section 2 presents the model, Section 3 presents the outcomes of a series of shocks to a hypothetical economy, and discusses the plausibility of these outcomes, and Section 4 concludes, and evaluates the possibility of testing and further applying this new model.

TABLE 1: Hypothetical, Two Region, Two Industry, Input-Output Table
(= Base Scenario)

	Region 1		Region 2		Local Consumption		Foreign Exports	Total
	I1	I2	I1	I2	Region 1	Region 2		
Region 1, Industry 1	15	10	5	6	22	15	27	100
Region 1, Industry 2	11	29	9	4	68	14	15	150
Region 2, Industry 1	10	8	35	29	22	49	47	200
Region 2, Industry 2	6	7	38	43	15	102	39	250
Foreign imports, I1	8	13	16	20	15	21		93
Foreign imports, I2	3	3	6	10	4	7		33
Value added	47	80	91	138				356
Total	100	150	200	250	146	208	128	
Additional totals	Foreign imports		126		National consumption			354

2. MODELING METHODOLOGY

The core idea of our model is that economic actors (firms, households, and governments), in the short run after a disruptive event, primarily try to re-establish the old size and pattern of their transactions. In the case of disasters, but not in case of trade boycotts, the disruptive event at hand will cause the destruction of primary factors of production (capital and labor) and transport infrastructures. Primarily in those cases, in the medium and long run, economic actors will also rebuild production and transport capabilities. This will result in a deviation of the old size and pattern of economic transactions for two reasons. First, because rebuilding requires investments that were absent in the pre-event situation, and, second, because new investments mostly imply new technologies that require new mixes of inputs. Hence, for the medium to long run, the outcomes of our model will less and less well predict the postevent size and pattern of the transactions in the economies at hand.

We measure the difference between the pre-event and postevent economic situation by means of the information measure of Kullback (1959) and Theil (1967), which equals $\sum_{ij} z_{ij} \ln z_{ij}^2$ where z_{ij} denotes the transaction between actor i and j . To simulate the *back to business-as-usual* behavior of economic actors, we minimize the difference in the information value of the postevent compared to pre-event market equilibrium, as measured by the interregional input–output table (IRIOT) of the economy at hand. We choose an interregional IOT to, specifically, show the impacts of a disaster in one region on the rest of the interregional economy. Our approach, however, could equally well be applied to a single-region IOT, as long as that IOT has full matrices with intermediate and final imports, as in Table 1.

The measure of Kullback and Theil, however, needs to be adapted to incorporate the criticism that arose upon the introduction of the Generalized RAS algorithm for updating IO matrices with both positive and negative entries (Junius and Oosterhaven, 2003). Huang, Kobayashi, and Tanji (2008) summarize this discussion and propose an Improved GRAS objective function (IGRAS). We use their IGRAS measure and not their comparably well-performing improved normalized squared differences (INSD), because INSD treats positive and negative deviations from the pre-event IRIOT symmetrically, whereas IGRAS puts a heavier penalty on negative deviations. The latter is desirable, as the maximum

²Maximizing entropy (cf. Wilson, 1970) is equivalent to minimizing the information gain. We choose the information gain specification because it allows for a more comprehensible behavioural interpretation.

negative deviation is restricted to -100 percent, whereas positive deviations may be larger than $+100$ percent. Moreover, and more importantly, having “to do” without something should be considered less desirable than being forced “to do” with twice as much. Finally, our actually used version of IGRAS is a little simpler than that of Huang et al., as we do not consider negative economic transactions.

In summary, we thus minimize the information gain of the post-event IRIOT compared to the pre-event IRIOT (indicated by the superscript ex):

$$\begin{aligned} \text{Minimize } & \sum_{ij}^{rs} \left[z_{ij}^{rs} \left(\ln \left(z_{ij}^{rs} / z_{ij}^{rs,ex} \right) - 1 \right) + z_{ij}^{rs,ex} \right] + \sum_i^{rs} \left[y_i^{rs} \left(\ln \left(y_i^{rs} / y_i^{rs,ex} \right) - 1 \right) + y_i^{rs,ex} \right] \\ (1) \quad & + \sum_i^r \left[e_i^r \left(\ln \left(e_i^r / e_i^{r,ex} \right) - 1 \right) + e_i^{r,ex} \right] + \sum_j^s \left[v_j^s \left(\ln \left(v_j^s / v_j^{s,ex} \right) - 1 \right) + v_j^{s,ex} \right], \end{aligned}$$

where z = intermediate demand, y = local final demand, e = foreign exports, and v = gross value added at market prices; with i and $j = 1, \dots, I$, with I = number of industries, $r = 1, \dots, R + 1$, with R = number of regions, $R + 1$ = rest of the world, and with $s = 1, \dots, R$. Note that a summation over the regional origin index r includes a full matrix of foreign imports, whereas a summation over the regional destination index s excludes foreign exports. Furthermore, note that adding the exogenous IRIOT values just before the four closing square brackets in Equation (1) does not influence its solution. It only secures that the minimum value of (1) for the pre-event IRIOT is zero, while it is semipositive for a postevent IRIOT.

The first restriction to minimizing (1) is that all transactions are nonnegative. This means that we do not include the depletion (i.e., negative change) of stocks, as part of final demand, to solve supply shortages. Including this ultra-short-run adaptation possibility (cf. Hallegatte, 2008, Mackenzie et al., 2012) requires information in the pre-event *levels* of stocks. IRIOTs, however, only give information about the historic changes in stocks, but not about their current levels. The latter type of information is usually not, or not easily, available. If available, adding the level of current stocks to the right-hand side of Equation (2) would still prevent introducing negative transactions.

Furthermore, in all scenarios we minimize (1) subject to the following additional constraints:

First and foremost, we assume that the economy is in short-run equilibrium, that is, that demand equals supply, per industry, per region:

$$(2) \quad \sum_j^s z_{ij}^{rs} + \sum_i^s y_i^{rs} + e_i^r = x_i^r, \forall i, r,$$

where, additionally, x = total output.

Second, we assume cost minimization under a Walras-Leontief production function, per industry, per region, which results in (Oosterhaven, 1996):

$$(3) \quad \sum_i^r z_{ij}^{rs} = a_{ij}^{rs} x_j^s \text{ and } v_j^s = c_j^s x_j^s, \forall i, j, s,$$

where, additionally, a = technical coefficients that indicate the need of intermediate inputs, from all regions of origin together, per unit of output, and c = value-added coefficients that indicate the need of primary inputs per unit of output. The a and c are calculated from the balanced pre-event IRIOT as $a_{ij}^{rs} = \sum_i^r z_{ij}^{rs,ex} / x_j^{s,ex}$ and $c_j^s = v_j^{s,ex} / x_j^{s,ex}$, and thus $\sum_i a_{ij}^{rs} + c_j^s = 1, \forall j, s$. Note that the combination of (2) and (3) secures that total

input equals total output for each industry in each region. This implies that the nonlinear program (1)–(3) satisfies the IRIOT accounting identities.

Third, we use the comparable approach of cost minimization under a Walras-Leontief utility function to model the composition of local final demand:

$$(4) \quad \sum_i^r y_i^{rs} = p_i^s y^s \quad \forall i, s,$$

where, additionally, $y^s = \sum_i^r y_i^{rs}$ = total local final demand, and p = package coefficients that indicate the need of final products, from all regions of origin together, per unit of total local final demand. The p 's are calculated from the balanced pre-event IRIOT as $p_i^s = \sum_i^r y_i^{rs, ex} / y^{s, ex}$, which implies that $\sum_i p_i^s = 1, \forall s$.

Fourth, in case of a disruptive event, we assume that the national government, for solidarity reasons, possibly with international aid, supports local final demand, resulting in a minimum regional consumption level:

$$(5) \quad y^s \geq \pi^{s(r)} y^{s, ex}, \quad \forall s,$$

where $\pi^{s(r)}$ defines the minimum level for region s relative to its pre-event value, in case of a disaster in region r . Note that the size of the disaster will limit the national government's ability to support each region's consumption level. If a disaster hits a more populated region, the national impact will be larger. Consequently, it will be more difficult to support regional consumption, leading to lower $\pi^{s(r)}$ compared to the case where the same type of disaster hits a less populated region. In all cases, for solidarity reasons, the $\pi^{s(r)}$ will most likely have a regionally uniform value.

We further assume a limited interregional mobility of primary inputs (capital and labor), which results in a maximum regional value added level:

$$(6) \quad v^s \leq \gamma^s v^{s, ex}, \quad \forall s,$$

where γ^s defines the maximum level for region s relative to its pre-event value. Note that γ^s will vary proportionally with the economic size of the origin regions, corrected for their distance to the destination region, and inversely with the size of the destination region s , as in a gravity model.³

We choose to test our model (1)–(6) with an hypothetical IRIOT with only two industries and two regions, in order to be able to inspect the changes in *all* economic transactions individually, and to avoid discussing the idiosyncratic properties of any specific country. The first test that our model ought to pass is that solving (1)–(6), with $\pi^s \leq 1$ and $\gamma^s \geq 1, \forall s$, that is, the base scenario, exactly reproduces the hypothetical IRIOT (see Table 1), and that is indeed the case. This first positive result, in fact, represents a *conditio sine qua non* of having a plausible simulation model.

The prime purpose of our modeling approach, however, is to analyze the difference between the base scenario and any series of disruptive events. In the further plausibility tests, we analyze two types of disaster scenarios, which consist of solving (1)–(6) with, respectively, the following additional constraints:

(1) In the case of a regional production shock, all output of region r is nullified:

$$(7) \quad \sum_i x_i^r = 0.$$

Model (1)–(6) with Equation (7) is run for each of the two Regions 1 and 2. This, of course, results in two extreme scenarios. In reality, even a major disaster is likely

³Earlier, we also added a positive foreign trade balance restriction, but that resulted in less likely outcomes (cf. Oosterhaven et al., 2013), while that restriction is only relevant in the very long run.

to diminish only partially the production capacity of only a subset of the industries in the region hit. For testing the plausibility of our approach, however, using an extreme scenario will give clearer outcomes than simulating a more realistic, that is, less extreme, scenario.

(2) In the case of an interregional trade shock, all trade from region r to s is nullified:

$$(8) \quad \sum_{ij} (z_{ij}^{rs} + y_i^{rs}) = 0.$$

Model (1)–(6) with Equation (8) is run for two trade stops, namely from Region 1 => Region 2 and from R2 => R1.⁴ Again, we use two extreme scenarios to test our model. In reality, when the cause of the trade stop is a destruction of interregional transport infrastructure, the trade stop will never be as complete as we assume here. On the other hand, in reality, especially in an infrastructure case, but also in a trade boycott case, a trade stop will most likely be two-directional, and not one-directional, as assumed here. Again, this choice is made to get clearer outcomes.

Next, we discuss the plausibility of the estimated impacts of the above shocks, and we discuss whether, based on that, our model represents a good alternative to the existing approaches discussed in Section 1.

3. MODELING OUTCOMES

Before discussing the four disaster scenarios, we summarize the properties of the pre-event market equilibrium.

The Base Scenario

The hypothetical IRIOT that represents this equilibrium (see Table 1) mimics an open economy with the following properties:

- (1) Industry 2 (I2; say Services) is economically larger, produces less tradable products, and generates more value added per unit of output than I1 (say Commodities);
- (2) Region 2 (R2; say Core) is economically larger, produces relatively more commodities and is more foreign export-oriented than R1 (say Periphery);
- (3) Core is a net saver ($91 + 138 - 208 = +21$), while Periphery is a net borrower ($47 + 80 - 146 = -19$), that is, the value added of Core partly finances the local final demand of Periphery; and
- (4) The foreign trade balance is positive ($128 - 126 = +2$), that is, national savings ($356 - 146 - 208 = +2$) are invested abroad.⁵

Note that any IRIOT, like Table 1, in fact, contains two welfare indicators, that is, value added created by region and value added consumed by region. The first indicator (regional GDP) is the best measure of a region's contribution to national welfare, whereas the second indicator (total regional consumption) is the best measure of the welfare of a region's own inhabitants.

⁴We abstained from testing a foreign export and import stop, to keep the number of scenarios small, and because foreign trade stops would be more representative of trade boycotts, whereas our current scenarios are more representative of natural disasters.

⁵Furthermore, possible re-exports of foreign imports are assumed to be zero, production of government and household services is included in Industry 2, thus value added of local consumption is zero, and total input equals total output for each industry in each region.

TABLE 2: The IRIOT After a Complete Production Stop in Region 2

	Region 1		Region 2		Local Consumption		Foreign Exports	Total
	I1	I2	I1	I2	Region 1	Region 2		
Region 1, Industry 1	19	13	0	0	21	21	21	95
Region 1, Industry 2	14	38	0	0	55	50	11	167
Region 2, Industry 1	0	0	0	0	0	0	0	0
Region 2, Industry 2	0	0	0	0	0	0	0	0
Foreign imports, I1	13	22	0	0	19	37		90
Foreign imports, I2	5	5	0	0	4	34		49
Value added	45	89	0	0				134
Total	95	167	0	0	99	141	32	
Additional totals	Foreign imports		139		National consumption			241

To simulate the two types of disaster scenarios, first, the parameters $\pi^{s(r)}$ and γ^s need to be set by means of the data from the base scenario in Table 1.

The disaster-specific theoretical maximum for a uniform minimum consumption level, $\pi^{s(r)}$ in Equation (5), is reached when the total value added of the nondisaster region s is spent proportionally to the pre-event regional consumption levels. In case of a full shutdown of all production in the economically small R1 this value equals $229/354 = 0.65$, and in case of a comparable shutdown in the much larger R2 it becomes as low as $127/354 = 0.36$ (see Table 1). Higher values are possible if international aid is substantial. Lower values are likely if interregional solidarity only relates to providing basic needs. In our tests, we halve the difference with 1.0 (i.e., the pre-event level of local consumption). This gives $\pi^{s(R1)} = 0.82$ for the most extreme R1 production shutdown and $\pi^{s(R2)} = 0.68$ for a comparable disruptive event in R2.

The region-specific theoretical maximum value-added level, γ^s in Equation (6), is determined by the maximum interregional migration of all primary inputs. This gives a γ^s of $356/127 = 2.80$ for the smaller R1 and $356/229 = 1.56$ for the larger R2 (see Table 1). Higher values are possible when international migration of capital and labor occurs. Lower values, however, are far more likely, because domestic mobility of capital and labor is limited in the short run, while part of the primary inputs in the disaster region will be destroyed. Assuming a maximum possible migration of only one-half of the primary inputs, we halve the difference with 1.0 (the zero migration case), which gives $\gamma^1 = 1.90$ and $\gamma^2 = 1.28$.

The Two Production Shock Scenarios

As said before, the solution of (1)–(6), with $\pi^{s(r)} \leq 1$ and $\gamma^s \geq 1$, exactly reproduces the pre-event IRIOT, as it should.⁶ Adding Equation (7) for Region 2 simulates the post-disaster equilibrium after a complete production stop in R2. Table 2 shows the outcomes of this simulation. The gray background indicates a negative deviation from the base scenario in Table 1, and a white background indicates a positive deviation. The simulation of a complete production stop in R1 results in the same pattern of deviations from the base scenario. Since the results for the smaller R1 are qualitatively the same, but have smaller amounts, they are not discussed.

⁶All scenarios are solved by means of the *fmincon* function with the *interior-point* algorithm from MATLAB, version 2014a.

At first sight, the cross of zeros in Table 2 suggests a result that is similar to applying the HE method to Region 2 (cf. Dietzenbacher, van der Linden, and Steenge, 1993). The same holds for the increase of the foreign import of intermediates, which substitutes for the loss of supply of intermediates from Region 1. Closer inspection, however, shows a series of differences.

Contrary to the increase of the foreign imports of intermediate products, the HE method does not predict an increase in the foreign import of final products, as final demand in the IO model is exogenous. In reality, however, the same spatial substitution for the lost supply of R2 would occur for final demand, which is what our model predicts and what CGE models allowing for spatial substitution would predict. Analogously, Table 2 also predicts an increase in the interregional import of final outputs into R2, which, as part of final demand, does not change with the HE method either.

The qualitatively biggest difference with the HE method occurs for the four intermediate transactions within R1 (see the upper left submatrix of Table 2). In the case of HE, the total output of both industries will decrease because of the loss of demand from R2. Consequently, all intermediate transactions within R1 will decrease proportionally because of the fixed interregional input coefficients of the IRIO model. Table 2, however, predicts an increase instead of a decrease, as would most CGE models, because not only foreign industries, but also domestic industries will step in to compensate for the loss of supply from the disaster region. In fact, *spatial substitution* will occur for both intermediate and final demand, and for international, interregional as well as intraregional transactions.

Interestingly, the counteracting demand, supply, and spatial substitution effects on the output of R1's industries, work out negatively for Industry 1 and positively for Industry 2. The direct loss of intermediate demand is -11 and -13, for I1 and I2, while the direct loss of intermediate supply is -16 and -15 (see Table 1). These comparable losses, however, are more severe for the smaller I1 than for the larger I2. Moreover, the substitution demand due to the drop in intraregional supply to consumers in R2 is much smaller for I1 (-49) than for I2 (-102, see Table 1). Consequently, it is not surprising that negative direct effects dominate in case of I1, but not for I2. Additionally, note that the net impact on the total value added of Region 1 is positive, whereas it would be considerably negative with the HE method.

The last differences are found for the foreign exports and intraregional final sales of R1's industries. With the HE method, these do not change, because they are exogenous in the IRIO model, but in Table 2 they decline. In both cases, a negative impact is far more plausible than no impact. The own regional consumers and foreign customers of R1's industries are supplied with less products to accommodate part of the big gap in the supply to their equivalents in R2. Our approach thus generates *partial* foreign export substitution along with *partial* foreign import substitution to compensate for the internal drop in supply. In both cases, the substitution is partial as domestic supply from R1 supplements the foreign supply, and because the drop in supply is not fully compensated.

The fact that R1's own consumers also help to mitigate the losses of R2 was not noted in the literature. This outcome, however, is very plausible in view of the impact on this economy's macro economy. Given the extremeness of the disaster, that is, a complete production stop in the Core region, it is not surprising that total national value added (GDP) declines from 356 in Table 1 to only 134 in Table 2. Because of the strong increase in foreign imports and the decrease in foreign exports, the foreign trade surplus of +2 in Table 1 turns into a deficit of -107 in Table 2. National consumption, consequently, declines much less than GDP, but still goes down from 354 to 241.

Without the minimum consumption restrictions (5), national consumption would have gone down more, as is evident from the positive shadow prices for Equation (5)

TABLE 3: Cost of Disaster and Main Shadow Prices for the Disaster Simulations

	Production Stop		Trade Stop	
	In Region 1	In Region 2	R1 => R2	R2 => R1
Value of objective function, Equation (1)	484	826	61	83
Disaster restriction, Equation (7)/(8)	6.4E + 11	1.1E + 12	6.6E+12	1.5E + 13
Use = supply for R1, I1, Equation (2)	1.98E + 11	0.240	-0.187	0.243
Use = supply for R1, I2, Equation (2)	1.98E + 11	0.316	-0.168	0.182
Use = supply for R2, I1, Equation (2)	0.074	3.50E + 11	0.101	-0.163
Use = supply for R2, I2, Equation (2)	0.168	3.47E + 11	0.085	-0.104
Min. consumption for R1, Equation (5)	0.996	0.146	0	0.282
Min. consumption for R2, Equation (5)	0.070	1.166	0.132	0

in the first two columns of Table 3, which indicates that these restrictions are binding, especially, of course, for the region hit by the disaster, but also for the nonhit region. A smaller disaster, obviously, would result in a smaller welfare loss, as is also evident from Table 3. The total cost (in row 1) and the marginal cost (in row 2) of a complete production stop in the smaller Region 1, in terms of objective function (1), are much smaller than those of a production stop in the larger Region 2. The same difference is found for the other shadow prices, which all show the marginal cost of imposing the corresponding restrictions in terms of the objection function (1). All model restrictions thus weigh less heavy in case of a smaller disaster, as may be expected.

Finally, note that the shadow prices for the maximum value added restrictions (6) are not shown in Table 3. The reason is that they all equal zero. This means that these restrictions are *not* binding, that is, they do not influence the predicted short-run impacts of the two production stops.

The Two Trade Shock Scenarios

Next, consider the two complete interregional trade stops, specified by Equation (8). To simulate these two shocks, the disaster-specific minimum regional consumption levels in Equation (5) are halved again to $\pi^{s(R1 \Rightarrow R2)} = 0.91$ in case of a trade stop from R1 => R2, and to $\pi^{s(R2 \Rightarrow R1)} = 0.84$ in case of the reverse trade stop. The shadow prices of the solution of adding (8) to (1)–(6) are shown in the last two columns of Table 3.

These columns confirm that the restrictions weigh less heavily for smaller disruptive events, as both the total and marginal cost, and the shadow prices of the two trade stops are far smaller than those of the two production stops. Moreover, note that the trade stops only affect interregional trade in one direction, while leaving regional production capacities intact. The latter, specifically, explains why the extreme values for the shadow prices of the market equilibrium conditions (2), in the first two columns of Table 3, disappear in the last two columns.

Finally, the most intriguing results in Table 3 are the gray-marked, negative shadow prices for the market equilibrium conditions (2) in case of both trade stops. Take the trade stop from R2 => R1 in the last column. This shock implies a loss of markets for the industries of R2. The negative shadow prices, in that case, indicate that exogenously adding stocks to the supply in R2 results in a further economic loss, as there are no ready customers for this additional supply, whereas exogenously adding stocks to the supply from R1 results in an economic gain, as it would compensate for the loss of supply from R2. Another result of the loss of export markets for industries in R2 is that meeting the minimum consumption requirement in their own region is not a problem anymore, as is evidenced by the zero shadow price for that constraint.

TABLE 4: The IRIOT After a Full Trade Stop from Region 2 => Region 1

	Region 1		Region 2		Local Consumption		Foreign Exports	Total
	I1	I2	I1	I2	Region 1	Region 2		
Region 1, Industry 1	19	12	3	4	26	12	21	98
Region 1, Industry 2	15	35	6	3	68	12	12	151
Region 2, Industry 1	0	0	33	30	0	58	55	176
Region 2, Industry 2	0	0	35	41	0	113	43	233
Foreign imports, I1	13	19	13	17	23	21		107
Foreign imports, I2	5	4	5	9	5	7		35
Value added	46	81	80	128				335
Total	98	151	176	233	123	222	132	
Additional totals	Foreign imports		142		National consumption			345

Table 4 shows the associated outcomes for the transaction volumes in case of a trade stop from the bigger R2 => R1. The zeros indicate which interregional trade flows are stopped. The results for a trade stop from the smaller R1 => R2 are qualitatively almost similar, which is why they are not discussed.⁷

First, we look into the impacts on Region 2. Table 4 shows that the loss of R2's exports to R1 leads to a supply-driven increase in the sales to R2's own consumers and R2's own foreign customers. In both industries, these increases are not sufficient to compensate for the loss of exports to R1. The resulting drop in output and value added leads to a proportional decrease in the demand for intermediate inputs by R2's industries. In case these inputs come from R2 itself, the increase in intraregional supply dampens the effect of the decrease in demand from R1, resulting in a small net decrease. In case these inputs come from R1 and abroad, no such countervailing force exists, resulting in far larger drops in imports (compare Table 1 with Table 4).

For the consumers in R2, the increase in the supply from R2's industries, of course, leads to a reduction in the demand for imports from R1 and from abroad. Still, as usual, the primary effect is larger than the secondary effect, resulting in a net increase in total consumption in R2. Note that, because of counterbalancing price effects, all of the above effects will also be predicted with most CGE models, whereas an IRIO model, because of its inability to handle supply effects and spatial (import and export) substitution effects, could never predict them.

Next, we look into the quite different impacts on Region 1. The drop in the supply of imports from R2 leads to an increase in R1's demand for R1's own products and its demand for foreign imports. An opposing force is the increase in the intraregional sales and foreign exports of R2, which reduces the demand for R1's outputs by R2 and the rest of the world. The net effect turns out to be positive for Industry 2 (value added +1), but negative for I1 (value added -1). Note again that, because of counterbalancing price effects, these types of impacts would also be predicted by most CGE models, but not by an IRIO model.

Finally, it is of interest to look at the impacts on regional savings and the foreign trade balance. The foreign trade balance changes, between Table 1 and Table 4, from +2 to -10, due to an increase in foreign exports of +4 (+12 for R2 and -9 for R1), and an increase in foreign imports of +16 (+23 for R1 and -8 for R2).⁸ Regional savings change, between Table 1 and Table 4, from -19 to +4 for R1, and from +21 to -14 for R2.

⁷The difference is that the value added and total output of both industries in Region 2 increases, instead of only those of Industry 2 in Table 4.

⁸The sums are not exact, as each number is rounded-off individually.

Consequently, the pre-event +19 contribution of R2's value added to R1's consumption changes into a reverse flow of +4 from R1 to R2.

In summary, we have simulated and discussed various opposing supply, demand, and spatial substitution effects, as well as their net effects on individual transactions, and we concluded that the varying impacts are plausible. In the case of the smaller interregional trade shocks, we even found opposing effects at the aggregate level for total regional consumption, which also makes sense, because industries that are cut off from part of their markets will increase their sales to local consumers.

4. CONCLUSION AND EVALUATION

To arrive at these results, we developed a new nonlinear programming model that mimics the short-run *back to business as usual* reactions of firms and households to a disruptive event in a specific region. We tested the model by exposing a hypothetical open, two regions, two industries economy to two extreme production and two extreme interregional trade shocks. We have chosen to test our model for an aggregated economy and for extreme shocks in order to be able to inspect the changes in all transactions and to get clear outcomes. The tests show plausible mixes of demand and supply effects, next to domestic and foreign, intermediate and final, import and export substitution. The model is also able to simulate situations where the negative direct demand and supply effects dominate as well as situations where the positive indirect substitution effects (of stepping in to fill the supply gaps) dominate.

The obvious next step in the further development of this model is to test it against a real interregional IO table and a real disaster. For a good test, this requires a major disaster that occurred in the beginning of a calendar year. Analyzing a major disaster reduces the need to specify the alternative development of the economy in absence of that disaster. Analyzing a disaster occurring in the beginning of a calendar year ascertains that the full short-run impacts show up in the IRIOT of that year. The difference between the modeling outcomes and reality, under those conditions, can be attributed primarily to the impacts of the disaster.

Furthermore, it would be desirable to test the model with more regions and, especially, with more industries. In the latter case, the extra-large multipliers that occur when the supply of nonreplaceable inputs is hampered are more likely to show up. The aggregate nature of our present test prevented such situations to occur.⁹ In addition, it would be desirable to disaggregate value added into the contributions of labor, capital, land, and natural resources, in order to differentiate the direct impacts of the disruptive event at hand, and to thus better specify the maximum regional primary input restrictions.

Finally, it is desirable to test the model with an interregional Social Accounting Matrix (ISAM) instead of with an IRIOT, as an ISAM specifies the interregional income redistribution process, which enables a more sophisticated modeling of the minimum regional consumption restrictions. In all, there is still a world of model development and testing ahead.

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⁹Technically, this is related to the absence of zeros for the trade in intermediate products in Table 1.

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