Fondazione Eni Enrico Mattei

Assessing the Consequences of Natural Disasters on Production Networks: A Disaggregated Approach

Fanny Henriet and Stéphane Hallegatte

NOTA DI LAVORO 100.2008

DECEMBER 2008

CCMP – Climate Change Modelling and Policy

Fanny Henriet, *Centre International de Recherche sur l'Environnement et le Développement, France*
Stéphane Hallegatte, *Centre International de Recherche sur l'Environnement et le Développement, France and Ecole Nationale de la Météorologie, Météo-France, France*

Assessing the Consequences of Natural Disasters on Production Networks: A Disaggregated Approach

Summary

This article proposes a framework to investigate the consequences of natural disasters. This framework is based on the disaggregation of Input-Output tables at the business level, through the representation of the regional economy as a network of production units. This framework accounts for (i) limits in business production capacity; (ii) forward propagations through input shortages; and (iii) backward propagations through decreases in demand. Adaptive behaviors are included, with the possibility for businesses to replace failed suppliers, entailing changes in the network structure. This framework suggests that disaster costs depend on the heterogeneity of losses and on the structure of the affected economic network. The model reproduces economic collapse, suggesting that it may help understand the difference between limited-consequence disasters and disasters leading to systemic failure.

Keywords: Natural disasters, Economic impacts, Economic Network

JEL: D20, Q54, R15

The authors want to thank Patrice Dumas, Jean-Yves Grandpeix, Francois Gusdorf, and Nicolas Naville for their useful comments and suggestions on an earlier version of this article.

Address for correspondence:

Stéphane Hallegatte
CIRED
45bis Av. de la Belle Gabrielle
F-94 736 Nogent-sur-Marne
France
Phone: +33 1 43 94 73 73
Fax: +33 1 43 94 73 70
E-mail: hallegatte@centre-cired.fr

1 Introduction

Recently, natural disasters have raised a growing concern about the response of local economies to large exogenous shocks. Clearly, our ability to assess the total long-term cost of a large scale event, such as the Katrina's landfall, is very poor. Not only is it very difficult to evaluate direct losses due to a natural disaster, i.e. the repairing or replacement cost of the assets that have been destroyed or damaged, but it is even more difficult to evaluate indirect losses. Indirect losses are sometimes even difficult to define, as shown by Rose (2004) who proposes useful definitions and reviews the risks of double-counting.

These indirect impacts are due to complex interactions between businesses and other economic agents. In particular, they arise from production bottlenecks through chains of suppliers and producers. These bottlenecks may even be made more likely by the modern production organization (e.g., production on demand, small or absence of inventories, limited number of suppliers) that makes each production unit more dependent on the ability of its suppliers to produce in due time the required amount of intermediate goods. The assessment of the cost of these interactions is all the more difficult because they are highly variable (from one event to another, from one region to another) and depend deeply on the economic structure and on the shock specificities. It seems obvious, for instance, that a given amount of damages would have more serious consequences if the damages affect mainly an infrastructure sector (e.g., electricity production and distribution) than if these damages are spread equitably among sectors.

These questions have already been the topic of intense modeling effort (Rose et al., 1997; Brookshire et al., 1997; Cochrane, 2004; Okuyama, 2004; Okuyama and Chang, 2004; Rose and Liao, 2005; Hallegatte, 2008). A useful review of these methods, and of their shortcomings, is proposed in Rose (2004). In these studies, as in multi-sector RBC literature (e.g. Horwath, 1998; Dupor, 1998), however, the economy is described as an ensemble of economic sectors, which interact through an input-output table. As shown in Hallegatte (2008), however, such a representation of the economy may be insufficient to model disaster consequences. Indeed, business interruptions and production losses due to production bottlenecks after a disaster can arise from many small-scale mechanisms, including supplier failures, lifeline and transportation perturbations, impossibility for customers or workers to reach the production location, or bankruptcy of individual businesses. These mechanisms are very difficult to represent at the sector scale and need a much more detailed analysis (see, e.g., Haimes and Jiang, 2001).

Moreover, these complex interactions between firms are likely to be an important source of nonlinearity and a model that would not take them into account is at risk of underestimating indirect losses. It is interesting to note, for instance, that the 2004 hurricanes [1] did not have the widespread consequences on the Florida economic system that hurricane Katrina had in Louisiana (compare, for instance, McCarty and Smith (2005) on the 2004 hurricanes and Bureau of Labor Statistics (2006) on the impact of Katrina). Of course, this is due to the facts (i) that Katrina was more violent than the 2004 hurricanes, and caused far more direct damages; (ii) that the area in the path of Katrina was evacuated, and many people had to leave their houses and could not return after the landfall; and (iii) that New-Orleans suffered from floods, which were not insured for, making the recovery more difficult. But the most important factor is probably the fact that Katrina affected the *systemic functioning* of the Louisiana and New Orleans economies, by disrupting the economic system in such a way that even businesses that did not suffer any damage could not function normally. These disruptions made economic production almost impossible and, therefore, lead to an almost complete collapse of the local economy. On the opposite, the losses due to the 2004 hurricanes were important, but they spread over a wider area and did not impair the whole Florida economic production in 2004, ensuring that reconstruction could be easily and rapidly performed. It seems, therefore, that there is a threshold between the 2004 losses in Florida and the 2005 losses in New Orleans: in the former case, losses remained below a critical level and did not impact too badly crucial sectors and, as a consequence, the economy remained able to function almost normally in spite of the losses; in the latter case, losses exceeded a critical level, and the economic system was basically paralyzed by the losses, making the reconstruction very difficult [1] . The main aim of this paper is to provide insights on this threshold and its determinants.

To do so, this article proposes a disaggregated Input-Output (IO) model, in which the economy is described as a network of production units (PU), in the line of Delli Gatti et al. (2005); Battiston et al. (2007); Weisbuch and Battiston (2008). This network is subject to shocks, due to disasters, and reacts with various adaptation processes.

The aim of this first analysis is to get a better understanding of the mechanisms at stake, and to identify the decisive parameters in the recovery of a local economy. It is important to note that the model that is proposed in this paper disregards many essential mechanisms (e.g., impact on consumer demand, links with non-affected regions, recovery and reconstruction process), so that the model cannot provide a quantitative assessment of the cost of any given disaster. The model, therefore, cannot be considered as an operational model. So far, the model proposes explanations and models for stylized facts that have been observed in disaster aftermaths, and highlights where more research is needed. Hopefully, follow-up papers will expand this first tentative model to take into account additional dimensions of disaster consequences. By identifying decisive parameters, moreover, this analysis suggests

[1] During the 2004 hurricane season, four hurricanes made landfall on Florida: Charley, Frances, Ivan, and Jeanne.

[1] See an analysis of the link between reconstruction capacity and disaster total cost in Hallegatte et al. (2007).

that additional data collection is necessary and emphasizes which data should be collected.

The next section reviews briefly (and non-exhaustively) empirical findings from the literature on direct and indirect impacts of historical extreme events, to justify our modeling approach. Section 3 presents the features of our disaggregated input-output model. Section 4 uses then a simple synthetic disaster to investigate the model behavior, providing both a reference simulation, with our best-guess parameters, and a sensitivity analysis on the most important features of our model, namely the characteristics of the adaptation process, the number of PUs in the economy, the redundancy in the economic system, and the level of inventories. Section 5 investigates systematically the influence of loss heterogeneity on total economic losses, with distributions of direct losses inspired by the landfall of Katrina on Louisiana. Section 6 concludes and emphasizes needs for future research.

2 Economic impacts of historical extreme events

The literature about the impacts of natural disasters is abundant and cannot be easily summarized in a few paragraphs. This section focuses therefore on the most salient stylized facts of disaster consequences, and especially on the impacts on production systems, i.e. on the firms and their network.

Tierney (1997) studies the impacts of the Northridge earthquake in 1994, and provides a very useful quantitative assessment of direct and indirect impacts. According to her analysis, 57% of the businesses of the affected area suffered some degree of physical damage in the earthquake. Most importantly, damages were distributed very heterogeneously among firms: the mean loss was $156 273, while the median loss was only $5 000. A number of businesses reported very high losses, the highest loss being $14 million, but minor damages were widespread.

As far as indirect impacts are concerned, the earthquake produced extensive lifeline service interruption and the loss of lifelines was a larger source of business interruption than direct physical damages. In addition to direct physical impacts and the interruption of critical utility services, the disaster caused business losses through the disruption of customer and worker ability to reach business locations. Moreover, nearly one business in four had problems with the delivery of goods and services following the earthquake and, on average, businesses were closed for about 2 days. In this case, direct damages to the business building were only the seventh cause of closure, present in 32% of the cases.

On the same event, Gordon et al. (1998) and Boarnet (1998) confirm the fact that indirect impacts are essential. They find that a substantial share of business interruption were due to off-site problems, such as disruptions in the transportation system that restricted the movement of goods and supplies and the inability of employees to come to work. It is very important to note that, irrespective of their own individual levels of damage and disruption, firms had more difficulty to remain active if they were located in the high-impact area.

Kroll et al. (1991) investigate the consequences of the Loma Prieta earthquake (1989) on small business and on their ability to recover after the disaster. According to their analysis, the long term recovery of a small business depends on its location, the amount of direct losses it suffered, its level of inventories, and on local characteristics of the economy. For example, the economic consequences of the Loma Prieta earthquake have been limited in Santa Cruz, because this location was located farther from the earthquake epicenter, but also because (i) this economy was particularly diversified; (ii) the transportation network was very redundant; and (iii) the closure duration of utilities was short. They also find that small businesses suffered more from the disaster than larger ones, mainly because they depend more strongly on the local economy and because they cannot turn as easily to other customers after the disaster.

Webb et al. (2002) examine the long-term impacts of two natural disasters on firms: the Loma Prieta earthquake (1989) and the hurricane Andrew (1992). Even if most of the firms in the affected region claimed that they were better off after than before the disaster [2], in the Dade County, where hurricane Andrew caused most of the losses, firms were in majority worse off after the disaster than before, showing that individual firm situations depend strongly on the loss density. Also, the firms that were present in a national or international market, i.e. the firms whose clients were not exclusively in the damaged area, were more likely to recover than the firms that only sold goods or services within their local market. Finally, they conclude that, among the determinants of recovery, both direct and indirect damages are decisive.

The indirect impacts of a disaster on a production network depend on which sectors suffer the most from direct damages. For instance, the water and electricity sectors play essential roles for the whole economy, and their vulnerability to disaster can be crucial. In Rose et al. (2007), for instance, the authors mention results by the National Federation of Independent Business concerning the impacts of the Los Angeles black-out in 2001. They found that one half of affected firms were forced to decrease their operations. Approximately 15.2% of firms suffered from indirect effects (because of disruptions in services and transportation), and 13.7% could not sell their production because the customers were not able to come. Importantly, they evaluates that the cost of the blackout was twice the cost of direct effects. In Rose and Liao (2005) and Rose et al. (2007), the authors model these effects, using a general equilibrium framework where adaptation capacity is taken into account using elasticities of substitution. They show both that indirect effects are potentially large and that adaptation mechanisms can be very efficient in reducing these indirect losses (by up to 86% in their case study on a terrorist attack on the electricity power grid serving Los Angeles County).

[2] Macroeconomic changes at the national level may have played a role in this change.

These findings suggest that indirect impacts are often significant and highlight the need to focus on the mechanisms that lead to such impacts. The indirect losses on the whole economy depend on which sector is affected by direct losses, for instance the disruption in the transportation network and lifelines are a widespread cause of indirect losses in disaster aftermaths. The firm location plays a significant role in its ability to recover, and the indirect losses depend on the production network characteristics and on the damages heterogeneity among firms. These facts imply that modeling the economy as a set of interacting sectors is not enough to assess disaster costs, and that a much finer modeling, e.g. at the production-unit scale, is necessary.

3 ARIO-network, a model at the production-unit scale

The ARIO-network model is an extension of the Input-Output ARIO model presented in Hallegatte (2008). But while ARIO is disaggregated at the sector level, ARIO-network is disaggregated at the firm level and introduces inventory dynamics.

ARIO-network describes how each firm from each sector uses input from other firms to produce goods or services. This disaggregated model takes into account the interaction between production units and is in line of Delli Gatti et al. (2005); Battiston et al. (2007); Weisbuch and Battiston (2008), except that the modeled network is built to be consistent with IO table at the sector scale. It represents the fact that each firm relies on regional suppliers and clients and that a decrease in a firm production can result in ripple effects through chains of suppliers and clients. The extent of these ripple effects depends on whether there are alternative producers elsewhere and on how much time the perturbation lasts. But it also depends on adjustment mechanisms. For instance, when a supplier is not able to produce enough, the production of its client does not automatically decrease, because adjustments that allow it to maintain production can take place: (i) it may be possible for the client to import intermediate goods from outside the damaged area; or (ii) the client may find an alternative local producer that is able to produce more than its usual production and replace the failing one; or (iii) the client may have enough inventories to wait for its suppliers to restore their activity.

In this first attempt to assess disaster consequences, we focus on the impact on the production system, and we do not model the impact on households, and the corresponding effect on final demand and labor supply. We consider a closed production system, without imports and exports. We also disregard the reconstruction process, assuming that production units that are damaged will remain damaged for ever: we investigate, therefore, how the economic system can adjust to the definitive loss of Production Units (PUs), without pretending to reproduce the full effect of a disaster. Finally, we did not include in the model the possibility of business financial bankruptcy, which is an important process in the case of Katrina. In future works, households, reconstruction and bankruptcies will be implemented into the model, in order to be able to assess the overall consequences of natural disasters.

This model version is not, therefore, able to quantify the economic losses caused by a disaster. In spite of its limited scope, however, the current model version already provides interesting insights into disaster consequences, and explores the difficulties in quantifying them.

3.1 The economic network

3.1.1 From sectoral to disaggregated IO tables

There is no data that describe in a comprehensive manner the economic network of any region at the production-unit (PU) scale. This situation will not change in the near future: such a data set would be extremely difficult to collect and constant changes in the economic system would make it obsolete before its completion. But there exist innovative and interesting attempts to improve our understanding of plant-to-plant relationships. For instance, Hortacsu and Syverson (2007) combine information from various sources to build useful plant-to-plant databases. This type of work provides information about the network structure (e.g., number of suppliers per plant in various sectors). However, it is unlikely that it will ever provide the full description of the economic network that would be needed for an explicit modeling of the economic network.

This is why the disaggregated model proposed here is based on a synthetic production-unit input-output (PU-IO) table, developed from a sectoral input-output table and from simple network characteristics (e.g., number of PUs per sector, number of suppliers per PU, number of clients per PU). Compared with previous works (e.g., Battiston et al., 2007), the difference here is that we created a PU-IO table that is consistent with aggregated IO data at the sector level and with network characteristics that we chose in an *ad hoc* manner.

Because of numerical limitations, the current model represents an economy that is not as complex as the real one. For instance, the Louisiana economy has about 100 000 production units (see below) whereas in this paper, as a first step, the modeled economy consists only of 500 to 1000 production units.

We started from the 15 sectors of the Bureau of Economics Analysis IO table. The sectors are: (1) Agriculture; (2) Mining and extraction; (3) Utilities; (4) Construction ; (5) Manufacturing; (6) Wholesale trade; (7) Retail trade; (8) Transportation; (9) Information; (10) Finance; (11) Business services; (12) Education; (13) Arts and food; (14) Other services; (15) Government. From this U.S. table, a regional table for Louisiana has been built, using Gross State Product for Louisiana (see

Sector	Agric.	Min.	Constr.	Util.	Manuf.	Whole	Retail.	Transp
Proportion	4%	2%	2%	8%	4%	6%	18%	4%
Sector	Info.	Finance	Busi.serv.	Educ., health	Food, Art	Serv.	Gov.	
Proportion	2%	12%	12%	12%	10%	10%	4%	

Table 1
The proportion of production units among sectors.

details in Hallegatte, 2008) and simple assumptions about the proportion of each sector production that is exported outside the region.

Building the disaggregated IO table requires then to know the number of PUs in each sector or, if the full economy cannot be modeled, the proportion of these PUs for each sector relative to the total number. We used data on Louisiana in 2004, from the Census bureau, which give the number of PUs per sector and their size distribution (*www.census.gov*). The proportion of PUs per sector is given in Tab.1.

Using this information, we expand the sectoral IO table into a PU-IO table, which describes the exchanges between all PUs of the local economy. Obviously, this PU-IO table is much larger than the sectoral one, since its size is NxN, where N is the number of PUs in the economy. Also, this table contains mostly zeros, since most PUs have no direct relationship with each other.

For simplicity, we assume that all the PUs from a given sector produce the same commodity and have the same size. In a future evolution of the model, it could be the case that PUs among a sector produce imperfectly substitutable commodities and have different sizes. In the current version, however, computational limitations on the size of the modeled economy makes it impossible to reproduce the observed distribution of plant sizes, and we chose to assume that they have the same size in each sector (PUs from different sectors have different sizes). All PUs produce and exchange intermediate consumption goods and services, and produce final consumption goods and services for local demand. We assume that all PUs need input from PUs that belong to all the other sectors. Also, each PU has several suppliers from each sector. Given that we have assumed that all PUs from the same sector have the same characteristics (same production and same size), we assume that they have the same number of suppliers.

Of course, there are many restrictions to the PU-IO table structure (see an example on detailed sectoral IO tables in Carvalho, 2008). For instance, the sum of the ith line is the production of the ith PU that is sold to other PUs and must, therefore, be consistent with the sum of the ith column, when sales to consumers, wages and profits are taken into account. In this article, we do not try to investigate all possible network structures, focusing on the agent behavior modeling. As a consequence, we use a single network structure, described hereafter, that satisfies the consistency constraints. We are well aware of the existence of other possible structures, which could yield different model results. Because of length constraints, however, an investigation of various possible network structures is left for future research.

We define the *sectoral connection matrix* $C_{p,l}$, which is composed of 0 and 1 and describes which clients from the sector p buys intermediate goods from which suppliers of the sector l. The component $C_{p,l}(i,j)$ is equal to one if the i^{th} PU from sector p buys goods from the j^{th} PU from sector l, and to zero otherwise. Here, we assume that this matrix has the following structure:

$$C_{p,l} = \begin{bmatrix} 0 & 1 & ... & 1 & 1 & 0 & ... & 0 & 0 & 0 \\ 0 & 0 & 1 & ... & 1 & 1 & 0 & ... & 0 & 0 \\ 0 & 0 & 0 & 1 & ... & 1 & 1 & 0 & ... & 0 \\ ... \\ 0 \\ 1 & 0 \\ 1 & 1 & 0 & ... & 0 & 0 & 0 & 0 & 1 & ... \\ ... & 1 & 1 & 0 & ... & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The number of suppliers from the sector l of a PU from the sector p is given by $\alpha_{p,l} \times n_l$ where n_l is the total number of firms from sector l and $\alpha_{p,l}$ is a redundancy parameter. Similarly, the number of clients in sector p of a PU from sector l is given by $\alpha_{p,l} \times n_p$. Once $\alpha_{p,l}$, n_l, n_p are chosen, the total amount of exchanges between the two sectors, given by the aggregated IO table, is divided by the number of transactions, which is equal to the number of 1 in the matrix $C_{p,l}$, to get the connection size $\gamma_{p,l}$, i.e the amount bought by one PU from sector p to one PU from sector l. All the $\gamma_{p,l} \cdot C_{p,l}$ matrix are then gathered in a large matrix A, the *PU-IO* matrix, which describes the amounts exchanged between all the PUs of the economy. During the adaptation process, PUs will have the opportunity to change the structure of A, by adding new links and by strengthening or weakening existing links.

The values of the $\alpha_{p,l}$ are chosen to set the density of the production network and the redundancy of the links between sectors. The *PU-IO* matrix that is used here is obviously very distinctive and a more in-depth research on graphs would probably suggest different types of networks that are consistent with the sectoral IO table. For instance, the “configuration model” (Newman, 2003) could be used to create networks with different structures. As a first analysis in this direction, however, this simple matrix form has been used.

As one can notice, all the vertices do not have the same degree. For instance, PUs from small sectors, i.e. sectors that have few PUs, have many clients and suppliers and vice-et-versa. For instance, power plants have a very high degree, since they are “hubs” in the network. The network of sales and purchases can be seen as an oriented graph, where orientation corresponds to the fact that the interaction is a sale or a purchase. The degree of a vertex from sector p is: $\sum_l (\alpha_{p,l} + \alpha_{l,p}) \frac{n_l}{n_p}$. It depends on the vertex sector size (with respect to other sector sizes) and on the redundancy parameters.

3.1.2 Stockable and non-stockable goods

Some commodities, for instance those produced by the manufacturing sector, can be stocked, while it is almost impossible to stock electricity. As a consequence, in case of black-out, all PUs that depend on electricity will stop producing ; while if a PU from the manufacturing sector is damaged, its client will have the possibility to draw from their inventories in order to produce at least a fraction of their usual production for a certain period of time.

To take into account this difference, we introduce inventories in the production process. Practically, all PUs have inventories of the goods or services produced by each of their suppliers. At each point in time, production in all PUs is done using inventories only. These inventories are measured in numbers of days of pre-event consumption by the PU. For instance, an automaker factory may have a tire inventory allowing it to produce cars during 15 days at the pre-event production pace. For simplicity, non-stockable goods – like electricity – are modeled assuming that their inventories cannot be larger than what is needed to produce during one day. It means that, if electricity is shut down, production in the affected area will be stopped the next day only. This assumption is not fully satisfying, but it allows for a useful simplification of the model without changing in a significant manner the results.

3.2 A disaggregated model of the production system

In this model, like in Battiston et al. (2007), we represent the independent behavior of each PU. Each PU, indeed, acts according (i) to demand, which depends on the orders it receives from its clients; (ii) to input availability, which depends on its supplier production; and (iii) to its own internal constraints. Of course, like in any agent-based model, the behavioral rules that are used in this model are somehow *ad hoc*, and other functional forms would also be possible [3] . We assume, however, that these behavioral rules are realistic and that, with a sufficiently large number of PUs, the aggregated results should not be too sensitive to the detailed modeling of agent behaviors. This assumption will be tested in details in Section 4, using systematic sensitivity analyses.

[3] These behavioral rules, however, are not more *ad hoc* than the Cobb-Douglas production functions that are used in most classical growth models.

We assume that P is the vector of outputs of the different PUs and A is the PU-IO matrix. As already stated, we do not model here households and reconstruction and we assume that final demand is not impacted by the disaster. Final demand, therefore, remains constant in our model. The production is used to satisfy the demand of intermediate goods and final demand. The equilibrium equation is then:

$$P = AP + C \tag{2}$$

Where C is the vector of final demands and P the equilibrium production. Classically, the optimal production is:

$$P^0 = (I - A)^{-1}C \tag{3}$$

P^0 would be the production if the production capacities were not bounded and if there were no inventory. In the present model, we will, however, consider the production capacity of each PU – a PU cannot produce more than what it has been designed to produce – and the impact of inventories on demands.

3.2.1 Inventories and demand model

We define $D_i(t)$, as the demand to the i^{th} PU at the time t. This demand consists of final demand and of PU-to-PU demand (i.e. intermediate consumption demand). The PUs, indeed, produce commodities by drawing from their commodity inventories. They have then to order new inputs to their suppliers, in order to restore their inventories. The inventory level at the end of each time step is used to determine the demand to suppliers.

We assume that the PU i has an inventory $S(i, j)$ of the commodity produced by the PU j, and that the demand of the PU i to its suppliers j is designed to restore its inventory $S(i, j)$ to a level equal to a given number of days n_j^i of consumption at the production level needed to satisfy its clients [4] . As an example, consider an automaker factory that had a tire inventory allowing for 10 days of production at the pre-event production pace. If the demand to this plant increases by 10 percent, the plant will increase its tire inventory, such that it will have a tire inventory that still allows for 10 days of production at the pace needed to satisfy this increased demand. The tire inventory, therefore, will also be increased by 10 percent. On the opposite, if demand decreases, the level of inventory will be reduced by the same fraction.

[4] Of course, if $A(i, j) = 0$, i.e. if the PU i is not a client of the PU j, then $S(i, j) = 0$.

The orders $O(i,j)$ from the PU i to its supplier j reads [5] :

$$O(i,j) = A(i,j)\frac{D_i(t-1)}{P_i^{ini}} + \frac{1}{\tau}\left(n_j^i \cdot \frac{D_i(t-1)}{P_i^{ini}} \cdot A(i,j) - S(i,j)\right) \tag{4}$$

Where $D_i(t-1)$ is the demand directed toward the PU i (by all its clients) at the previous time step. The parameter P_i^{ini} is the pre-event production of firm i, assumed equal to demand in the initial situation. To produce P_i^{ini}, the PU i needs an amount $A(i,j)$ of inputs from the PU j. So, the first term of the right-hand side of Eq. (4), $A(i,j)D_i(t-1)/P_i^{ini}$, is the amount of commodity needed by the i^{th} PU to satisfy the demand at the previous time step $D_i(t-1)$. The second term of the RHS of Eq. (4) represents the orders that make the inventory converge toward its equilibrium value, i.e. toward n_j^i days of current consumption. The parameter τ is the characteristic time of the inventory restoration. In the following, we assume that $\tau = 6$ days. This choice is arbitrary, and there are no data available on this information.

This modeling provides the total demand directed toward each firm j at the time step t, by adding all demands from individual PUs, plus final demand C_j [6] :

$$D_j(t) = C_j + \sum_i O(i,j) \tag{5}$$

3.2.2 Production model

Without constraint, each PU j would produce at each time step t the exact level of demand $D_j(t)$. But production can be lower than demand either (i) because its production capacity is insufficient; or because (ii) its inventories are insufficient as a result of the inability of other PUs to produce enough (forward propagation). The production capacity of each PU depends on its stock of productive capital (e.g., factory, equipments), and on the direct damages to the firm capital (e.g., a firm that suffer from disaster damages can produce less).

The capacity and inventory constraints are described by the following relationships:

- Limitation by production capacity:
  Independantly of its suppliers, the production capacity P_i^{cap} of the i^{th} PU reads:

$$P_i^{cap} = P_i^{ini}(1 - \Delta_i) \tag{6}$$

[5] In this equation and in the following ones, $A(i,j)$, $O(i,j)$ and $S(i,j)$ depend on the time step t, but we omit it for simplicity.
[6] This total demand is the equivalent of the *desired output* of Battiston et al. (2007).

Where P_i^{ini} is the pre-event production of this PU, assumed equal to the normal level of production. The variable Δ_i is the percentage of the productive capital of the PU i that has been destroyed by the disaster.

- Limitation by inventories:

  A PU can also be limited by insufficient inventories. Of course, since all PUs from a sector s produce the same commodity s, if a PU i has two suppliers from sector s (the PUs j_1 and j_2), it can compensate an insufficient inventory $S(i, j_1)$ using more commodity from the inventory $S(i, j_2)$. To model this compensation, we define the total inventory of commodity s, $S_{tot}(i, s)$, which is equal to the sum of the inventories owned by the PU i of the commodities produced by all producers from the sector s:

$$S_{tot}(i, s) = \sum_{j \in \text{sector } s} S(i, j) \tag{7}$$

  Also, in the pre-event situation, the PU i produces an amount P_i^{ini} and consumes an amount $A(i, j)$ from each PU j. So, it consumes a total amount $A_{tot}(i, j)$ of commodity s, which is equal to:

$$A_{tot}(i, s) = \sum_{j \in \text{sector } s} A(i, j) \tag{8}$$

  As a consequence, with an amount of available inventories $S_{tot}(i, s)$ for the commodity s, the maximum production is limited at:

$$P_i^s(t) = S_{tot}(i, s) \frac{P_i^{ini}}{A_{tot}(i, s)} \tag{9}$$

  In this equation, $P_i^{ini}/A_{tot}(i, s)$ is the amount of commodity s needed by the PU i to produce one unit of commodity. $S_{tot}(i, s)P_i^{ini}/A_{tot}(i, s)$ is therefore the maximum production of i allowed by the amount of commodity s.

- Taking into account both production capacity and limited inventories, the maximum production level of the i^{th} PU is :

$$P_i^{max}(t) = \mathsf{Min}\left(P_i^{cap}(t), \mathsf{Min}_s\left(P_i^s(t)\right)\right) \tag{10}$$

  Actual production P_i^a is then given by :

$$P_i^a(t) = \mathsf{Min}\left(P_i^{max}(t), D_i(t)\right) \tag{11}$$

The vector $P_i^a(t)$ is the vector of actual production by each PU, taking into account the two production constraints [7] . These constraints then spread into the economy: if a firm reveals unable to produce enough to satisfy the demand, it will both (i) ration its clients, and (ii) demand less to its suppliers. These two effects, forward and backward propagations, affect the entire economy.

[7] This actual production is the equivalent of the *effective output* of Battiston et al. (2007).

3.2.3 Market modeling, rationing scheme and inventory dynamics

When a PU is not able to produce enough to satisfy demand, it has to ration its clients. We have, therefore, to introduce a rationing scheme. In our framework, in absence of market equilibrium, demand can be larger than actual production (in such a case $P_i^a = P_i^{max}$):

$$D_i = \sum_{j=1}^{N} O\ (j,i) + C_i \geq P_i^a$$

From these incompatible demand and supply, the actual sales and purchases must be balanced however:

$$D_i^* = \sum_{j=1}^{N} O^*(j,i) + C_i^* = P_i^a$$

Some agents, therefore, must be rationed. The rationing scheme gives the sales and purchases of each agent, depending on the demands and supplies of all the agents. In the present case, since we are interested in disasters, there is only underproduction and the suppliers can sell all their production while clients only get a fraction of their demand. In this model, we have assumed that the rationing scheme is a *proportional rationing scheme* [8] (Bénassy, 1984). The rationing fraction is equal for each client (PUs and final consumers).

$$O^*(j,i) = O(j,i) \cdot \min\left(1, \frac{D_i^*}{P_i^a}\right) \tag{12}$$

$$C_i^* = C_i \cdot \min\left(1, \frac{D_i^*}{P_i^a}\right) \tag{13}$$

In the model, the actual sales of PU i to PU j ($O^*(j,i)$) are those that increase the inventories of the PU j from one time step to the next one:

$$S(j,i)(t+1) = S(j,i)(t) + O^*(j,i) - A(j,i)\frac{P_j^a(t)}{P_j^{ini}} \tag{14}$$

where the term $O^*_{i,j}$ is the increase in inventory thanks to purchases from the supplier, and the last term is the decrease in inventory due to the commodity consump-

[8] The problem of this rationing procedure is than it can theoretically be manipulated: an agent can declare a higher demand to increase his transactions. In the present study, we assume that PUs declare their true demand, that is to say the amount of intermediate good they actually need to satisfy their own demand.

tion needed to produce the amount $P_j^a(t)$.

3.3 Adaptation in the production system

When a firm is not able to satisfy demand, the economic system allows for some flexibility in order to maintain production. For instance, businesses can turn to new suppliers or adjust the production processes to cope with a reduced availability of some inputs. While Rose and Liao (2005) and Rose et al. (2007) focus on the latter, we investigate here the former, i.e. how PUs can create new business relations to cope with insufficient production from their normal suppliers. It would be possible to assume that this adaptation is made in an optimal way (using, e.g., a Ghosh model or the Cochrane (1997) approach). Here, we assume instead that adaptation is carried out by individual agents in a decentralized manner. Such a modeling is considered more realistic by the authors in disaster aftermaths, during which perfect-market assumptions are not satisfied (e.g., concerning the presence of rationing). The drawback of such a modeling is that it introduces many degrees of freedom. These degrees of freedom, however, exist in the real world, since each economic agent has to react independently to the disaster, and must therefore be taken into account in the modeling approach.

If the i^{th} PU is not able to satisfy demand and if the k^{th} PU from the same sector is able to produce more than current demand, the clients of the i^{th} PU can turn to the k^{th} PU. The problem is that the k^{th} PU may have additional production capacity but it is unlikely to be able to satisfy the unsatisfied demands of all the former clients of the i^{th} PU. So, only a fraction of the unsatisfied demand to the i^{th} PU will be satisfied by the k^{th} PU. The problem is that there is no simple or single way of determining this fraction, and that multiple strategies are possible. The actual outcome of the adaptation process will depend on many small-scale processes like personal relationships between business owners and managers, or the existence of risk management plans that include alternative suppliers in case of supply chain disruption.

In such a situation of uncertainty and multiple possibilities, a deterministic model may not be the most adequate tool. Instead, we introduce a stochastic module inspired by agent-based modeling approaches: a random process decides which fraction of the unsatisfied demand of each PU shifts to each available PU. Of course, various parameters influence this random process, and several modeling of the adaptation process can be imagined. To cope with this large uncertainty, several modeling will be proposed and compared in a systematic way in Section 4.2.

In practice, we model this adaptation process using the following algorithm.

As described above, P_k^{max} is the maximum production of the PU k, limited by its production capacity and by the lack of inputs from all the other sectors. If there exist PUs that are able to produce more than their current demand (i.e. there is k such that $P_k^{max}(t) > D_k(t)$), some PUs will have the opportunity to turn to this new supplier, leading to a modification of the matrix A. We assume that each PU can implement one adaptation action per day, i.e. creating an additional link with a new supplier each day [9] .

The adaptation process follows this scheme: first, among the PUs that have a defaulting supplier, we select the first one that will adapt; second, this PU chooses which PU will replace its defaulting supplier. In our model, the first choice can be done using three rules:

- Stochastic. The first PU to capture the unused capacity is chosen randomly.
- The better-off first. The PU that had the largest production at the previous time step (relative to its initial production) has priority to capture unused production capacities.
- The worst-off first. The PU that had the lowest production at the previous time step (relative to its initial production) has priority to capture unused production capacities.

The second choice can be done using two rules:

- Alphabetical order. The PUs that need additional capacity turn first on the first PU that has available resources.
- Largest capacity first. The PUs that need additional capacity turn first on the PU that has the largest unused capacity.

Practically, these adaptation strategies lead to the multiplication by 10 or 100 of the number of links, i.e. of the number of suppliers of each PU. This unrealistic result is satisfying in a sense, because it seems obvious that, in absence of transaction costs associated with the creation of a link, businesses have an interest in having as many suppliers as possible, since it increases their robustness. So, the fact that this first module leads to a large multiplication of the number of suppliers appears consistent with what one can expect. Moreover, most connections added by this adaptation process are of a negligible magnitude, which is again unrealistic is presence of transaction costs [10] . To be more realistic, a restriction of the number of suppliers per PU is introduced, assuming that a PU cannot deal with more than a given number of suppliers. Once a PU has reached its maximum number of suppliers, the adaptation process can continue but the PU can only adapt its demand level to the suppliers it is already connected to. The maximum number of suppliers is assumed to be 1.5 times the initial number of suppliers. This choice is *ad hoc*, because no data is available on this point. A systematic sensitivity analysis, however, is proposed in Section 4.2.

[9] Note that the adaptation is “supply-lead”: PUs that need supplies look for new suppliers, while PUs that lost clients do not look for new clients.

[10] One can notice that using an aggregated IO model is equivalent to a uniform distribution of the risks, i.e. to the assumption that all PUs are connected to all PUs.

Importantly, we assume that there is no adaptation in the non-stockable sectors, because one cannot turn to another supplier of, e.g., electricity or water. This assumption is clearly too strong, for example because water can be transported by trucks and electricity can be locally produced using individual generating set if the grid is affected. Rose and Liao (2005) also show how production process can be adjusted to cope with water or electricity scarcity. Given their specificities, however, these sectors require a more detailed analysis than what can be proposed in this article and this issue is left for future research.

As already stated, PUs cannot turn to importations to obtain additional intermediate goods in the current model version, as we focus in the present study on the robustness of an independent economic network.

4 Investigating the model behavior using a synthetic disaster

This section investigates the model behavior and highlights the most important parameters. It uses synthetic disasters that help understand the model. It starts with a description of a reference simulation, using our best-guess parameter values, and then presents sensitivity analysis on four modeling choices and parameters: (i) the characteristics of the adaptation process; (ii) the number of PUs in the economy; (iii) the redundancy in the economic system; and (iv) the level of inventories. Except when explicitly mentioned, parameter values are those shown in Tab. 2.

First simulations show a large vulnerability of the economy to the destruction of PUs in the non-stockable sectors (e.g., electricity, transportation, water). The definitive disappearance of one PU in these sectors lead the entire economy to collapse and total output to go to zero in less than one month. This result is not surprising given that we did not allow for reconstruction or for the creation of new PUs to compensate the disappearance of destroyed ones, and that no adaptation is allowed in the non-stockable sectors like utilities or transportation. The destruction of a PU in sectors where adaptation is not allowed spreads and makes the economy collapse [11] . These results are in line with the intuition that the impacts on these non-stockable network-shaped sectors are major drivers to total losses and have thus to be analyzed in priority (e.g., Rose et al., 1997; Boarnet, 1998; Gordon et al., 1998; Rose and Liao, 2005; Rose et al., 2007). In this article, however, we will focus on the propagation effects in other sectors.

[11] Note that this result could be different with another network structure.

Parameters	Values
Number of PUs	500
Inventories in days	10
Max. number of suppliers	1.5 x initial number of supplier
Adaptation process	Stochastic/Alphabetical

Table 2
Default parameter values.

4.1 Reference simulation

If the sectors where adaptation is allowed are affected, indeed, the situation is more complex and requires more analysis. To get a better understanding of the model behavior in such a situation, we consider a disaster that affect 5% of the PUs from the manufacturing sector and $1/30$ of the PUs from the wholesale trade, making them instantaneously and definitively unable to produce. This disaster has losses that are, therefore, extremely heterogeneous among PUs. As a reference, we also indicated the production level in case of a disaster that reduces the production capacity of all PUs by 5% in the manufacturing sector and by $1/30$ in the wholesale trade sector. In these two cases, the total amounts of direct damages are equal, but damages are equally distributed among the firms of one sector in the latter case, while they are very heterogeneously distributed in the former one.

Fig. 1 shows the result of 50 simulations where the first PU to adapt is chosen randomly and turn toward the first PU that has unused capacity, and where parameters have the values of Tab. 2. The bold red line shows the result of the simulation where all damages are equally distributed in affected sectors, while the thin lines are for disasters with heterogeneously distributed damages. The left panel shows that, with these hypotheses, a disaster with heterogeneous losses leads to much larger losses than a disaster with homogenous losses, justifying the focus of the present paper. In particular, the model can reproduce an economic collapse due to a disaster, suggesting that it may be used to investigate the existence of a threshold in terms of disaster losses and to discriminate between limited-consequence disasters (e.g., the 2004 hurricanes in Florida) and widespread-consequences disasters with systemic failure (e.g., Katrina in New Orleans in 2005).

Moreover, this figure shows that various simulations can lead to very different results, with production loss after 100 days being between 3% (sensibly equivalent to the homogenous disaster) and 100% (total economic collapse). The right panel is an histogram of final production (in fraction of initial production) that shows that 35% of the simulations lead to a collapse (or at least to a final production lower than 10% of initial production), while 20% of the simulations lead to a final production larger than 90% of initial production [12] .

[12] This histogram may differ from the real result distribution because of the insufficient

These differences arise from the randomness in the adaptation process. Depending on how the economic system reacts to the shock by creating new connections between PUs, production can be maintained or not. Basically, the outcome depends on whether the economic system is able to create new links such that destroyed PUs are isolated from the rest of the economic system. The fundamental question is how creating these links can be done at a decentralized level, each PU acting on its own like in the real world. From our analysis, the aggregate outcome depends on the many individual PU decisions and the network may be able to restore its viability or not. According to these results, the consequences of a natural disaster will be largely driven by uncountable adaptation actions undertaken at the production-unit level, making their assessment extremely difficult.

The large range of possible outcomes of our model, in response to a unique disaster and with unchanged parameters, may appear surprising. There is no established evidence, however, that a disaster impacting an economy can have only one possible outcome and that the details of the adaptation process cannot influence significantly the outcome, like in our model. Moreover, we model a small economy, with only 500 PUs. In such a small economy, the importance of the choice made by one PU can be essential, while the importance of individual decisions is likely to be milder in a larger economy [13] . This idea will be confirmed by a sensitivity analysis presented in Section 4.3 and 4.4.

Most importantly, as shown for instance in Section 5 and in Fig. 8, the large range of possible outcomes does not prevent the model from providing interesting insights, because the likelihood of each outcome depend on the characteristics of the disaster (allowing to distinguish between more or less serious disasters) and of the affected economies (allowing to discuss the resilience of different economies). For instance, a small disaster *can* lead to a large economic impact, but it does so only rarely, in a few simulations: in most simulations, such a disaster leads to a mild aggregate impact. A large disaster, on the other hand, causes a large aggregate impact in most simulations, and a small impact only in a few simulations.

Our results, therefore, support the idea that it is more relevant to produce disaster cost assessment in the form of probabilistic results (e.g., probability distribution function of the total losses, or histograms as in the right panel of Fig. 1) instead of "best guess" estimates. In the same way, risk reduction strategies may have to be assessed using probabilistic measures, even when the event characteristics are fixed

---

number of simulations, which is due to computational time limitation.

[13] This problem echoes that of statistical mechanics, where fluctuations in aggregate variables decrease with the number of particles. At the thermodynamic limit, with many particles, aggregate variables can be modeled in a deterministic way. With fewer particles, aggregate variables can vary significantly and a probabilistic approach is required. Our economic modeling faces the same difficulties and it seems that, with 500 PUs, we are still far from a "thermodynamic limit," making it necessary to model the aggregate variable (total production) in a probabilistic manner. It is possible that, with much more PUs, total production will become deterministic. These hypotheses will be tested in future research.

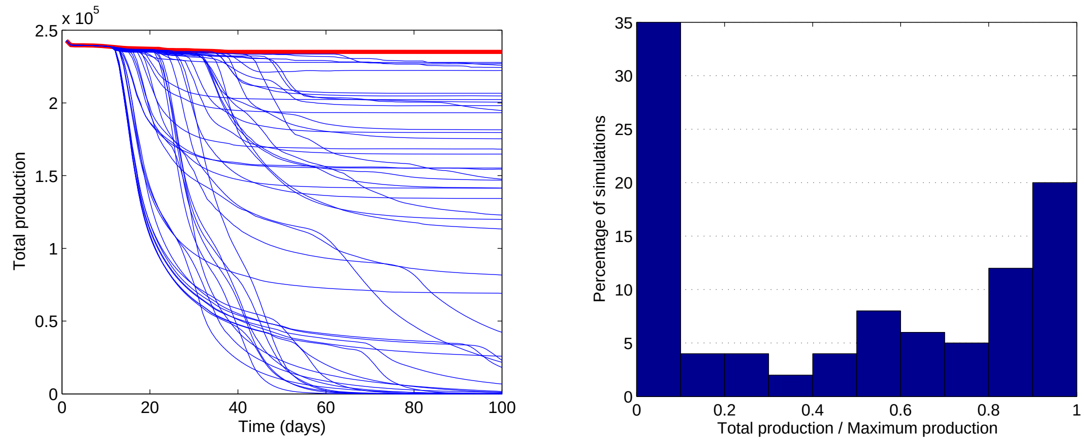

Fig. 1. Left panel: 50 simulations of the synthetic disaster in an economy with 500 PUs, assuming the Stochastic/Alphabetical adaptation process. The bold red line shows the result if all damages are equally distributed in the affected sectors. Right panel: Histogram of the final situation.

(using statements like “if a M8 earthquake hits the location A, recovery plans would reduce by x% the probability of a y% reduction in output”). Even though Monte Carlo analysis of disaster consequences is widely used in disaster assessment, our results suggest that the use of probabilistic measures is not only made necessary by the randomness of natural disasters and of the corresponding direct losses (e.g., fragility curves), but also by the randomness in the response by economic agents.

Our model reproduces frequent economic collapses, while such collapses are exceptional after known historical disasters. This difference between observations and model results can, however, be explained by three factors:

- First, reconstruction is not modeled, making it necessary for the network to adjust very efficiently. With recovery and reconstruction, most businesses can restore their operation in a few days or weeks (Kroll et al., 1991; Tierney, 1997), and it is likely that the efficiency of network adaptation would only influence the deepness of the trough, without leading to a collapse even in the most pessimistic scenarios. Our results are not, therefore, in contradiction with observations, but the comparison with observations stresses the need to include recovery and reconstruction in the model.
- Second, these model simulations are carried out with a closed 500-PU economy, while real economies are in practice much larger and well connected with the rest of the world.
- Third, the current network structure in the model is very specific and may not represent correctly real economies. In particular, small world networks may be more robust and more realistic than our current network (e.g. Callaway et al., 2000; Corso et al., 2003; Newman, 2003; Cowan and Jonard, 2004). Future research will focus on the resilience of other network structures, derived from theoretical analysis or empirical evidences (e.g. Carvalho, 2008).

Considering the high level of uncertainty in many components of this model, the following sections propose sensitivity analyses on the most uncertain modeling and parameters of the model. With such a model, sensitivity analyses are mainly meant to identify where more research is most needed.

4.2 Sensitivity to the adaptation modeling

One of the main results of this study is that the adaptation process is an essential component in disaster cost assessment. First, we investigate the adaptation process itself, i.e. the choice between the various strategies described in Section 3.3 (stochastic/better-off first/worst-off first; largest capacity first/alphabetical). Second, we investigate the limitation to the number of suppliers.

4.2.1 Adaptation process

To assess the influence of adaptation process modeling, we compared four adaptation processes in addition to the one proposed in the reference simulation presented in Fig. 1. First, the adaptation process is modeled assuming that the better-off PUs are first to capture the unused resources as additional suppliers, or that the worst-off companies are the first to capture them. The second dimension concerns the alternative suppliers: when a PU looks for a new supplier to compensate for the loss of a historical supplier, it can turn toward the PU that has the largest unused capacity first, or to the first available supplier (in alphabetical order).

Figure 2 shows the results of this sensitivity analysis. On the upper panels, the better-off PUs are first to capture the used resources; on the bottom panel, the worst-off PUs are the first ones. On the left hand side, the PUs turns first toward the PUs that have the largest unused capacity; on the right hand side, they turn to any PU, chosen randomly among those that have available capacity. This figure shows that the adaptation process is much more efficient if the better-off PUs can capture first the unused resources, and slightly more efficient if they turn first toward the PUs that have the largest unused capacity [14] .

The adaptation order seems decisive in the ability of the economy to recover. From many simulations, it appears that the most favorable order is when the firms that have the largest production relative to their initial production have priority, and when they turn first on the firms which can produce the most relative to their demand. Indeed, this is a way of allowing as many firms as possible to adapt: the firms that can produce the most relative to their initial production are those that need less input from alternative suppliers, leaving capacity for other firms. This process can also be understood as a process in which the most affected firms are “sacrificed” to protect the least affected ones. This results is interesting in that it suggests a

[14] This result is confirmed by the analysis of histograms (not shown).

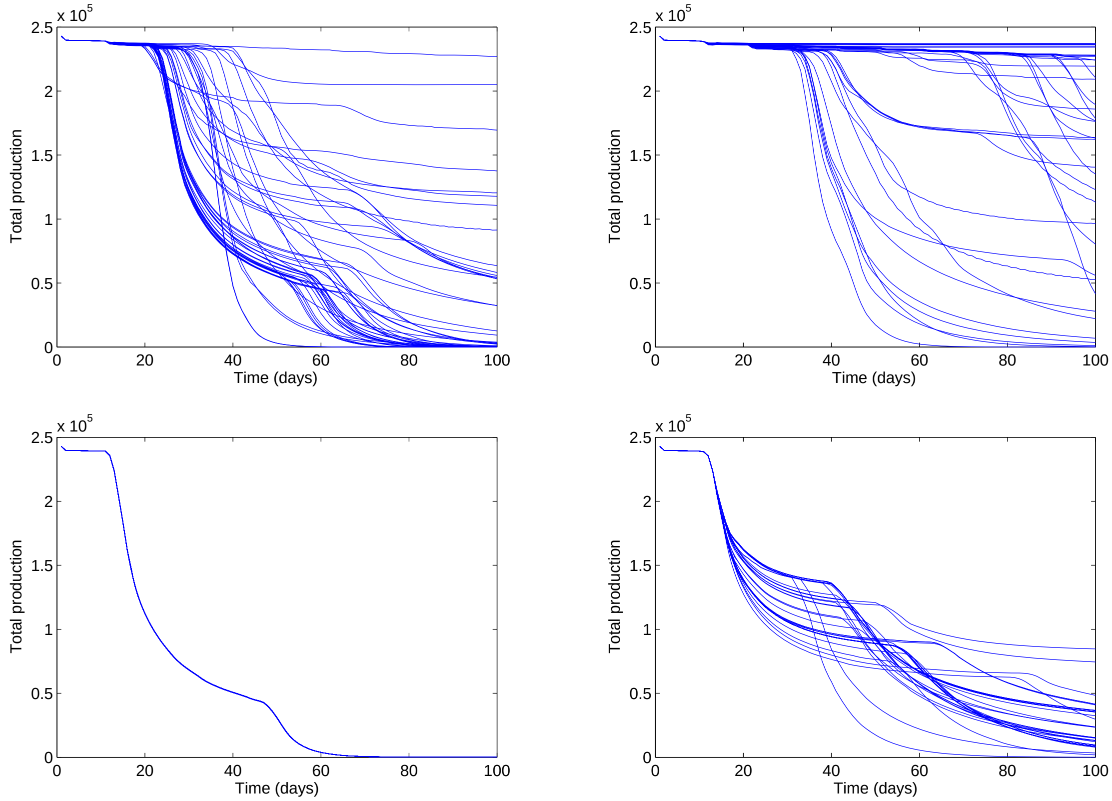

Fig. 2. Consequence of the synthetic disaster in an economy with 500 PUs, with different adaptation processes. On the upper panels, the adaptation follows the “better-off” process: the less affected PUs look first to suppliers with unused resources. On the bottom panels, the adaptation follows the “worst-off” process: the most affected PUs are the first to look for new suppliers. On the left hand side, PUs select the first supplier with unused resources (Alphabetical). On the right hand side, PUs turn first toward suppliers with the largest unused resources.

counter-intuitive strategy to help affected region cope with disasters, by allocating scarce production to the least affected businesses [15] .

4.2.2 Limitation of the number of suppliers.

Previous simulations were carried out assuming that the number of suppliers and clients per PU could not exceed 1.5 times the initial value. To investigate the importance of this point, this section assumes a stochastic/alphabetical adaptation process and varies the maximum number of suppliers and clients.

Figure 3 shows the results of simulation with different values for the maximum

[15] Of course, this strategy is assessed from an efficiency point-of-view only, while equity, ethical, and political aspects need to be accounted for. In particular, focusing aid on the least affected businesses would be unacceptable if transfers are not organized to help the most affected households. Moreover, the confidence in the strategies proposed by our model should not be overstated.

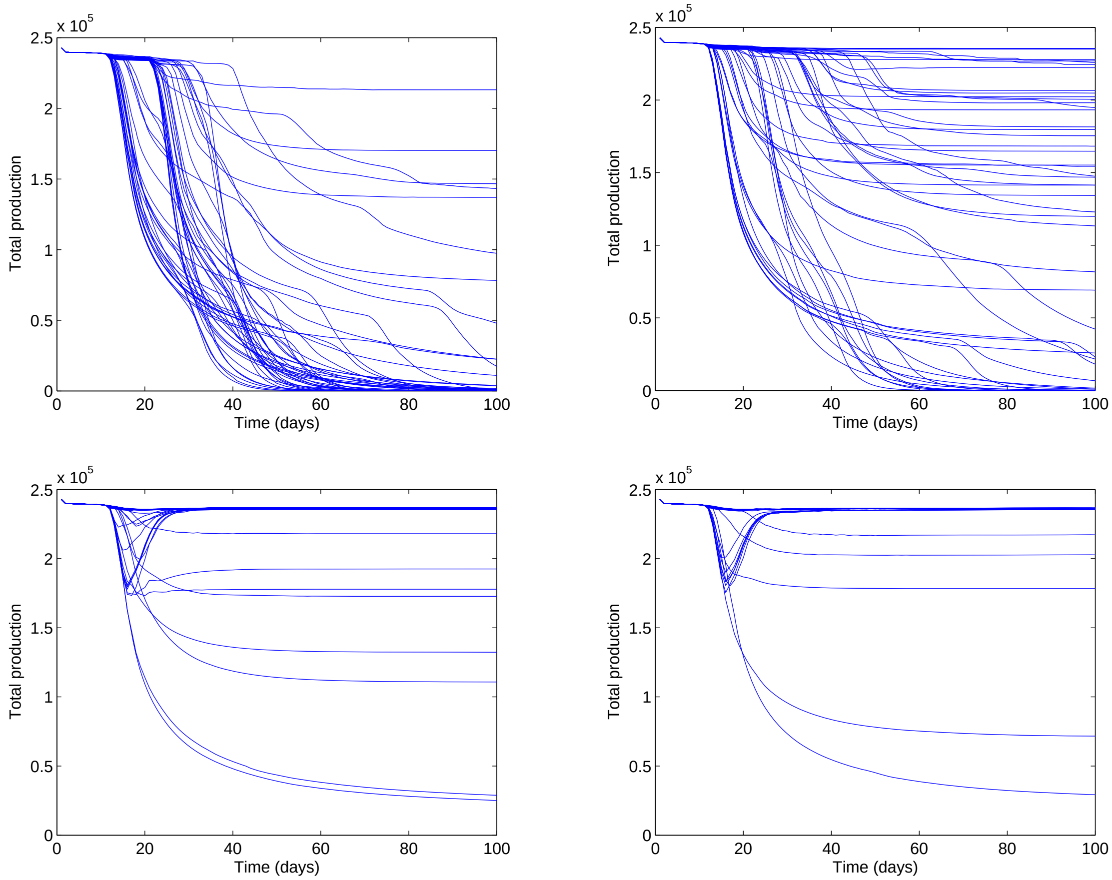

Fig. 3. Consequence of the synthetic disaster in an economy with 500 PUs, with the stochastic adaptation process and different limits on the maximum number of suppliers: 1.2 times the initial number in the upper-left panel; 1.5 in the upper-right one; 10 times in the bottom-left one; and no limit in the bottom-right one. (50 simulations)

number of suppliers per PU, from 1.2 times the initial number to an unlimited number. These simulations demonstrate that this factor is essential, suggesting that the taking into account of microeconomic mechanisms (e.g., the transaction costs associated with a larger number of suppliers) is needed to understand economic resilience of natural disasters. This factor is important in the current context of reduction in the number of suppliers, which suggests that the cost of having more suppliers is not negligible. It is likely, therefore, that there is a trade-off between economic efficiency and economic robustness. This trade-off can be investigated using supply-chain analysis (e.g., Thomas and Griffin, 1996; Beamon, 1999; Londsdale, 2004).

4.3 Sensitivity to the number of PUs

To assess how the model depends on the size of the economy that is modeled, we compared simulations with 500 or 1000 PUs, with the same matrix density, i.e.

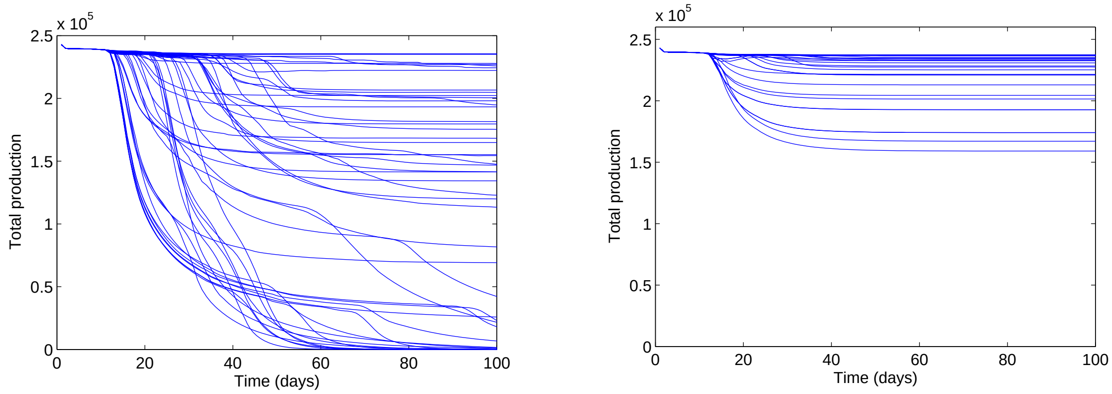

Fig. 4. Consequence of the synthetic disaster, in two economies with the same density and, respectively, 500 PUs on the left and 1000 PUs on the right (50 simulations).

twice as many suppliers and clients per PU in the 1000x1000 matrix than in the 500x500 matrix.

Results are shown in Fig. 4. According to our simulations, at unchanged density, the larger the economy is, the more robust it is. In the 1000-PU simulation, all simulations show a limited reduction in production, and stabilize at a production level that is less than 25% below the initial level. In the 500-PU simulation, many simulations lead to a large reduction in production, including total collapses. With unchanged density, therefore, the larger economy is more robust.

It has to be mentioned, however, that when an economy gets larger, its network is likely to become less dense, since each PU of a larger economy does not have to have more connections (i.e., suppliers and clients) than a same-sized PU of a smaller economy. It is important, therefore, to investigate also the role of changes in network density, i.e. in redundancy. This is done in the next section.

4.4 Sensitivity to redundancy in the economic system

To assess the sensitivity of the model to the redundancy in the economic system, i.e. to the number of suppliers and clients per PU, two sets of simulations are carried out. In the first one, the economy consists of 1000 PUs with normal density. In the second one, the economy still consists of 1000 PUs, but density is double, i.e. each PU has twice as many suppliers and clients as with normal density. Figure 5 shows the result of this analysis. In the first case, all simulations lead to a strong reduction in production (by more than 50%), while all simulations of the second case show only a limited production reduction. It is clear, therefore, that redundancy is very efficient in increasing the economy robustness to disasters, and in decreasing the likelihood of an economic collapse after a disaster.

In the present study, we consider 500- or 1000-PU networks, instead of the $100\,000$ PUs of the real economy of Louisiana. This limitation has consequences both in

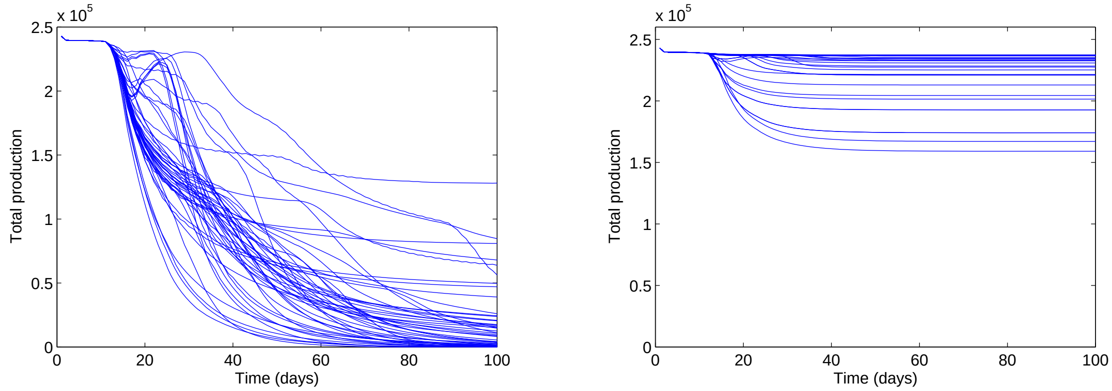

Fig. 5. Consequence of the synthetic disaster in an economy with 1000 PUs, with the normal matrix density on the left and a matrix with twice as many suppliers and clients on the right (50 simulations).

terms of network size and density. With an unchanged number of clients and suppliers per PU, increasing the network size from 500 to 1000 PUs increases slightly the economy vulnerability, as shown by the comparison of the left hand panels of Fig. 4 and 5. Our model, therefore, is sensitive to the size of the modeled economy. This sensitivity is an issue because it is much more difficult to model a very large economy.

From the comparison between the left hand panels of Fig. 4 and 5, it seems possible that the range of results due to adaptation stochasticity gets narrower when the number of PUs increases. This result would be consistent with the intuition that individual PU decisions have much more influence on the final aggregated results in a modeled 500-PU economy than in a real economy with tens of thousands of PUs. As a consequence, our model results may be too sensitive to the random processes that are introduced in the adaptation process. This sensitivity suggests that the model needs to represent very large networks to be able to produce realistic results, leading to difficult numerical and computational problems.

4.5 Sensitivity to the inventory level

This section investigates the impact of the initial inventory level on the ability of the economy to recover. Figure 6 shows 20 simulations of the response of the same economy, but with different initial inventory levels in each PU. On the top panels, we assume that all PUs have 5 days of inventory, while on the middle and bottom panels, they have 5 and 10 days of inventory. Clearly, increasing inventories from 2 to 10 days enhances the robustness to disasters. Inventories, indeed, makes it possible for PUs to keep producing in the immediate disaster aftermath, allowing more time for the adaptation process to take place and restore economic viability [16]. Larger inventories, therefore, decrease the likelihood of a disaster-related

[16] And, in the real world, for recovery and reconstruction to take place

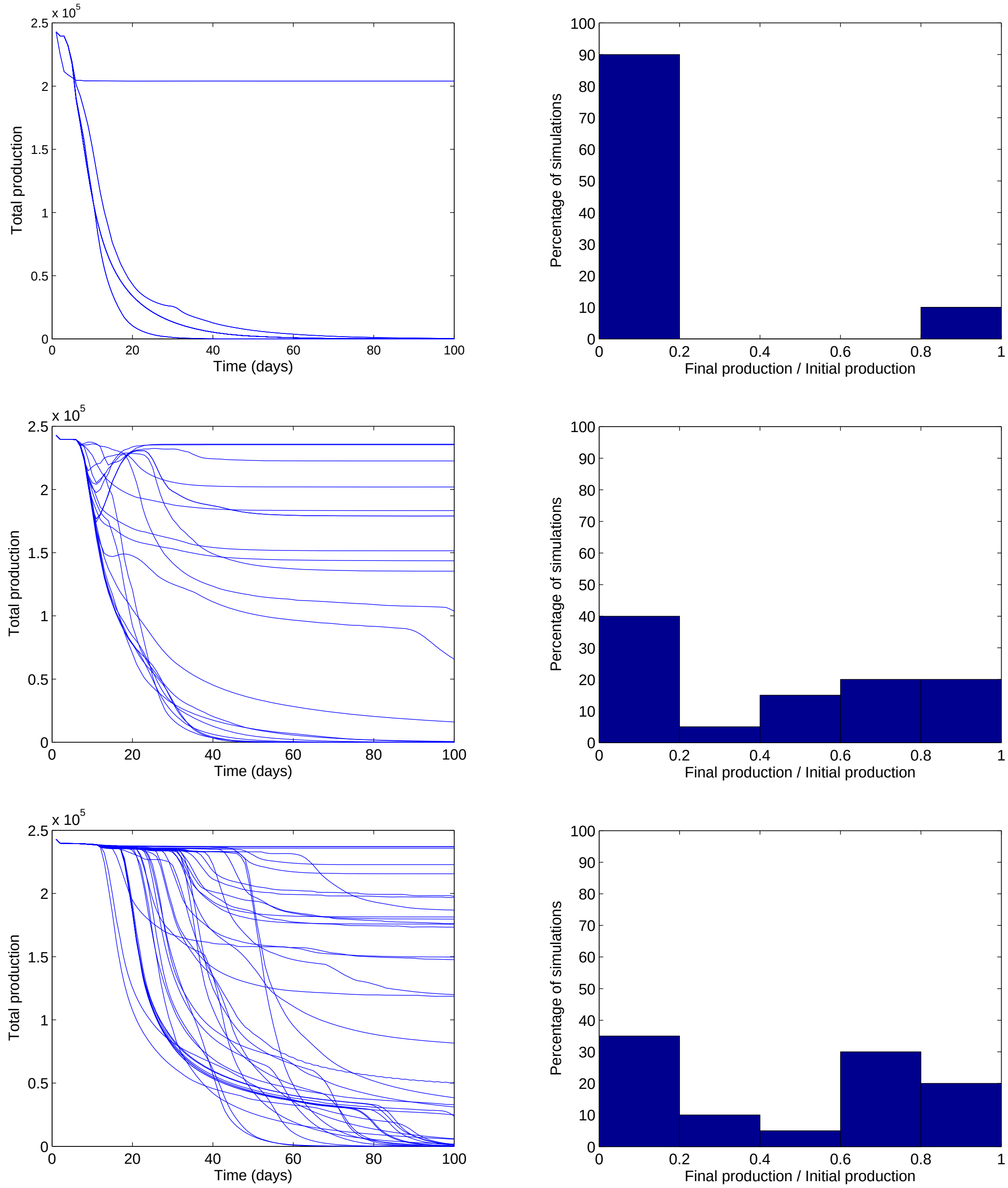

Fig. 6. Consequence of the synthetic disaster in an economy with 500 PUs, with different inventory levels. On the upper panels, PUs have the equivalent of 2 days of inventories; on the middle panels, they have 5 days of inventories; on the bottom panels, they have 10 days of inventories. The left hand panels show 20 simulations of the models in each case; the right hand panel shows a histogram of the final production (wrt to initial production).

economic collapse.

5 Assessing the role of direct losses heterogeneity

To create a “realistic” distribution of losses, we used the data from hurricane Katrina and the damages repartition per sector described in Hallegatte (2008). In absence of any better information, we used data on the Northridge earthquake from Tierney (1997) and considered that 60% of PUs suffered from direct losses in each sector. Direct losses are then distributed among the affected PUs of each sector using a lognormal probability distribution function. We chose a lognormal law to represent the fact that high damages occur with a low probability and minor damages are very widespread (Tierney, 1997). The mean of this function is the mean value of the damages per affected PUs in this sector, i.e. the amount of damages in the sector divided by the number of affected PUs.

Formally, consider a sector i consisting of n_i PUs. The total amount M_i of direct losses in this sector has been determined in Hallegatte (2008): Katrina's damages are assumed to amount $17 billion for the government and $63.20 billion for the private sector, of which $30 billion in the mining sector and $5 billion in the utilities sector, the rest being distributed according to the size of the sector. Knowing M_i and n_i for each sector, we select randomly 60% of the PUs from sector i, which we assume to be the affected PUs. We then consider that the amount of direct losses of each of these PUs is a random variable distributed according to a log-normal law with parameters $\mu = M_i/(0.6n_i)$ and σ (variance parameter). The log-normal distribution has the probability density function:

$$f(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \tag{15}$$

In reality, the damage variance among PUs depends on the geographical concentration of PUs: if all PUs are located in the same area, they will suffer approximately the same amount of damages. On the opposite, if they are spread out over a large region, or if the disaster damages are very heterogeneous, the PU losses will be very different, and the variance will be large. This is an important point because, as far as indirect damages are concerned, a loss of 10% of each PU productive capital does not have the same effect on the economy as a loss of 100% of the capital of 10% of the PUs. In absence of information about the geographical distribution of PUs, we carried out a systematic sensitivity analysis on the loss variance.

Figure 7 shows simulations of the economic response for various disasters that cause the same losses at the sector-scale, but with different loss variance parameters, i.e with different losses at the PU-level. On the left-hand side, the variance parameter is equal to 0.5, while on the right hand side, the variance parameter is 1.5. The difference in response is obvious: production losses are below 20% in all cases when the variance is small, but reaches very large values (including collapse) if the variance is high. For unchanged aggregated losses, therefore, the economy is much more vulnerable to a disaster that affects heavily a few PUs than to a disas-

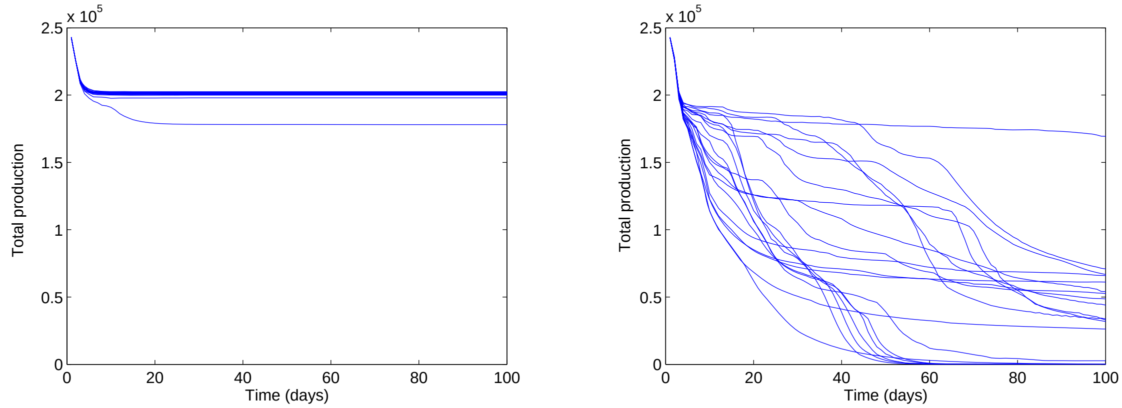

Fig. 7. Economic responses to the disaster (20 simulations), for two values of loss variance parameter, 0.5 on the left and 1.5 on the right.

ter that slightly affects all PUs. In particular, the model suggests that an economic collapse is likely if variance is large, while it is apparently impossible if variance is small enough. It seems, therefore, that loss heterogeneity is an essential parameter in the assessment of the risk of an economic systemic failure.

This result can be interpreted as a consistency issue in the economic system. In absence of adaptation process, if all PUs are affected in the same way, and have to reduce their production by x percent, the economic production and exchange system remains consistent. In such a situation, the loss is minimum, equal in relative terms to the loss of each PU, i.e. x percent. Still without adaptation and in absence of idle resources, if only one PU is affected, and if its production is reduced by x percent, all its clients will also have to reduce their own productions by x percent because of input scarcity. If all PUs are connected in the network, all PUs will finally reduce their production by x percent. So, without adaptation and without unused resources, a x-percent loss at one PU (i.e. a very small heterogeneous loss) has the same aggregate impact than a x-percent loss at all PUs (i.e. a very large homogenous loss). Adaptation in the economic network reduces the difference between these two outcomes, since a x-percent loss at one PU leads only to a small reduction in aggregate production. But adaptation cannot cancel this effect of heterogeneity.

In other terms, this result arises from the complementarity of intermediate goods in an Input-Output production framework: with constant technical coefficients, if one intermediate goods is scarce, other intermediate goods cannot be used, and a reduction of their production has no aggregate consequence. With adaptation of technical coefficient (i.e., adaptation of the economic network in our framework), this effect is not as strong, but is still responsible for larger losses when a disaster has heterogeneous impacts.

This result is confirmed by Fig. 8, which shows the average response for various variances ranging from 0 to 2. The most favourable case is when the variance is null, i.e. when damages are equally distributed among the PUs of each sector. This

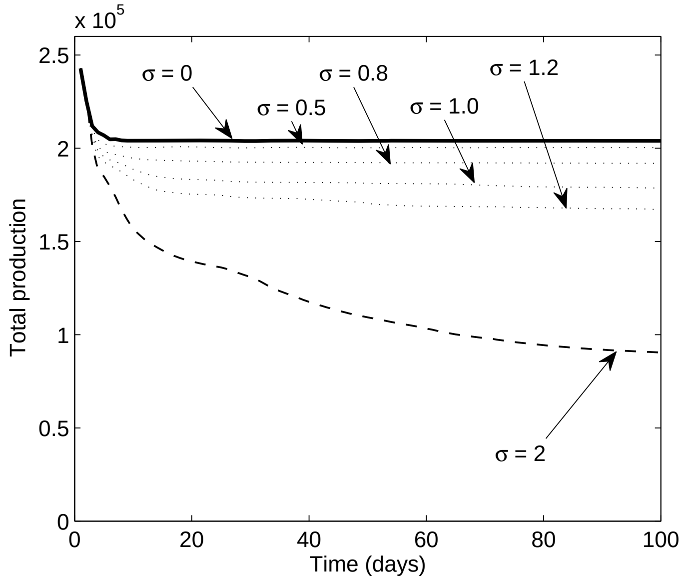

Fig. 8. Average economic response to the disaster, for different values of loss variance parameter σ.

scenario is the one that can be captured using an IO model (Hallegatte, 2008). But it is also an unlikely scenario, since the observed variance is often very high (e.g., Tierney, 1997). This result justifies our disaggregated approach: taking into account loss heterogeneity is found of the foremost importance. It also highlights the need for detailed location data about production units and for spatialized loss data. It seems, indeed, that indirect losses will strongly depend on how the disaster footprint overlaps the localization footprint of each sector.

6 Conclusion

Our modeling framework does not pretend to allow for the assessment of the real full cost of a disaster. We claim, however, that our analysis makes a contribution in that it justifies the development of a more disaggregated approach to model natural disaster economic consequences. Indeed, we have showed that classical IO models may be too optimistic, given that they stand for the most favorable case in which risks and losses are optimally shared, that is to say in which each firm is a client and supplier of each other firm, and in which losses are uniformly distributed.

A disaggregated approach is necessary to evaluate cost amplifications due to loss heterogeneity and to business interactions within the production network. In particular, the cost of a disaster results from the intersection between the geographical disaster footprint and the firm localizations. This result shows the importance of analyses in the line of Kroll et al. (1991) and Tierney (1997) that provide detailed information on disaster impacts at the business level.

Moreover, the model can reproduce economic collapse, suggesting that it may be used to investigate the existence and location of a threshold in terms of disaster losses. This approach may be able, e.g., to discriminate between limited-consequence disasters like the 2004 hurricanes in Florida and widespread-consequences disasters leading to systemic failure like Katrina in New Orleans in 2005. It seems, for instance, that loss heterogeneity is an essential parameter in the assessment of the risk of an economic systemic failure.

In spite of large uncertainties in the modeling approach, the model is interesting because it suggests ways to increase the economic robustness to natural disasters. First, economic collapse is found much less likely if production units diversify risks by having many clients and suppliers and large inventories. This point suggests the existence of a trade-off between economic efficiency and disaster resilience. This issue raises the need for additional research at the supply-chain level. This result is consistent with the well-accepted intuition that risk diversification increases robustness. More surprisingly, however, the model suggests that recovery is easier if, in disaster aftermath, the remaining production is allocated in priority to the least affected businesses. In other terms, it suggests that maximizing economic resilience can be done through the sacrifice of the most affected businesses. This questionable and counter-intuitive result also needs to be investigated in more details.

Our analysis highlights also the drawbacks of our approach. First, with the small number of production units that are modeled, results are unrealistically dependent on the decisions made by individual production-unit managers. As a consequence, the same disaster can lead to very different outcomes depending on these decisions. This sensitivity is thought to originate from the unrealistically small size of our model economy, and a model with a more realistic firm number may produce more consistent results, in spite of a large number of degrees of freedom. Reproducing realistic economic response may require the modeling of a much larger economic network, which creates difficult numerical and computational issues. Future research will investigate strategies to overcome these difficulties, possibly in the line of Haimes and Jiang (2001).

Finally, this analysis does not investigate factors that are of great importance, namely the recovery and reconstruction of individual production units, the impact of financial bankruptcies, the existence of unused capacity (see, e.g., Hallegatte and Ghil, 2008; West and Lenze, 1994) and the role of imports and other links with actors located outside the affected region. Also, transportation, energy and water infrastructures have specific characteristics that may require specific modeling approaches, in the line of, e.g., Cho et al. (2001) and Rose and Liao (2005). All these factors have been found essential in classical IO analysis and have to be included in any network-based analysis.

Also of the foremost importance is the shape of the economic network. Many analyses on network robustness (e.g., Albert et al., 2000; Callaway et al., 2000; Holme et al., 2002; Newman, 2003; Tanizawa et al., 2005) have concluded that real-world networks, which often possess power-law or other highly skewed degree distributions, are particularly robust to random node failures. Moreover, Carvalho (2008) models the economy as a network of sectors, and find that the existence of sectoral hubs (i.e. sectors that provide inputs to many sectors) changes the way sectoral shocks can cause fluctuations in macroeconomic aggregate. This result proves that the economic-network structure matters in determining the economic response to exogenous shocks, supporting the approach followed in this article. Considering these conclusions and their high sensitivity to network characteristics, our simplistic network structure has clearly to be elaborated and validated against real data. This work will be carried out in a follow-up paper, in which the methodologies proposed in Carvalho (2008) will be very useful. The analysis proposed in this article should, therefore, be considered as the first step of a long-term research program and as an identification of the more promising research directions.

7 Acknowledgments

The authors want to thank Patrice Dumas, Jean-Yves Grandpeix, Francois Gusdorf, and Nicolas Naville for their useful comments and suggestions on an earlier version of this article.

References

Albert, R., Jeong, H., Barabasi, A. L., 2000. Attack and error tolerance of complex networks. Nature 406, 378–382.

Battiston, S., Delli Gatti, D., Gallegati, M., Greenwald, B., Stiglitz, J., 2007. Credit chains and bankruptcy propagation in production networks. Journal of Economic Dynamics and Control 31, 2061–2084.

Beamon, B., 1999. Measuring supply chain performance. Journal of Operations and Production Management 19 (3), 275–292.

Bénassy, J., 1984. Macroéconomie et Théorie du Déséquilibre. Dunod, Paris, France.

Boarnet, M. G., 1998. Business losses, transportation damages, and the Northridge earthquake. Journal of Transportation and Statistics 1, 49–63.

Brookshire, D. S., Chang, S. E., Cochrane, H., Olson, R., Rose, A., Steenson, J., 1997. Direct and indirect economic losses for earthquake damage. Earthquake Spectra 13, 683–701.

Bureau of Labor Statistics, 2006. The labor market impact of hurricane katrina: an overview. Monthly Labor Review 129 (8), 3–10.

Callaway, D. S., Newman, M. E. J., Strogatz, S. H., Watts, D. J., Dec 2000. Network robustness and fragility: Percolation on random graphs. Phys. Rev. Lett. 85 (25), 5468–5471.

Carvalho, V., 2008. Aggregate fluctuations and the network structure of intersectoral trade. Job Market Paper, University of Chicago.

Cho, S., Gordon, P., Moore, J., Richardson, H., Shinozuka, M., Chang, S., 2001. Integrating transportation network and regional economic models to estimate the costs of a large urban earthquake. Journal of Regional Science 41, 39–65.

Cochrane, H., 1997. Forecasting the economic impact of a Midwest earthquake. In: Jones, B. (Ed.), Economic consequences of earthquakes: preparing for te unexpected. Buffalo, NY: National Center for Earthquake Engineering Research, pp. 223–247.

Cochrane, H., 2004. Economic loss: myth and measurement. Disaster Prevention and Management 13, 290–296.

Corso, G., Lucena, L., Thome, Z., 2003. The small-world of economy: a speculative proposal. Physica A 324 (1), 430–436.

Cowan, R., Jonard, N., 2004. Network structure and the diffusion of knowledge. Journal of Economic Dynamics and Control 28 (8), 1557–1575.

Delli Gatti, D., Di Guilmi, C., Gaffeo, E., Giulioni, G., Gallegati, M., Palestrini, A., 2005. A new approach to business fluctuations: heterogeneous interacting agents, scaling laws and financial fragility. Journal of Economic Behavior and Organization 56 (4), 489–512.

Dupor, B., 1998. Aggregation and irrelevance in multi-sector models. Journal of Monetary Economics 43, 391–409.

Gordon, P., Richardson, H., Davis, B., 1998. Transport-related impacts of the Northridge earthquake. Journal of Transportation and Statistics 1, 21–36.

Haimes, Y., Jiang, P., 2001. Leontieff-based model of risk in complex interconnected infrastructures. Journal of Infrastructure Systems 7 (1), 1–12.

Hallegatte, S., 2008. An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. Risk Analysis 28 (3), 779–799.

Hallegatte, S., Ghil, M., 2008. Natural disasters impacting a macroeconomic model with endogenous dynamics. Ecological Economics, in press.

Hallegatte, S., Hourcade, J.-C., Dumas, P., 2007. Why economic dynamics matter in assessing climate change damages : illustration on extreme events. Ecological Economics 62 (2), 330–340.

Holme, P., Kim, B. J., Yoon, C. N., Han, S., 2002. Attack vulnerability of complex networks. Physical Review E 65, 056109.

Hortacsu, A., Syverson, C., 2007. Vertical integration and production: some plant-level evidence. Working Paper, University of Chicago.

Horwath, M., 1998. Cyclicality and sectoral linkages: Aggregate fluctuations from independent sectoral shocks. Review of Economic Dynamics 1, 781–808.

Kroll, C. A., Landis, J. D., Shen, Q., Stryker, S., 1991. Economic Impacts of the Loma Prieta Earthquake: A Focus on Small Business. Studies on the Loma Prieta Earthquake, University of California, Transportation Center.

Londsdale, C., 2004. effectively managing vertical supply relationships: a risk management model for outsourcing. Supply Chain Management: An International Journal 4 (4), 176–183.

McCarty, C., Smith, S., 2005. Florida's 2004 hurricane season: Local effects.

Florida Focus, BEBR University of Florida 1.
Newman, M., 2003. The structure and function of complex networks. SIAM Review 45 (2), 167–256.
Okuyama, Y., 2004. Modeling spatial economic impacts of an earthquake: input-output approaches. Disaster Prevention and Management 13, 297–306.
Okuyama, Y., Chang, S., 2004. Modeling Spatial and Economic Impacts of Disasters. Springer.
Rose, A., 2004. Economic principles, issues, and research priorities in hazard loss estimation. In: Okuyama, Y., Chang, S. (Eds.), Modeling Spatial and Economic Impacts of Disasters. Springer.
Rose, A., Benavides, J., Chang, S. E., Szczesniak, P., Lim., D., 1997. The regional economic impact of an earthquake: direct and indirect effects of electricity lifeline disruptions. Journal of Regional Science 37, 437–458.
Rose, A., Liao, S.-Y., 2005. Modeling regional economic resilience to disasters: a computable general equilibrium analysis of water service disruptions. Journal of Regional Science 45, 75–112.
Rose, A., Oladosu, G., Liao, S.-Y., 2007. Business interruption impacts of a terrorist attack on the electric power system of los angeles: Customer resilience to a total blackout. Risk Analysis 27 (3), 513–531.
Tanizawa, T., Paul, G., Cohen, R., Havlin, S., Stanley, H., 2005. Optimization of network robustness to waves of targeted and random attacks. Physical Review E 71 (3), 047101.
Thomas, D., Griffin, P., 1996. Coordinated supply chain management. European Journal of Operational Research 94 (1), 1–15.
Tierney, K., 1997. Business impacts of the northridge earthquake. Journal of Continencies and Crisis Management 5, 87–97.
Webb, G., Tierney, K., Dahlhamer, J., 2002. Predicting long-term business recovery from disaster: a comparison of the Lome Prieta earthquake and hurricane Andrew. University of Delaware, Disaster Research Center, Preliminary paper 328.
Weisbuch, G., Battiston, S., 2008. From production networks to geographical economics. Journal of Economic Behavior and Organization, forthcoming.
West, C., Lenze, D., 1994. Modeling the regional impact of natural disaster and recovery: a general framework and an application to hurricane Andrew. International Regional Science Review 17, 121–150.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:

http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm
http://www.ssrn.com/link/feem.html
http://www.repec.org
http://agecon.lib.umn.edu
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2008

CCMP	1.2008	*Valentina Bosetti, Carlo Carraro and Emanuele Massetti*: Banking Permits: Economic Efficiency and Distributional Effects
CCMP	2.2008	*Ruslana Palatnik and Mordechai Shechter*: Can Climate Change Mitigation Policy Benefit the Israeli Economy? A Computable General Equilibrium Analysis
KTHC	3.2008	*Lorenzo Casaburi, Valeria Gattai and G. Alfredo Minerva*: Firms' International Status and Heterogeneity in Performance: Evidence From Italy
KTHC	4.2008	*Fabio Sabatini*: Does Social Capital Mitigate Precariousness?
SIEV	5.2008	*Wisdom Akpalu*: On the Economics of Rational Self-Medication
CCMP	6.2008	*Carlo Carraro and Alessandra Sgobbi*: Climate Change Impacts and Adaptation Strategies In Italy. An Economic Assessment
ETA	7.2008	*Elodie Rouvière and Raphaël Soubeyran*: Collective Reputation, Entry and Minimum Quality Standard
IEM	8.2008	*Cristina Cattaneo, Matteo Manera and Elisa Scarpa*: Industrial Coal Demand in China: A Provincial Analysis
IEM	9.2008	*Massimiliano Serati, Matteo Manera and Michele Plotegher*: Modeling Electricity Prices: From the State of the Art to a Draft of a New Proposal
CCMP	10.2008	*Bob van der Zwaan and Reyer Gerlagh*: The Economics of Geological CO_2 Storage and Leakage
KTHC	11.2008	*Maria Francesca Cracolici and Teodora Erika Uberti*: Geographical Distribution of Crime in Italian Provinces: A Spatial Econometric Analysis
KTHC	12.2008	*Victor Ginsburgh, Shlomo Weber and Sheila Weyers*: Economics of Literary Translation. A Simple Theory and Evidence
NRM	13.2008	*Carlo Giupponi, Jaroslav Mysiak and Alessandra Sgobbi*: Participatory Modelling and Decision Support for Natural Resources Management in Climate Change Research
NRM	14.2008	*Yaella Depietri and Carlo Giupponi*: Science-Policy Communication for Improved Water Resources Management: Contributions of the Nostrum-DSS Project
CCMP	15.2008	*Valentina Bosetti, Alexander Golub, Anil Markandya, Emanuele Massetti and Massimo Tavoni*: Abatement Cost Uncertainty and Policy Instrument Selection under a Stringent Climate Policy. A Dynamic Analysis
KTHC	16.2008	*Francesco D'Amuri, Gianmarco I.P. Ottaviano and Giovanni Peri*: The Labor Market Impact of Immigration in Western Germany in the 1990's
KTHC	17.2008	*Jean Gabszewicz, Victor Ginsburgh and Shlomo Weber*: Bilingualism and Communicative Benefits
CCMP	18.2008	*Benno Torgler, María A.GarcíaValiñas and Alison Macintyre*: Differences in Preferences Towards the Environment: The Impact of a Gender, Age and Parental Effect
PRCG	19.2008	*Gian Luigi Albano and Berardino Cesi*: Past Performance Evaluation in Repeated Procurement: A Simple Model of Handicapping
CTN	20.2008	*Pedro Pintassilgo, Michael Finus, Marko Lindroos and Gordon Munro* (lxxxiv): Stability and Success of Regional Fisheries Management Organizations
CTN	21.2008	*Hubert Kempf and Leopold von Thadden* (lxxxiv): On Policy Interactions Among Nations: When Do Cooperation and Commitment Matter?
CTN	22.2008	*Markus Kinateder* (lxxxiv): Repeated Games Played in a Network
CTN	23.2008	*Taiji Furusawa and Hideo Konishi* (lxxxiv): Contributing or Free-Riding? A Theory of Endogenous Lobby Formation
CTN	24.2008	*Paolo Pin, Silvio Franz and Matteo Marsili* (lxxxiv): Opportunity and Choice in Social Networks
CTN	25.2008	*Vasileios Zikos* (lxxxiv): R&D Collaboration Networks in Mixed Oligopoly
CTN	26.2008	*Hans-Peter Weikard and Rob Dellink* (lxxxiv): Sticks and Carrots for the Design of International Climate Agreements with Renegotiations
CTN	27.2008	*Jingang Zhao* (lxxxiv): The Maximal Payoff and Coalition Formation in Coalitional Games
CTN	28.2008	*Giacomo Pasini, Paolo Pin and Simon Weidenholzer* (lxxxiv): A Network Model of Price Dispersion
CTN	29.2008	*Ana Mauleon, Vincent Vannetelbosch and Wouter Vergote* (lxxxiv): Von Neumann-Morgenstern Farsightedly Stable Sets in Two-Sided Matching
CTN	30.2008	*Rahmi İlkiliç* (lxxxiv): Network of Commons
CTN	31.2008	*Marco J. van der Leij and I. Sebastian Buhai* (lxxxiv): A Social Network Analysis of Occupational Segregation
CTN	32.2008	*Billand Pascal, Frachisse David and Massard Nadine* (lxxxiv): The Sixth Framework Program as an Affiliation Network: Representation and Analysis
CTN	33.2008	*Michèle Breton, Lucia Sbragia and Georges Zaccour* (lxxxiv): Dynamic Models for International Environmental Agreements

PRCG	34.2008	*Carmine Guerriero*: The Political Economy of Incentive Regulation: Theory and Evidence from US States
IEM	35.2008	*Irene Valsecchi*: Learning from Experts
PRCG	36.2008	*P. A. Ferrari and S. Salini*: Measuring Service Quality: The Opinion of Europeans about Utilities
ETA	37.2008	*Michele Moretto and Gianpaolo Rossini*: Vertical Integration and Operational Flexibility
CCMP	38.2008	*William K. Jaeger and Van Kolpin*: The Environmental Kuznets Curve from Multiple Perspectives
PRCG	39.2008	*Benno Torgler and Bin Dong*: Corruption and Political Interest: Empirical Evidence at the Micro Level
KTHC	40.2008	*Laura Onofri, Paulo A.L.D. Nunes, Jasone Cenoz and Durk Gorter*: Language Diversity in Urban Landscapes: An econometric study
CTN	41.2008	*Michel Le Breton, Valery Makarov, Alexei Savvateev and Shlomo Weber* (lxxxiv): Multiple Membership and Federal Sructures
NRM	42.2008	*Gideon Kruseman and Lorenzo Pellegrini*: Institutions and Forest Management: A Case Study from Swat, Pakistan
SIEV	43.2008	*Pietro Caratti and Ludovico Ferraguto*: Analysing Regional Sustainability Through a Systemic Approach: The Lombardy Case Study
KTHC	44.2008	*Barbara Del Corpo, Ugo Gasparino, Elena Bellini and William Malizia*: Effects of Tourism Upon the Economy of Small and Medium-Sized European Cities. Cultural Tourists and "The Others"
CTN	45.2008	*Dinko Dimitrov and Emiliya Lazarova*: Coalitional Matchings
ETA	46.2008	*Joan Canton, Maia David and Bernard Sinclair-Desgagné*: Environmental Regulation and Horizontal Mergers in the Eco-industry
ETA	47.2008	*Stéphane Hallegatte*: A Proposal for a New Prescriptive Discounting Scheme: The Intergenerational Discount Rate
KTHC	48.2008	*Angelo Antoci, Paolo Russu and Elisa Ticci*: Structural Change, Environment and Well-being: Interactions Between Production and Consumption Choices of the Rich and the Poor in Developing Countries
PRCG	49.2008	*Gian Luigi Albano, Federico Dini Roberto Zampino and Marta Fana*: The Determinants of Suppliers' Performance in E-Procurement: Evidence from the Italian Government's E-Procurement Platform
CCMP	50.2008	*Inmaculada Martínez-Zarzoso*: The Impact of Urbanization on CO2 Emissions: Evidence from Developing Countries
KTHC	51.2008	*Michele Moretto and Sergio Vergalli*: Managing Migration through Quotas: an Option-theory Perspective
KTHC	52.2008	*Ugo Gasparino, Elena Bellini, Barbara Del Corpo and William Malizia*: Measuring the Impact of Tourism Upon Urban Economies: A Review of Literature
ETA	53.2008	*Reyer Gerlagh, Snorre Kverndokk and Knut Einar Rosendahl*: Linking Environmental and Innovation Policy
KTHC	54.2008	*Oguzhan C. Dincer and Burak Gunalp*: Corruption, Income Inequality, and Poverty in the United States
PRCG	55.2008	*Carmine Guerriero*: Accountability in Government and Regulatory Policies: Theory and Evidence
KTHC	56.2008	*Tanmoyee Banerjee (Chatterjee) and Nilanjana Mitra*: Export, Assembly-line FDI or FDI with the Possibility of Technology Diffusion: Optimal Entry Mode for Multinationals
ETA	57.2008	*Xavier Pautrel*: Environmental Policy, Education and Growth: A Reappraisal when Lifetime Is Finite
CCMP	58.2008	*Natalia Zugravu, Katrin Millock and Gérard Duchene*: The Factors Behind CO2 Emission Reduction in Transition Economies
NRM	59.2008	*Benno Torgler, María A.García-Valiñas and Alison Macintyre*: Justifiability of Littering: An Empirical Investigation
SIEV	60.2008	*Paolo Rosato, Anna Alberini, Valentina Zanatta and Margaretha Breil*: Redeveloping Derelict and Underused Historic City Areas: Evidence from a Survey of Real Estate Developers
CTN	61.2008	*Ricardo Nieva*: Networks with Group Counterproposals
CTN	62.2008	*Michael Finus and Dirk T.G. Rübbelke*: Coalition Formation and the Ancillary Benefits of Climate Policy
SIEV	63.2008	*Elisabetta Strazzera, Elisabetta Cerchi and Silvia Ferrini*: A Choice Modelling Approach for Assessment of Use and Quasi-Option Values in Urban Planning for Areas of Environmental Interest
SIEV	64.2008	*Paolo Rosato, Lucia Rotaris, Margaretha Breil and Valentina Zanatta*: Do We Care about Built Cultural Heritage? The Empirical Evidence Based on the Veneto House Market
KTHC	65.2008	*Luca Petruzzellis and Antonia Rosa Guerrieri*: Does Network Matter in International Expansion? Evidence from Italian SMEs
NRM	66.2008	*Sheila M. Olmstead and Robert N. Stavins*: Comparing Price and Non-price Approaches to Urban Water Conservation
CCMP	67.2008	*Robert N. Stavins*: Addressing Climate Change with a Comprehensive U.S. Cap-and-Trade System
CCMP	68.2008	*Geoffrey J. Blanford, Richard G. Richels and Thomas F. Rutherford*: Impact of Revised CO_2 Growth Projections for China on Global Stabilization Goals
CCMP	69.2008	*Valentina Bosetti, Carlo Carraro, Alessandra Sgobbi and Massimo Tavoni*: Delayed Action and Uncertain Targets. How Much Will Climate Policy Cost?
CCMP	70.2008	*Valentina Bosetti, Carlo Carraro and Massimo Tavoni*: Delayed Participation of Developing Countries to Climate Agreements: Should Action in the EU and US be Postponed?
SIEV	71.2008	*Massimiliano Mazzanti, Anna Montini and Francesco Nicolli*: Embedding Landfill Diversion in Economic, Geographical and Policy Settings Panel based evidence from Italy
ETA	72.2008	*Reyer Gerlagh and Matti Liski*: Strategic Resource Dependence
CCMP	73.2008	*Sonia Ben Kheder and Natalia Zugravu*: The Pollution Haven Hypothesis: A Geographic Economy Model in a Comparative Study
SIEV	74.2008	*Jérôme Massiani and Paolo Rosato*: The Preferences of Trieste Inhabitants for the Re-use of the Old Port: A Conjoint Choice Experiment
SIEV	75.2008	*Martin F. Quaas and Sjak Smulders*: Pollution and the Efficiency of Urban Growth
CCMP	76.2008	*Anil Markandya and Dirk T.G. Rübbelke*: Impure Public Technologies and Environmental Policy

KTHC	77.2008	*Gianmarco I P Ottaviano and Giovanni Peri*: Immigration and National Wages: Clarifying the Theory and the Empirics
CCMP	78.2008	*Vivekananda Mukherjee, Dirk T.G. Rübbelke and Tilak Sanyal*: Technology Transfer in the Non-traded Sector as a Means to Combat Global Warming
SIEV	79.2008	*A. Ghermandi, J.C.J.M. van den Bergh, L.M. Brander, H.L.F. de Groot, and P.A.L.D. Nunes*: The Economic Value of Wetland Conservation and Creation: A Meta-Analysis
CCMP	80.2008	*Snorre Kverndokk and Adam Rose*: Equity and Justice in Global Warming Policy
ETA	81.2008	*Sonia Oreffice*: Sexual Orientation and Household Decision Making. Same-Sex Couples' Balance of Power and Labor Supply Choices
CCMP	82.2008	*Robert N. Stavins*: A Meaningful U.S. Cap-and-Trade System to Address Climate Change
NRM	83.2008	*Ruben N. Lubowski, Andrew J. Plantinga and Robert N. Stavins*: What Drives Land-Use Change in the United States? A National Analysis of Landowner Decisions
CSRM	84.2008	*Forest L. Reinhardt, Robert N. Stavins, and Richard H. K. Vietor*: Corporate Social Responsibility Through an Economic Lens
CCMP	85.2008	*Valentina Bosetti, Carlo Carraro, Alessandra Sgobbi and Massimo Tavoni*: Modelling Economic Impacts of Alternative International Climate Policy Architectures. A Quantitative and Comparative Assessment of Architectures for Agreement
PRCG	86.2008	*Gian Luigi Albano, Federico Dini and Roberto Zampino*: Bidding for Complex Projects: Evidence From the Acquisitions of IT Services
SIEV	87.2008	*Dennis Guignet and Anna Alberini*: Voluntary Cleanups and Redevelopment Potential: Lessons from Baltimore, Maryland
IEM	88.2008	*Louis-Gaëtan Giraudet and Philippe Quirion*: Efficiency and Distributional Impacts of Tradable White Certificates Compared to Taxes, Subsidies and Regulations
CCMP	89.2008	*Damien Demailly and Philippe Quirion*: Changing the Allocation Rules in the EU ETS: Impact on Competitiveness and Economic Efficiency
CCMP	90.2008	*Judson Jaffe and Robert N. Stavins*: Linkage of Tradable Permit Systems in International Climate Policy Architecture
SIEV	91.2008	*Silvio Giove, Paolo Rosato and Margaretha Breil*: A Multicriteria Approach for the Evaluation of the Sustainability of Re-use of Historic Buildings in Venice
CCMP	92.2008	*Corrado Di Maria, Sjak Smulders and Edwin van derWerf*: Absolute Abundance and Relative Scarcity: Announced Policy, Resource Extraction, and Carbon Emissions
CCMP	93.2008	*Dirk T.G. Rübbelke and Nathan Rive*: Effects of the CDM on Poverty Eradication and Global Climate Protection
SIEV	94.2008	*Massimiliano Mazzanti and Roberto Zoboli*: Waste Generation, Incineration and Landfill Diversion. De-coupling Trends, Socio-Economic Drivers and Policy Effectiveness in the EU
CCMP	95.2008	*Benno Torgler, María A.García Valiñas and Alison Macintyre*: Environmental Participation and Environmental Motivation
CCMP	96.2008	*Geoffrey Heal and Nori Tarui*: Technology Diffusion, Abatement Cost, and Transboundary Pollution
CCMP	97.2008	*Alessio D'Amato and Edilio Valentini*: Enforcement and Environmental Quality in a Decentralized Emission Trading System
CTN	98.2008	*Shao-Chin Sung and Dinko Dimitrov*: Computational Complexity in Additive Hedonic Games
CCMP	99.2008	*Giulio Cainelli, Massimiliano Mazzanti and Roberto Zoboli:* The Relationship Between Environmental Efficiency and Manufacturing Firm's Growth
CCMP	100.2008	*Fanny Henriet and Stéphane Hallegatte*: Assessing the Consequences of Natural Disasters on Production Networks: a Disaggregated Approach

(lxxxiv) This paper was presented at the 13th Coalition Theory Network Workshop organised by the Fondazione Eni Enrico Mattei (FEEM), held in Venice, Italy on 24-25 January 2008.

2008 SERIES	
CCMP	*Climate Change Modelling and Policy* (Editor: Carlo Carraro)
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Carlo Carraro)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Matteo Manera)
CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Giulio Sapelli)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*