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Modeling the Roles of Heterogeneity, Substitution, and Inventories in the Assessment of Natural Disaster Economic Costs

Stéphane Hallegatte

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Abstract

Based on an IO structure, the ARIO-inventory model simulates the economic consequences and responses to a natural disaster. It represents explicitly production bottlenecks, models a flexibility in production capacity in case of scarcity, and introduces inventories as an additional flexibility in the production system. Moreover, it takes into account the heterogeneity in goods and services within sectors, and the consequences on production bottlenecks and substitution possibilities.

The model is applied to the landfall of hurricane Katrina in Louisiana. Sensitivity analyses show that results are extremely sensitive to several uncertain model parameters. In particular, accounting for heterogeneity within sectors has a large negative influence on production bottlenecks, and thus increases total economic losses from natural disasters and other supply-side shocks. This paper shows that current models disregard important mechanisms and proposes an approach to take them into account.

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Modeling the roles of heterogeneity, substitution, and inventories in the assessment of natural disaster economic costs

Stéphane Hallegatte [a,b,*]

[a] *The World Bank, Sustainable Development Network, Washington D.C., USA*

[b] *Ecole Nationale de la Météorologie, Toulouse, France*

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1 Introduction

Natural disasters have multiples impacts. Beyond their direct impacts on human lives and assets, they also perturb the functioning of the economic system, leading to additional losses, often referred to as indirect losses or higher-order losses (see Pelling et al., 2002, Lindell and Prater, 2003, Cochrane, 2004, Rose, 2004, and a review in Hallegatte and Przyluski, 2010).

Part of these indirect losses arises from output losses, i.e from reductions in economic value-added production. These reductions can be due to the disaster itself, or to its impact on productive

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* Corresponding author: Stéphane Hallegatte.
Email address: `hallegatte@centre-cired.fr` (Stéphane Hallegatte).

capital and infrastructure. The recent Iceland volcano eruption interrupted air transport for a week and canceled the output of the entire air transport sector. A damaged factory after a hurricane cannot produce until it is rebuilt or repaired; a collapsed bridge cannot provide its services until it is rebuilt.

But output losses are also due to complex interactions between businesses. When a business cannot function, it can indeed be because it suffered direct damages (e.g., its building collapsed during an earthquake). As shown in Kroll et al. (1991) or Tierney (1997), it may also be due to lifeline interruption (water, electricity, communication) or because transportation issues make it impossible for workers or customers to access the business (see also Gordon et al., 1998; Tsuchiya et al., 2007). Finally, business perturbations may also arise from production bottlenecks through supply-chains of suppliers and producers (see, e.g., Henriet and Hallegatte, 2008; Henriet et al., 2012).

These effects are tragically illustrated by the recent Tohoku-Pacific earthquake in Japan, and its wide consequences on industrial production and exports, especially in car-making. As an example, The Economic Times (2011), an Indian newspaper, reports that *“Japan’s Toyota Motor will cut production at its Indian subsidiary by up to 70% between April 25 and June 4 due to disruption of supplies.”* The New York Times (2011b) also reports on the impact on Honda production: *“But auto production in Japan is at only half the normal level for Honda — as it is for Honda’s bigger rivals, Toyota and Nissan. That is mainly because many of the 20,000 to 30,000 parts that go into a Japanese car come from the earthquake-stricken region in northeastern Japan, where numerous suppliers were knocked off line. Unless parts makers can resume production soon, the auto companies might have to shut down once again. ’We cannot continue for a long time,’ said Ko Katayama, the general manager at Honda’s factory here, declining to specify how long production could continue. ’Sooner or later, it’s going to run out.’ ”* These examples refer to highly-visible global supply chains, but such bottlenecks can also occur at the local scale, and even for small businesses.

As mentioned in Hallegatte (2008), hereafter H08, these ripple-effects can be labeled “backward” or “forward.” Backward ripple-effects arise when the impact propagates from clients to suppliers, i.e. when a business cannot produce, and thus reduces its demand to its suppliers, reducing their own activity (even in absence of direct damages). Forward ripple-effects arise when the impact propagates from suppliers to clients, i.e. when a business cannot produce and thus cannot provide its clients with inputs needed for their own production.

This paper focuses on these inter-industry interactions and on their role in natural-disaster aftermaths. It proposes a new version of the ARIO model, which was first presented in H08. This new version is better able to represent production bottlenecks and ripple-effects, through the taking into account of inventories, production dynamics, and heterogeneity within sectors. The next section summarizes existing tools to assess output losses due to natural disasters and highlights shortcomings on which progress is most necessary. Section 3 presents the new version of the model (ARIO-inventory) and explains how it answers some of the identified needs. Section 4 presents the case study on Louisiana and the landfall of Katrina, and the sensitivity analyses that highlight the importance of modeling heterogeneity to avoid overoptimistic estimates of supply-side shock consequences. This section does not aim at providing a new estimate of the cost of Katrina, but it emphasizes the importance of a few uncertain mechanisms. Section 5 concludes.

2 Existing modeling approaches

Post-disaster interindustry ripple-effects have already been the topic of intense research (West and Lenze, 1994; Rose et al., 1997; Brookshire et al., 1997; Haimes and Jiang, 2001; Cochrane, 2004; Okuyama, 2004; Okuyama et al., 2004; Haimes et al., 2005; Rose and Liao, 2005). In these studies, the economy is described as an ensemble of economic sectors, which interact through intermediate consumptions.

Some models are based on the Input-Output (IO) linear assumption (Leontieff, 1951), in which the production of one unit in one sector requires a fixed amount of inputs from other sectors, and in which prices do not play any role (e.g., Rose et al., 1997; Haimes et Jiang, 2001; Bockarjova et al., 2004; Okuyama, 2004; Okuyama et al., 2004; Santos and Haimes, 2004). In this framework, producing one unit in the automotive industry requires a fixed amount of energy, water, steel, financial services, transport, etc. Even though the IO model is originally a demand-driven model (see, e.g., Oosterhaven,1988; Cochrane, 2004), it has been used to model disasters, which are largely supply-side shocks. Extentions of IO models have been used to include supply constraints and production dynamics within IO-model disaster assessments (e.g., Okuyama, 2004; Okuyama et al., 2004). The IO approach is based on the idea that, over the short term, the production system is fixed, and that local production capacity is constrained by existing capacities, equipments and infrastructure. For instance, this approach assumes that the non-affected capital cannot increase its production to compensate for lost production from affected capital. Only imports from outside the affected region and postponement of some non-urgent tasks (e.g., maintenance) can create a limited flexibility over the short-term (e.g., Cole, 1998).

Other models are based on the Computable General Equilibrium (CGE) framework, which assumes that changes in relative prices balance supply and demand (e.g., Rose and Liao, 2005; and Rose et al., 2007). In this framework, there is no rationing in the economic system. A disaster-caused destruction of production capital in a sector translates into a reduction in the production of the corresponding commodity, and into an increase in its price. This increase in price leads in turn to a reduction in its consumption, restoring the equality between demand and the reduced production. Moreover, in CGE models based on Cobb-Douglas or Constant Elasticity of Substitution production function, the production technology is not fixed any more and there is short-term input substitution: in presence of scarcity in one input, production can be carried out using less of this input, and using more of other inputs. Because of socio-economic inertia, transaction costs, anti-gouging legislation (e.g., Rapp, 2006) and social norms, however, the adjustment through prices appears unlikely in disaster aftermath. In post-disaster situations, little changes in prices have been observed, except in the construction sector. But prices and elasticity in CGE can also be seen as an artificial way of modeling flexibility. In that case, prices in the model should be considered as proxies for scarcity, more than actual observable prices. The CGE-model flexibilities (the signaling effect of prices, reduction in demand, and substitution in the production process) smooth any exogenous shock and mitigate disaster consequences.

Economic losses caused by a disaster are smaller in a CGE setting than in an IO setting. It is often considered that IO models represent the short-term economic dynamics, in which production technologies are fixed and prices cannot adjust. CGE models, on the other hand, represent the long-term dynamics, in which flexibility in production processes and markets allow for an adjustment of the economic system. In reality, it is likely that IO models are pessimistic in their assessment of disaster output losses, because there is flexibility even over the short term (for instance, maintenance can be postponed; workers can do more hours for cope with the shock; production can be rescheduled, see Rose et al., 2007). It is also likely that CGE models are optimistic, even in the long run, because prices have stickiness and cannot adjust perfectly, and because substitution has technical limits that are not always adequately represented in production functions.

Natural disasters and their reconstruction phases are medium-term events, spanning from the first hours of the shock to years of reconstruction after large scale events. Some authors have looked for intermediate approaches to natural disaster modeling, trying to find a common ground between IO and CGE. Rose and Liao (2005) and Rose et al. (2007) use a CGE framework, but with a lower substitution elasticity to take into account the fact that substitution is more limited over the medium term than over the long term. Going in the other direction, other authors developed IO models that answer previous IO-model shortcomings by introducing explicit supply constraints and production flexibility (e.g., Okuyama, 2004; Okuyama et al., 2004). In H08, an IO model is complemented by a flexibility in IO coefficients. These coefficient are modeled dynamically, assuming they vary in response to scarcity indicators (namely the ratio of production over total demand), to represent additional hours by workers, increased capacity, and the increased use of imports when local production is impaired.

To make progress in the modeling of natural disaster economic consequences, three difficulties remain particularly important to tackle. The first one is the representation of network-shaped industries (electricity, water, transport) in more explicit manners, to take into account their specificities and the fact that they are not economic sectors like the others. Gordon et al. (1998), Cho et al. (2001), and Tsuchiya et al. (2007), among others, go in this direction.

The second difficulty lies in the aggregation level of these models, which represent economic sectors, i.e. thousand of businesses located in different places, as a unique producer. In such a framework, all businesses from one sector are assumed to suffer from the same direct impacts from disasters; in other terms, impacts are homogeneously distributed among the businesses from each sector. Also, if one business cannot produce, it is assumed that its production can be replaced by output from any other business of the same sector. These two assumptions are clearly overoptimistic, as they overestimate substitution capacity in the economic system. Taking into account the multiplicity of producing units, their location, and explicit supply-chains would allow for a much more realistic representation of natural disaster consequences. Haimes and Jiang

(2001), Anderson et al. (2007), Battiston et al., (2007), Weisbuch and Battiston (2008), Coluzzi et al. (2010), and Henriet et al (2012) investigate this issue and propose modeling approaches to account for these effects. In this paper, we approach this problem in an implicit manner, i.e. without explicitly representing supply chains and heterogeneous impacts. In practice, we take into account these heterogeneities at the sector level, in the assessment of production bottlenecks and substitution capacity. As will be shown, assumptions on heterogeneity and substitution capacity have a large influence on model results.

The third difficulty is related to the role of inventories, to production dynamics, and more generally to the representation of supply shortages (Okuyama, 2004; Okuyama et al., 2004). Some inputs are absolutely necessary for production, and a short interruption can cause significant perturbation in production. Examples are electricity, water, fresh goods, and all other goods that are required for production and cannot be stocked. Other inputs are also necessary for production, but they can be stocked, and a short interruption in supply does not create large difficulties. An example is steel and tires for automakers, which are indispensable but stockable. Finally, other inputs are not absolutely necessary for production, and reasonably long interruptions can be managed. This is the case for instance of many business services, education and professional training and — to a certain extent — for maintenance.

Inventories matter because they influence bottlenecks in the production system. They introduce an additional — and critical — flexibility into the system, as mentioned in the case of the Honda production in the New York Times (2011b). Investigating inventories is also interesting because modern production organization tends to reduce the use of inventories with production-on-demand and just-in-time delivery. Added to other trends (e.g. outsourcing, reduction in the number of suppliers), these changes may make each production unit more dependent on the ability of its suppliers to produce in due time the required amount of intermediate goods. As a result, these changes may increase the overall vulnerability of the economic system to natural disasters, in a trade-off between robustness on the one hand, and efficiency in normal times on the other hand (Henriet et al., 2012). To account for this issue and investigate how inventories influence robustness and resilience, this paper proposes a model that describes inventories dynamics in an explicit manner.

This paper proposes a modified version of the ARIO model described in H08, to make it able to account for the heterogeneity within sectors, for limited substitution capacity, and for inventory effects in the production system. This version appears also more satisfying than the previous version in the way it models production bottlenecks and the impact of input scarcity in the production system.

3 The ARIO-inventory model

The ARIO model is the Adaptive Regional Input-Output model. This model has been used on Louisiana and New Orleans to investigate the cost of hurricane Katrina in 2005 (H08), on Copenhagen to assess the risks from coastal floods in a climate change context (Hallegatte et al., 2011), on Mumbai with a slightly modified version, to assess flood risks and climate change impacts (Ranger et al., 2011), and on the Sichuan region to assess the cost of the 2008 Wenchuan Earthquake (Wu et al., 2011).

In its initial version, the model has a one-month time step, and has no inventories. The new version presented here is based on the same ideas, but has a one-day time step, and introduces an inventory dynamics, which makes it more different from classical IO models. The model code is available upon request.

The modeling strategy is inspired from Levine and Romanoff (1989) and Romanoff and Levine (1977, 1986, 1993), who introduced the Sequential Interindustry Model (SIM) framework to evolve from the classic static IO model to a dynamic model. Doing so requires the introduction of inventories and specific demand dynamics, and has been used already in disaster assessment, for instance in Okuyama (2004) and Okuyama et al. (2004).

3.1 Model principles and equations

Each economic sector produces according to (i) observed demand, which depends on the orders it receives from its clients (households and other sectors); (ii) input availability, which depends on supplier production and the level of inventories; and (iii) its own internal production constraints (i.e. productive capital). In this version, labor is not considered as a possible constraints. The following description only describes changes with respect to the H08 model.

We assume that Y is the vector of outputs of the different sectors and A is the IO matrix, i.e. the matrix that describes the quantity each sector is providing (or, equivalently, purchasing) to other sectors. The coefficient $A(i,j)$ is the consumption of commodity j by the production process of sector i. The production is used to satisfy the demand for intermediate goods and final demand. The equilibrium equation is then:

$$Y = AY + C \tag{1}$$

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

$$Y^0 = (I - A)^{-1} C \tag{2}$$

Y^0 would be the production if the production capacities were not bounded and if there were no inventory. In the present model, however, each sector production capacity will be taken into account, and the impacts of inventories and input availability on demands will be modelled.

3.1.1 Inventories and demand model

We define $D_j(t)$ as the total demand to the j^{th} sector at the time t. It includes household final demand, government consumption, business investments, and interindustry demands (i.e. intermediate consumption demand). Each sector produces commodities by drawing from their commodity inventories. They have then to order new inputs to their supplying sectors, in order to restore their inventories. The inventory levels at the end of each time step are used to determine the demands to supplying sectors.

We assume that the i^{th} sector has an inventory $S(i,j)$ of the commodity produced by the j^{th} sector. Some commodities, for instance those produced by the manufacturing sector, can be stocked, while it is almost impossible to stock electricity. For simplicity, non-stockable goods – like electricity – are modeled assuming that their inventories cannot be larger than what is needed to produce during three day.[1] It means that, if electricity or water is shut down, production in the affected area will be stopped only a few days later. This is not perfect, but it simplifies significantly the model. Also, it can be interpreted as the flexibility from the use of generators, batteries, and small water reservoirs in case of lifeline interruptions.

The demand from the i^{th} sector to the j^{th} sector is designed to restore the inventory $S(i,j)$ to a target level $S^t(i,j)$, equal to a given number of days n^i_j of intermediate consumption, at the production level needed to satisfy total demand (or the maximum production, considering

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[1] With a model time step of one day, any time period shorter than three days create numerical instabilities.

existing production capacity). The target inventory level is given by the following equation: [2]

$$S^t(i,j) = n^i_j \cdot \mathsf{Min}\left(P^{cap}_i, D_i\right) \cdot A(i,j)\ , \tag{3}$$

where P^{cap}_i is the production capacity of the i^{th} sector, as defined by Eq.(6) below.

The orders $O(i,j)$ from the i^{th} sector to the j^{th} sector j then reads:

$$O(i,j)(t+1) = A(i,j)P^a_i + \frac{\delta t}{\tau^i_s}\Big(S^t(i,j) - S(i,j)\Big) \tag{4}$$

The parameter δt is the model time step (i.e., one day). The variable P^a_i is the actual production of sector i (see Eq.(11) below). So, $A(i,j)P^a_i$ is the amount of commodity j that has been used in the production process of the sector i during the current time step. The first term of the RHS of Eq. (4) represents thus simply the orders needed to compensate for the current consumption of commodity j by sector i. The second term of the RHS of Eq. (4) represents the orders that make the inventory converge toward its target value, i.e. toward n^i_j days of target consumption. The parameter τ^i_s is the characteristic time of inventory restoration, which is assumed identical in all sectors (except for non-stockable commodities). The influence of this parameter will be analyzed in Section 4.3.

This modeling provides the total demand directed toward each sector j for the next time step, i.e. at $t+1$, by adding all demands from individual sectors, plus final demand C_j, reconstruction demand R_j and exports E_j:

$$D_j(t+1) = \sum_i O(i,j)(t) + C_j(t) + R_j(t) + E_j(t) \tag{5}$$

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[2] In this equation and in the following ones, variables depend on the time step t, which is omitted for simplicity.

The modeling of C_j, R_j and E_j is detailed in H08. Ranger et al. (2011) proposes a model version including a modeling of the household budget and of its influence on final consumption. This modeling of demand makes it possible to represent backward ripple-effects: if a sector produces less, then Eq.(4) shows that it will demand less to its suppliers, reducing their own production.

3.1.2 Production model

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

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

- *Limitation by production capacity.* Independently of its suppliers, the production capacity P_i^{cap} of the i^{th} sector reads:

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

  where P_i^{ini} is the pre-event production of this sector, assumed equal to the normal production capacity. The variable Δ_i is the reduction in productive capacity due to the disaster, directly because of the disaster (e.g., the volcano ash case) or through capital destructions. Like in H08, we assume that if a disaster reduces the productive capital of the industry i by x percent, then the production capacity of this industry is also reduced by x percent:

  $$\Delta_i = \frac{L_i}{K_i} \ , \tag{7}$$

where K_i is the stock of productive capital in sector i, and L_i the amount of damages to this sector productive capital.

The variable α_i is the over-production capacity; its modeling is the same than in H08 and is recalled in Section 3.1.3 below. This variable represents the ability of economic sectors to increase their production above its normal level thanks to, e.g., longer hours from workers, more efficient use of existing capital, and imports of qualified workers and equipment from other regions.

In absence of inventory constraint, the production in sector i would be:

$$P_i^{opt} = \mathsf{Min}\left(P_i^{cap}, D_i\right) \tag{8}$$

- *Limitation by supplies.* In the model, production is done using inventories only. Production can thus be limited by insufficient inventories. It is assumed that if inventories are lower than their required levels, then production is reduced. Each supplying-sector j creates an additional constraint, if the corresponding inventory is lower than a share ψ of its required level $S^r(i,j)$, which is given by:

$$S^r(i,j) = n_j^i \cdot P_i^a \cdot A(i,j) \ , \tag{9}$$

where $P_i^a \cdot A(i,j)$ is the required consumption flux of commodity j to produce the level of production the previous time step [3] If the actual inventory is lower than the required one, it is

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[3] The required level of inventory $S^r(i,j)$ and the target level of inventory $S^t(i,j)$ are different. The former represents the amount of input necessary to produce (see a discussion of its impact on production below), while the latter represents orders to replenish inventories. The former takes into account constraints on other supplies; not the latter.

assumed that production is reduced following:

$$P_i^{max}(j) = \begin{cases} P_i^{opt} & \text{if } S(j,i) \geq \psi S^r(j,i) \\ \\ P_i^{opt} \cdot \text{Min}\left(1, \frac{S(j,i)}{\psi S^r(j,i)}\right) & \text{if } S(j,i) < \psi S^r(j,i) \end{cases} \tag{10}$$

The actual production P_i^a is given by the minimum of all sectoral constraints:

$$P_i^a = \text{Min}\left(P^{max}(j,i), \text{for all } j\right) \tag{11}$$

This modeling aims at taking into account the heterogeneity in the economic system. This heterogeneity can arise from heterogeneity in disaster losses and impacts: when a sector production is reduced by x% by disaster losses, it is unlikely that all production units have their production reduced homogenously by x%. Instead, as shown by Tierney (1997), impacts are heterogeneous and a few businesses are likely to be responsible for most of the decrease in production. In the same way, when a sector inventory is lower than its optimal value, it is likely that the inventory of some business are very low or even empty, causing production problems, while other businesses have their inventories at normal levels and can keep producing normally.

If this model, setting $\psi = 0$ amounts to assuming that a reduction by x% in a sector inventory (wrt to the required inventory level) represents a situation in which all businesses have an inventory reduced by x% and can keep producing until the sector inventory $S(j,i)$ is empty. In such a situation, an inventory shortage by x% (with respect to the required level) leads to no production reduction until $x = 100\%$; in this latter case, production has to stop.

Setting $\psi = 1$ amounts to assuming that a reduction by x% in a sector inventory (wrt to the required inventory level) represents a situation in which x% of the businesses have an empty inventory and stop producing, while other businesses are at (or above) their required inventory level and can keep producing. In this situation, an inventory shortage by x% (with respect to the required level) leads to a reduction by x% in production.

The parameter ψ also depends on the heterogeneity of produced goods and services within each sector of the model. If $\psi = 0$, all businesses in one sector produce the same goods or services, and one business that cannot produce can be replaced by another business of the same sector. As a consequence, model inventories consist of only one type of goods (or of perfectly substituable goods). Production is thus impaired only if the inventory of one sector production is totally empty. If $\psi = 1$, then businesses from a sector produce different goods and services that are not perfect substitutes. Model inventories include thus many different (and imperfectly substituable) goods. A reduction by x% in the sector i inventory of goods j represents thus a situation in which some goods produced by the sector j are scarce and reduce production in sector i, while other goods produced by sector j are still available in inventories. For instance, if sector i is the manufacturing sector and sector j is "mining and extraction", a reduction in the manufacturing-sector inventory of mining goods can mean that the manufacturing sector is lacking iron, even though sufficient oil supplies are available. In such a situation, even a small reduction in inventory can lead to a reduction in production by the manufacturing sector. [4]

The choice of ψ is therefore a crucial one, which represents assumptions about scales and heterogeneity in the economic system. First, the choice of ψ may be different if the model represents a small economy that is entirely affected by the event (ψ would then be low), or a large

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[4] As an illustration of how difficult it can be to find alternative suppliers, The New York Times (2011a) explains that Ford had to deal in March 2011 with a shortage of a metallic pigment that comes from a plant in the evacuation zone around Japans Fukushima Daiichi nuclear plant. It reports that *"Ford, which has stopped taking orders for vehicles to be painted tuxedo black and is building fewer models in several red hues, is studying whether it can get a substitute from another supplier, according to a company spokesman, Todd Nissen. But making such a switch is not simple, Mr. Nissen explained, because each component on a vehicle undergoes complex testing, and swapping in a new paint could result in mismatched portions or a less durable finish. In addition, finding replacement parts in the proper color later on could be impossible."*

economy that sees one of its regions affected (ψ would then be larger). Second, this choice depend on the disaggregation level of the model: if the model has few sectors, then each sector produces very heterogeneous goods and services, and ψ should be higher. Third, this choice depends on the economic structure. If all businesses are connected to all businesses, all business inventories would be reduced equivalently after a shock, and $\psi = 0$. If businesses have only one supplier in each other sector, and if the disaster creates heterogeneous impacts, then the impact on inventory will be very heterogeneous and ψ will be close of one. Considering the importance of this parameter, a sensitivity analysis is carried out in Section 4.3.

The vector $P_i^a(t)$ is the vector of actual production by each sector, taking into account the two production constraints. These constraints then propagate into the economy: if a sector 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 ripple-effects, affect the entire economy.

3.1.3 Overproduction capacity

The overproduction capacity is modeled with the variable α_i (see Eq. (6)). This modeling assumes that when production is insufficient, the variable α_i increases toward a maximum value α_{max}, with a characteristic time τ_α:

$$\alpha_i(t+1) = \alpha_i(t) + (\alpha_{max} - \alpha_i)\frac{D_i - P_i^a}{D_i} \cdot \frac{\delta t}{\tau_\alpha} \tag{12}$$

The term $(D_i - P_i^a)/D_i$ is a scarcity index. [5] This modeling implies that overproduction capacity can increase up to α_{max}, in a time delay τ_α, in response to production shortages. When the situation is back to normal, this overproduction capacity goes back to one, with the characteristic time τ_α:

$$\alpha_i(t+1) = \alpha_i(t) + (\alpha^b - \alpha_i)\frac{\delta t}{\tau_\alpha} \tag{13}$$

where α^b is the overproduction capacity before the disaster, assumed equal to one.

3.1.4 Market modeling, rationing scheme and inventory dynamics

When a sector is not able to produce enough to satisfy the demand, in absence of an optimal price response to restore the production–demand equality like in a CGE model, producers have to ration their clients. To model this effect, it is necessary to introduce a rationing scheme.

In our framework, in absence of market equilibrium, demand can be larger than actual production (see Eq. (11)):

$$D_i = \sum_{j=1}^{N} O(i,j) + C_i + R_i + E_i \geq P_i^a \tag{14}$$

where C_i is the normal final demand, R_i is the reconstruction demand, and E_i is the export demand. From these incompatible demand and supply, the actual sales and purchases must be balanced however:

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[5] In CGE models, scarcity information are included in prices, which drive substitution and other economic responses. Here, there are explicit scarcity indexes that drive all economic responses, including longer work hours and the replacement of impaired local production with imports.

$$D_i^* = \sum_{j=1}^{N} O^*(i,j) + C_i^* + R_i^* + E_i^* = P_i^a \tag{15}$$

Some agents, therefore, must be rationed (Benassy, 1984). 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 may only get a fraction of their demand. Assumptions on rationing are extremely important: to maximize economic output, indeed, households should be rationed before other industries. Indeed, when an industry is rationed by \$1, it cannot create value and the loss in output is larger than \$1; when a household is rationed by \$1, the output loss is only \$1. In an optimal world, therefore, the rationing scheme should give priority to other industry, and this is what was modeled in H08.

In practice, however, doing so can be impossible because an economic sector produces heterogeneous goods destinated either to final demand and to other industries. If businesses are highly specialized, there is no flexibility in the system: if one business cannot produce, households will be rationed if the business produces commodities for household and other businesses will be rationed if the business produces commodities for intermediate consumption. And even for homogeneous goods, it is not always possible to have priorities toward other businesses: when a road is cut by hurricane damages, it cannot be used by either a business or a household, and the capacity of the transport system is reduced equally for final and intermediate demands.

In the model, we have assumed that businesses were highly specialized and we introduced a *proportional rationing* scheme (Benassy, 1984): if a sector reduces its production by x%, then households and other industries receive only $(1-x)$% of what they demand.[6] [7]

For interindustry demands, it means that:

$$O^*(i,j) = O(i,j) \cdot \frac{P_i^a}{D_i} \tag{16}$$

And for final demands:

$$C_i^* = C_i \cdot \frac{P_i^a}{D_i} \tag{17}$$
$$R_i^* = R_i \cdot \frac{P_i^a}{D_i} \tag{18}$$
$$E_i^* = E_i \cdot \frac{P_i^a}{D_i} \ , \tag{19}$$

Since orders from a sector depends on the demand it observes (see Eq. (4)), there is a flexibility in the use of production in this model: sectors in which the demand is highest also demand more to other sectors, and receive therefore a larger quantity of supply as a result of the proportional rationing.

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

$$S(i,j)(t+1) = S(i,j)(t) + \delta t \left(O^*(i,j) - A(i,j)P_i^a(t)\right) \tag{20}$$

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[6] 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 sectors declare their true demand, that is to say the amount of intermediate good they actually need to satisfy their own demand.

[7] The rationing can also be modeled in a linear programming framework in which the objective is to maximize the regional output, as suggested in Cochrane (1974), but such an optimal distribution of resources represents a best-case scenario.

where the term $O^*_{i,j}$ is the increase in inventory thanks to purchases from the supplier i, and the last term is the decrease in inventory due to the commodity consumption needed to produce the amount $P^a_i(t)$.

3.1.5 Rest of the model

The rest of the model is unchanged compared with H08, with two important exceptions.

First, the housing sector was considered separately from the IO table and the other economic sectors in H08. In particular, a loss in housing services had no consequences on other sectors, and VA losses were separated into industry VA losses and housing service losses. In the new version, losses in the housing sector are included in the IO matrix, within the sector “finance, insurance, real estate, rental, and leasing.” If too large to be accommodated, therefore, a reduction in housing sector production may lead to reduced production in other sectors. The reconstruction process is unchanged, but private and business reconstruction are considered jointly in the new version.

Second, the flexibility of the economic system is modeled by the inventories, and the dynamics of the IO table coefficients and of the final demand is not present anymore in the new version. It means that the inventory modeling potentially represents more than the effect of inventories, but also the use of imports, the flexibility in the production system (e.g., the possibility to delay maintenance), and the possibility of reschedule production. The interest of this new modeling is to make it easier to calibrate the model: what is needed is information about how long a sector can keep producing when another sector reduces its production. For instance, one could survey businesses, asking how long they can manage an interruption in utility services (probably a very short duration), an interruption in manufacturing goods supplies (probably a few weeks), or an interruption in construction-sector services (probably several years). The ARIO-inventory model represents the short-term flexibility of the production system with inventories, while CGE models (e.g., Rose et al., 2005) use constant-elasticity substitution depending on price levels.

3.2 Data and parameters

The economic data is the same than in H08, with two major differences. First, as already stated, the housing service is now included in the table. Second, new estimates of the amount of productive capital in each sector have been produced. In H08, a unique ratio of sector productive capital to sector value added was used, in all sectors. In this new version, US-scale data on the amount of private and government capital, from the Bureau of Economic Analysis, are used to assess national sector-scale ratios of productive capital to value added. These ratios are then used for Louisiana, assuming that the structure of each economic sector is similar in Louisiana and in the US as a whole. These ratios are reproduced in Tab.1.

No data are available on the distribution of damages to productive capital among sectors. The Congressional Budget Office produced estimates in broad categories: 17 to 33 billion US$ in housing; 5 to 9 US$ in consumer durable goods; 18 to 31 US$ in the energy sector; 16 to 32 US$ in other private sector businesses; 13 to 25 US$ for the government. Taking the conservative side of these estimates, these losses were distributed among the different sectors according to their respective size and other information, to assess productive capital losses in all sectors. Housing losses and consumer durable goods were included in the financial and real estate sector; Energy sector losses were distributed in the utilities and mining and extraction sectors ($5 billion and $15 billion, respectively); Government losses were distributed in the energy, transport, and government sectors; Other private-sector losses were distributed in all other sectors, following their respective productive capital. All losses are reproduced in Tab. 1. Aggregated direct losses amount to $63 billion, and are significantly lower than estimates used in H08 ($107 billion).

Sector	Ratio Capital to VA	Direct losses from Katrina (million US$)
Agriculture, forestry, etc.	2.9	262
Mining and extraction	5.1	15,000
Utilities	4.3	5,000
Construction	0.4	221
Manufacturing	1.4	2,382
Wholesale trade	0.6	404
Retail trade	1.1	1,027
Transportation and warehousing	2.7	5,000
Information	2.4	835
Finance, insurance, real estate, rental and leasing	6.9	22,000
Professional and business services	0.5	408
Educational services, health care, and social assistance	1.1	1,053
Arts, recreation, accommodation and food services	1.2	769
Other services, except government	1.2	364
Government	4.9	8,000

Table 1

Ratios of productive capital to value added in the 15 sectors of the Louisiana economy, and direct losses caused by hurricane Katrina (see text for details).

Name	value
α^b	100%
α^{max}	125%
τ_α	1 year
n_j^i	90 days
τ_s	30 days
ψ	0.8

Table 2

Parameter values.

The introduction of inventories makes it necessary to define three new parameters:

- The target inventory measured in days of demand (n_j^i); in the reference model version, this level is assumed to be 90 days of demand, except(1) in the non-stockable-goods sectors (utility and transport), in which it is three days; (ii) in the construction sector, in which it is infinite (i.e. we assume that rationing from the construction sector cannot affect the production process in other sectors).
- The parameter τ_s, i.e. the characteristic time of inventory restoration, which is assumed equal to 30 days, except for non-stockable commodities, in which it is taken equal to one day.
- The parameter ψ drives the reduction in production when inventories are insufficient and differs depending on how heterogeneous the sectors are. In the reference case, ψ is equal to 0.8.

Parameter values are presented in Tab. 2. The large uncertainty is all of these values has to be acknowledged, and a sensitivity analysis on these parameters is provided in Section 4.3.

4 Results on Louisiana and hurricane Katrina

The introduction of inventories introduces an additional flexibility in the system and is likely to increase robustness (production interruptions in stockable-goods sectors do not have immediate impacts on other sectors). On the other hand, the new modeling of rationing means that businesses are much more rationed than in the H08 model. This latter effect increases production losses compared with the initial model in which bottlenecks were exceptional. [8]

4.1 Impacts of inventories on the cost of Katrina

The total cost of Katrina is Louisiana is found to be lower in this new model version, with output losses amounting to \$11 billion. In H08, the estimate was \$42 billion. One fraction of the difference arises from including housing losses in the IO table (instead of a separate treatment), from changes in sector capital, from changes in the loss distribution, from using different parameters, and from the change in rationing scheme, which introduces production bottlenecks in the economic systems. But most of the change arises from more optimistic estimates of direct losses (\$63 vs. \$107 billion of direct losses). Regardless, the objective of this section and of this paper is not to provide a new estimate of the cost of Katrina. Instead, it aims at investigating additional mechanisms that play an important role in disaster aftermath.

The dynamics effects are represented in Fig. 1. Just after the shock, the production is reduced by the decrease in production capacity due to destructions of productive capital (equipment, factories, infrastructure, etc.), but without sectoral interactions. Rapidly, however, sectoral bot-

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[8] With a priority to interindustry demands, businesses are rationed only when production losses in a sector are larger than final demand in the pre-disaster situation, which is very unlikely in a large region like Louisiana.

tlenecks are responsible for a drop in production that lasts about 8 months. The manufacturing sector becomes first a bottleneck for the economic system and reduces the total economic output of all other sectors. This is due — in part — to the increase in demand to this sector, driven by reconstruction needs. In response to this underproduction, the production capacity of the manufacturing sector starts to increase. After about 10 months, the manufacturing sector stops to be the main bottleneck, and the transportation sector becomes the limiting factor of the economic system, until about one year after the shock.

The recovery and reconstruction period is thus distributed in two periods: during the first year, there are large output reductions due to reduced production capacity and cross-sectoral forward ripple-effects; after that, and until full reconstruction, output losses are much lower and are only due to the reduction in production capacity (with no remaining forward ripple-effects). This somehow simplistic behavior can be explained by the fact that all sectors have the same inventory timescale and target inventory level in the model. Introducing heterogeneity in inventory timescales and target levels would make the whole picture more complicated, but also more realistic. A deeper investigation of these issues at the sector level thus appears needed to improve the model.

After about 2 years, total output is larger than before the disaster, due to the combined effect of higher demand (linked to reconstruction) and increased capacity (linked to the overproduction capacity). Compared with the H08 model, reconstruction is carried out more rapidly, in less than 5 years.

In this assessment, indirect losses represent the net impact of output and include gains in reconstruction sectors (especially the construction sectors) and large losses in other sectors. There are winners and losers in disaster aftermath, and the aggregate loss does not represent fairly welfare and economic losses at the sector, business and household levels (see also Section 4.3.4).

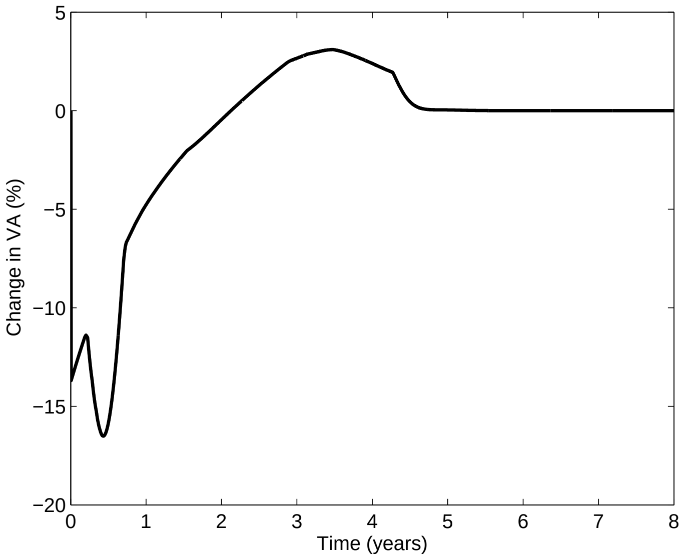


Fig. 1. Dynamics of VA losses in Lousiana after hurricane Katrina, as estimated by ARIO-inventory.

It is difficult to compare model results with economic data, for at least three reasons. First, a large share of losses is in the housing sector, which is difficult to measure in aggregated economic data. Second, the Louisiana economy was not only impacted by Katrina in 2005 and 2006, but also by numerous other events, including the rise in oil price, that was only partly linked to the Katrina landfall and created huge benefits to the local economy. Third, federal support to the state of Louisiana is not included in model simulations. Comparing the GDP impact at different point in time, however, it seems that the maximum GDP loss is later in the model than in the data, but this result varies depending on the sector. In 2004, growth rate in the manufacturing sector was 26.1% in Louisiana, vs. 5.6% in the entire U.S. In 2005, the rates were respectively 9.6 and 0.9%, and Katrina is likely to have contributed to the reduction in the gap between the two rates. In 2006, the rates were -11.4% and 5.5%, suggesting that the impact of Katrina may have been largest during the year 2006. These data support the idea that there are complex dynamics in the response to the disaster: the classical scenario of an instantaneous shock followed by a regular and monotonic return to equilibrium does not fit data very well. Bottlenecks and inventories may be an explanation to this complexity in response. The model, however, estimates the reduction in manufacturing output due to Katrina at 2.8% and 2.9% in 2005 and 2006, respectively. More generally, GDP losses seem to decrease rapidly in 2006 in the data, while they increase compared with 2005 in the model.

Even though data are difficult to interpret — again, they have many different drivers — they suggest that the model does not capture perfectly the different timescales involved. In particular, the assumption that all sectors have the same inventory timescale and target inventory level appears highly questionable. More work is required on the calibration of the model parameters, but this calibration requires first a careful analysis of the data, to extract the impact of the disaster from other determinants of sector-scale growth.

4.2 Sector production and bottlenecks

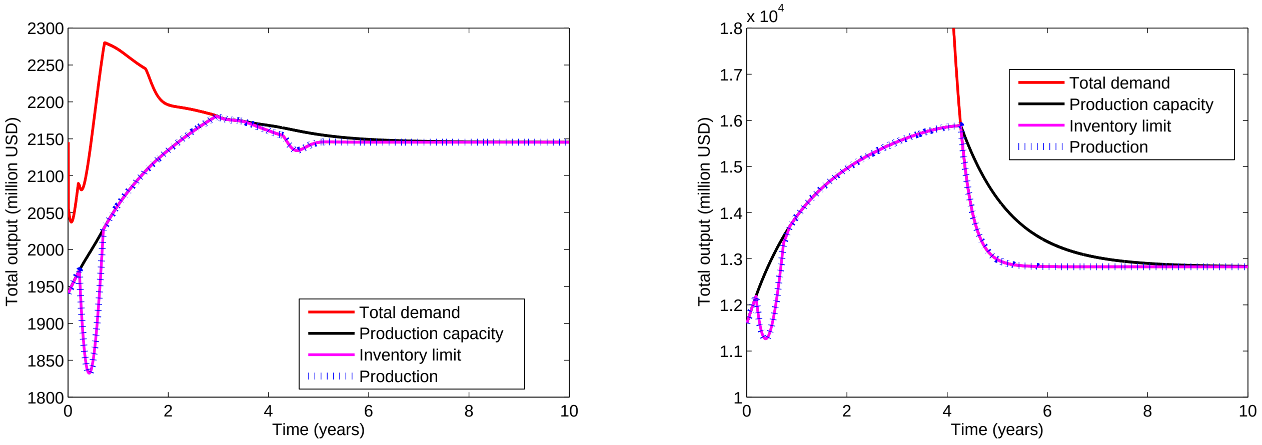
To get a better understanding of the model dynamics, it is interesting to focus on a few sectors, and investigate their behavior. In this section, we focus on the agriculture and construction sectors; see Fig. 2. These sectors are chosen because their dynamics are different and they illustrate possible constraints to production.

In the agriculture sector, demand (the red line) is significantly reduced by the disaster (because other industries cannot produce and reduce their purchase of manufacturing goods), but the decrease in production capacity is larger than the decrease in demand. Production (the dotted blue line) is first constrained by production capacity (the black line), which is directly reduced by disaster losses. Thanks to reconstruction and the overproduction capacity process, however, this limit increases over time. After a few months, inventories become the binding constraint (the magenta line), when insufficient supplies from the manufacture sector causes a reduction in agriculture production. In practice, the manufacturing sector has a reduced production capacity because of disaster-related capital losses and sees an increased final demand because of reconstruction needs. As a consequence, it cannot satisfy all demands and it rations all sectors, including the agriculture sector that in turns reduces its production. Reconstruction in the manufacturing sector reduces progressively this constraints, which is replaced after about a year by a constraint from the transportation sector, until this one disappears, about 12 months after the shock. Then, the reduced production capacity in the agriculture sector becomes again the binding constraint, until full return of the initial situation.

In the construction sector, demand becomes very large after the disaster, because of reconstruction needs. At first, production capacity in the construction sector is the main constraint on production: equipment and capital are lacking to satisfy the demand. Then, production capacity increases in view of this large demand (thanks to, e.g., imports of equipments), and does not remain the binding constraint. After a few months, inventories become the binding constraint on production. Like for agriculture, the manufacturing sector and then the transportation sector supplies become insufficient, thereby reducing the construction-sector output. After 4 years, however, reconstruction is almost completed and reconstruction demand starts to decrease. Demand to the construction sector then becomes lower than production capacity and inventory capacity (both of which have increased significantly over the years), and the construction sector is then in overproduction situation. At that time, demand becomes the binding constraint, until production capacity and inventories return to their pre-disaster levels.

4.3 Sensitivity analyses

Uncertainty in natural disaster economic losses is extremely large, and many important mechanisms are not well understood. For this reason, models cannot be trusted without a careful



(a) Agriculture (b) Construction

Fig. 2. Dynamics of production in the agriculture sector (left-hand side panel) and the construction sector (right-hand side panel), and the role of the three drivers of production, namely demand, production capacity, and inventory constraints. The figure shows that different constraints are binding at different stages of the reconstruction period. The actual production is always equal to the minimum of these possible productions.

analysis of their result robustness. To do so, we carry out in this section a sensitivity analyses on the most important parameters of the model. Beyond an estimate of result robustness, this analysis can help understand what are the most important drivers of disaster economic losses and provide insights on future research needs.

This section proposes an analysis of the model results sensitivity to the parameter ψ, which represents economic heterogeneity and drives production reductions when inventories are insufficient; to the parameters n_j^i that describe inventory size; to the time of inventory restoration τ_s; to the overproduction capacity parameters α_{max} and τ_α; and to the amount of direct losses.

4.3.1 Heterogeneity, substitution capacity, and production reduction parameter ψ

As explained in Section 3.1.2, the parameter ψ describes how production is reduced when inventories are insufficient. It would be equal to zero if all disaster impacts were homogeneous and if all businesses in a sector produced homogeneous and substituable goods and services. It would be equal to one if disaster impacts were very heterogeneous (a few businesses suffer from most of the losses) and if businesses in a sector produced non-substituable goods and services. Figure 3 shows that model results are extremely sensible to this parameter, which is not surprising since the ability to substitute for affected production is a key of economic robustness. In particular, if ψ is low enough (here lower or equal than about 0.7), substitution is sufficient to make it possible for all sector to satisfy interindustry demands, and there is no cross-sector forward ripple-effect. The only binding constraint in this situation is thus the reduced production capacity due to disaster damages. It ψ is larger, then substitution does not allow to satisfy interindustry demand and total losses soar.

The reference model assumes $\psi = 0.8$ and estimates output loss due to Katrina at \$11 billion. These output loss would be equal to \$7.5 billion with ψ lower or equal to 0.7, and to \$90 billion with $\psi = 1$. Importantly, with $\psi = 1$, production never exceeds its pre-disaster level, in spite of the increase in final demand. With $\psi \leq 0.7$, substitution is sufficient to prevent any forward cross-sector ripple-effects (i.e., production reduction due to input scarcity); losses are only due to reductions in production capacity and to reductions in demand. The corresponding output losses (\$7.5 billion) is thus the best-case scenario in which supply-chain disruptions are not taken into account or do not exist.

This extreme sensitivity shows what is most important for future research, namely an assessment of how the remaining production from non-affected businesses can be affected to the most productive uses. The possibility to do so depends largely on how one-business production can be

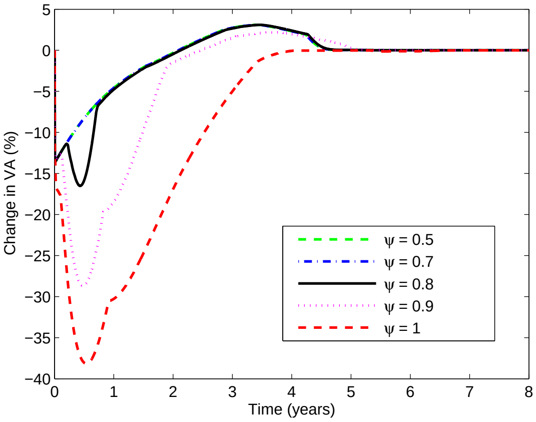


Fig. 3. Dynamics of production in the Louisiana economy, for five values of the parameter ψ, which depends on heterogeneity in the production system.

replaced by another-business production and on the existence of signals to affect production to the most productive uses. In a general equilibrium framework, one could assume that prices could play this latter role, but their ability to do can be questioned over the short term. In absence of efficient price signal, it is an open question what alternative signal could convey this information, considering how complex it is to determine an optimal use of resources.

Clearly, this question should be the focus of additional work, in the line of Haimes and Jiang (2001), Anderson et al. (2007), Battiston et al., (2007), Weisbuch and Battiston (2008), Coluzzi et al. (2010), and Henriet et al. (2012). Considering the sensitivity of model results to this parameter and the uncertainty on its value, numerical results from our modeling exercises should be considered with care and the main contribution of this paper is the elicitation of the importance of the corresponding mechanism and of the consequences of various assumptions.

4.3.2 The time of inventory restoration τ_s and the target inventory level n_j^i

Inventory parameters are also extremely important in determining output losses. Sensitivity analyses show that output losses decreases with the target inventory level in days of demand (n_j^i) in the stockable sectors (90 days in the reference simulation). Output losses decrease to \$7.5 billion for a target inventory level larger than or equal to 120 days: in this case, there is no cross-sectoral forward ripple-effects, and reduction in production capacity is the only cause for losses (this case is comparable with the case with $\psi \leq 0.5$). On the opposite, the modeled economy collapses if the initial and target inventories are only of 30 days. This results suggests (i) that there is a threshold in the amount of losses the economy can cope with in absence of external support; (ii) limited inventories increase the vulnerability of the economy to exogenous shocks like natural disasters. The collapse occurs when all sectors have consumed their input inventories and cannot keep producing, making it in turn impossible for their client sectors to produce. This type of collapsing behavior is common with ecological systems (Holling, 1973), and is also reproduced by this model of an economic system.

The same type of result is found with τ_s. Output losses are indeed lower with rapid inventory restoration (i.e. lower τ_s): output losses are equal to \$7.5 billion with $\tau_s = 7$ or 15 days, and in these cases there is no forward cross-sectoral ripple-effect (like with $\psi \leq 0.7$). Model numerical instabilities appear with $\tau_s = 7$ days. Losses increase rapidly when τ_s exceeds 30 days, reaching \$88 billion with $\tau_s = 60$. The modeled economy even collapses if τ_s is larger, as illustrated by the results with $\tau_s = 90$ days.

This extreme sensitivity can appear surprising. In fact, it is closely related to the modeling of the rationing process. With proportional rationing, indeed, what a sector receives depends on how much it demands. This is why Benassy (1984) says that this scheme can be manipulated: by exaggerating its demand, an economic actor can obtain more. In the model, interindustry demands

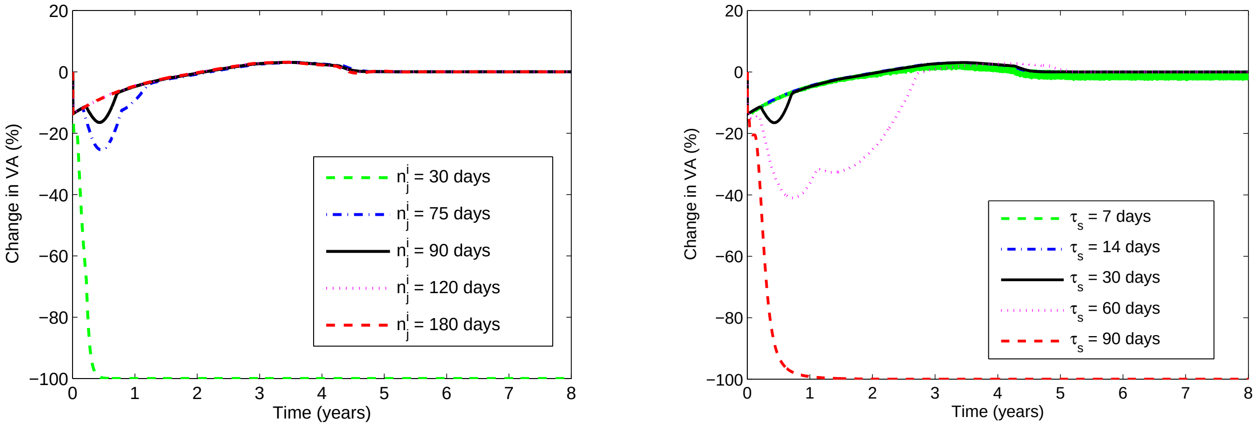


Fig. 4. Dynamics of production in the Louisiana economy, for five values of the parameters n_j^i, which describe the size of inventories (left panel), and for five values of the parameter τ_s, the characteristic time of the inventory restoration (right panel).

and final demand compete for scarce output, and final demand increases because of reconstruction needs. If τ_s is small, then interindustry demands increase rapidly as soon as inventories are below their target level, and sectors capture more of the available production than with a large τ_s. So, the parameter τ_s also describes the possibility to concentrate available production toward interindustry demands (at the expense of final demand). With a small τ_s, more of the production is channeled toward other sectors allowing to keep producing and increasing total output.

4.3.3 Overproduction capacity, α_{max} and τ_α

Sensitivity analyses are also carried out on α_{max} and τ_{ada}, i.e. the adaptation maximum and timescale (see Eq. (6)). These two parameters were found extremely important in H08, and it is still the case in the new version. With no overproduction, i.e. with $\alpha_{max} = 0$ or $\tau_\alpha = +\infty$, total output losses are equal to \$37 billion. With $\tau_\alpha = 1$ year, output losses lie between \$37 billion with no overproduction to \$2 billion with $\alpha_{max} = 1.5$. Output losses are even negative, with net gains of \$5.3 billion, with $\alpha_{max} = 2$. The left-hand side panel of Fig. 5 shows the dynamic

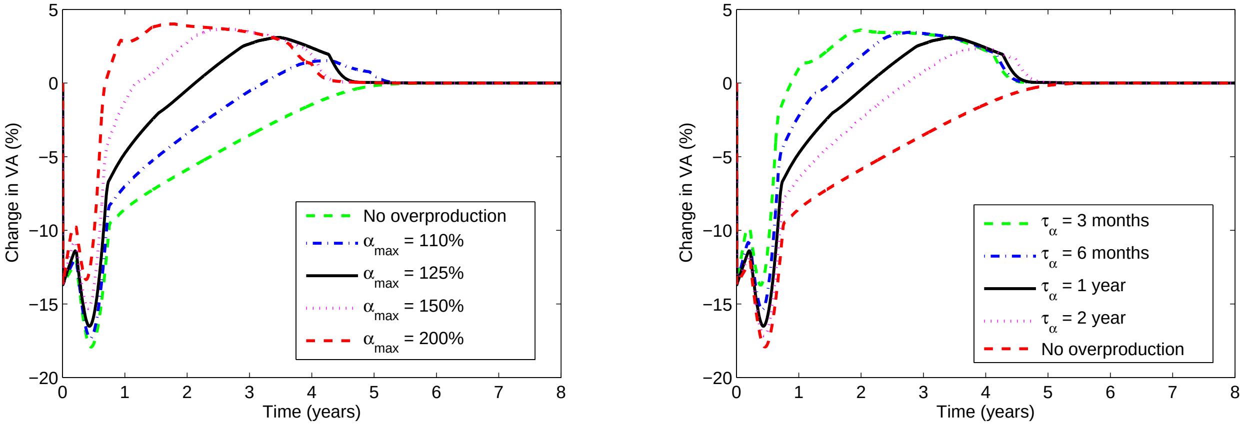


Fig. 5. Dynamics of production in the Louisiana economy, for five values of the parameter α_{max}, i.e. the maximum overproduction capacity (left-hand side panel) and five values of the parameter τ_α, i.e. the characteristic time of the adaptation process.

impacts of τ_{ada}. With $\alpha_{max} = 1.25$ and $\tau_\alpha = 3$ months, losses are negative, corresponding to net gains of $2.7 billion. With $\alpha_{max} = 1.25$ and $\tau_\alpha = 24$ months, losses reach $18 billion. The right-hand side panel of Fig. 5 shows the dynamic impacts of this parameter. When overproduction is easier (i.e. when α_{max} is larger or τ_{ada} lower), output losses are reduced because (i) gains in the construction sector are larger; (ii) losses in all sectors are lower, at each point in time; (iii) reconstruction is faster and the economy returns sooner to its pre-disaster situation.

4.3.4 Total amount of direct losses

All previous simulations were carried out using an estimate of direct losses from hurricane Katrina in Louisiana. There is, however, a large uncertainty on direct loss estimate, and this uncertainty needs to be taken into account. But more importantly, it is useful to assess the model sensitivity to direct losses, to estimate whether different mechanisms work for different types of disasters. It is very likely that small and large disasters do not lead to comparable economic responses and consequences. This assumption is supported by previous modeling work, as H08 found a nonlinear dependency of indirect losses with respect to direct losses: aggregated indirect losses were negligible for direct losses lower than \$50 billion and increasing nonlinearly beyond this threshold.

This assumption is also supported by econometric analyses. Econometrics analyses at national scale have indeed reached different conclusions on the impact of disasters on growth. Alabala-Bertrand (1993) and Skidmore and Toya (2002) suggest that natural disasters have a positive influence on long-term economic growth, probably thanks to both the stimulus effect of reconstruction and the productivity effect (the embodiment of higher-productivity technologies thanks to capital replacement; see Hallegatte and Dumas, 2009). Others, like Noy and Nualsri (2007), Noy (2009), Hochrainer (2009), Jaramillo (2009), and Raddatz (2009), suggest exactly the opposite conclusion, i.e. that the overall impact on growth is negative. As suggested by Cavallo and Noy (2010) and Loayza et al. (2009), the difference between both conclusions may arise from different impacts from small and large disasters, the latter having a negative impact on growth while the former enhance growth. Investigating model response for small vs. large disasters may help understand this difference.

To do so, simulations were carried out with “scaled” disasters, i.e. disaster with the same sectoral distribution of direct losses, but different levels of aggregate losses. In the left panel of Fig.6, simulation are carried out with disasters causing losses between 10 to 150% of Katrina losses. The simulations show that for “small” losses (direct losses lower than or equal to 50% of Katrina), output is reduced by direct losses, but is not affected by cross-sectoral interactions (thanks to the substitution assumed possible with the parameter $\psi = 0.8$). For larger losses, output is affected both by reduction in production capacity and by cross-sectoral interactions. It can be seen in the figure that the reduction in output increases rapidly with direct losses.

This reduction is confirmed by the right panel of Fig. 6, which shows the direct losses (in red)

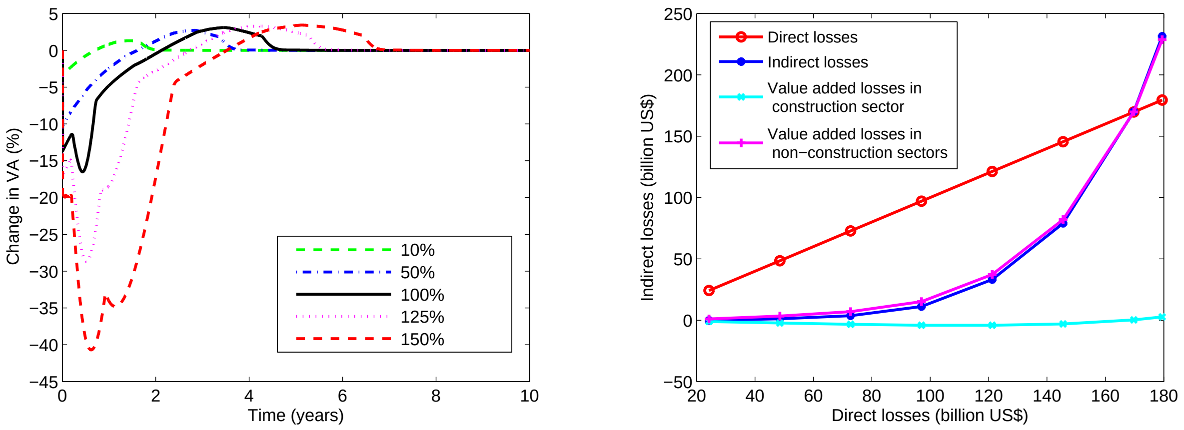


Fig. 6. Simulations for different amounts of direct losses (left hand side panel) and VA changes (total, in the construction sector, in the other sectors) as a function of the total amount of direct losses (right hand side panel).

and the total indirect losses (in blue) (as a function of direct losses). The nonlinearity identified in H08 is still present with this new model version. For direct losses amounting to $95 billion, the model estimates output losses about $80 billion, to be compared with only $11 billion output losses for $63 billion of direct losses (i.e. output losses multiplied by 7 for direct losses increase by 50%). For disaster causing more than $100 billion, output losses also exceed $100 billion.

To help interpret the figure, value added changes in the construction sector are separated (in light blue) from the other sectors (in purple). It can be seen that output losses in all sectors but construction increases non-linearly with direct losses. In the construction sector, there are gains (i.e. increase in value added) for small-enough disasters (up to about $110 billion of direct losses), and losses for larger disasters. This result suggests that, for small disasters, the construction sector benefits from higher demand and can increase production; for large disasters, the construction sector cannot benefit from the higher demand, because cross-sectoral ripple-effects constraint its production. This difference may explain — at least partly — why different econometric studies found positive and negative impacts of disasters on growth.

4.3.5 Conclusions of the sensitivity analysis

The conclusion is that this new model version requires a careful calibration of five parameters, namely ψ, i.e. the description of the heterogeneity in the economic system; τ_s and n_j^i, i.e. the characteristic time of the inventory restoration and the target level of inventories; and α_{max} and τ_α, i.e. the overproduction timescale. Considering the sensitivity of model results to these parameters, it is fair to admit that the model is a useful tool of explore the indirect consequences of disasters but cannot estimate the corresponding losses in absence of a careful — and unavailable so far — calibration of these parameters.

These high sensitivities can be translated into research needs to help understand and estimate disaster losses.

- First and foremost, heterogeneity and substitution capacity are key questions in disaster assessments. The model reaches quite different results depending on whether or not sectors are supposed homogeneous, implying that production reduction in one factory can be compensated by production in other factories (modeled through ψ in the model). Also, the possibility to target more of the remaining production toward other industries (instead of final demand) reduces losses (modeled through τ_s in the model). In the same way, focusing existing production toward reconstruction (instead to “normal” demand) accelerates reconstruction and reduces total losses. But the possibility to do so depends on the homogeneity in produced goods and services within each sector (e.g., is it possible to divert the manufacturing-sector production dedicated to final consumers to another industry?). Differentiating final consumption and interindustry consumption in different sectors in the model would be a good solution to solve this problem, and this change will be done in a follow-up model version.
- To go further on this question, the role of networks should be taken into account. Of course, this role has already been highlighted in the literature (e.g., Rose et al., 2007), but it requires

additional work: specific network-shaped economic sectors (e.g., electric system, water distribution, transportation) are especially important, but other sectors also involve network through the organization of supply-chains. It is crucial to understand how failure in one business or production unit translates into operational problems for its clients (because of rupture in production input) and its suppliers (because of the reduction in demand). Network structures may play a role in the vulnerability of the economic system (e.g., having fewer suppliers may increase the vulnerability of a business) and analysis at the sector-scale may reveal insufficient to understand it (e.g., Haimes and Jiang, 2001; Henriet et al., 2012).

- Third, one conclusion of our simulations is that the possibility to increase production capacity after the disaster (especially in non-affected factories and production units) can largely reduce total losses and accelerate reconstruction. This possibility depends on the ability to increase production in existing production sites (e.g., by working longer hours and eliminating inefficiencies) and on the possibility to “import” production capacity (skilled workers and equipment) from outside the affected area. More research should be dedicated to this problem, which is also related to demand surge, i.e. the increase in prices and wages in the construction sector, which creates incentives for skilled workers and contractors to move in the affected area.
- The three first points deal with the question of how to channel existing production (or production capacity) toward its best use, in order to minimize disaster losses. Determining the optimal distribution of goods and services is indeed extremely difficult since it requires the taking into account of all supply-chains and business relationship in the economic system, i.e. a perfect knowledge of the economic network. One possibility is to assume that prices include all existing and necessary information and make it possible to optimize the use of remaining production capacities; this assumption drives results from CGE models. Over the short-term, however, prices are unlikely to include all information. Prices cannot play this role because

they are influenced by many mechanisms. Natural disasters are indeed situations of abnormal solidarity and assistance, and different economic, governance and political processes take place. For instance, price increases that reflect real scarcity will appear socially unacceptable in disaster aftermath, as shown by the recent multiplication of (quite popular) anti-gouging laws in U.S. states. Moreover, as mentioned in Rapp (2006), anti-gouging regulations can make economic sense because of (i) imperfections in how prices are determined, especially in disaster aftermath and their response asymmetry; (ii) damages to the payment system in affected areas that can paralyze consumer markets. More research is needed on the role that prices play in channeling production toward its most efficient use, and on the other processes that influence rationing (e.g., the role of existing long-term business relationship, decisions by public authorities). Assessing the efficiency of these information-transfer mechanisms is crucial to assess disaster consequences.

These sensitivities can also be translated into policy recommendations. The importance of overproduction capacity, already mentioned in H08, suggests that the cost of disasters depend on two factors. First, increasing production above its pre-disaster level is easier when there are unused internal resources in the affected region, in terms of idle productive capital, unemployments, and worker capacity to increase their productivity and hours. As a consequence, economies in the recession phase of their business cycle may be more resilient to natural disasters than economies in expansion (see a theoretical analysis of this problem in Hallegatte and Ghil (2008) and some empirical evidence on Florida in 1992 in West and Lenze (1994)). Second, overproduction is easier when it is possible to “import” qualified workers and equipment from outside the affected region, to cope with high demand, especially in the construction sector. This result supports thus the idea that it is possible to reduce disaster costs by creating special work permits and reducing administrative burdens to worker migration and equipment imports.

5 Conclusion

In the debate between IO models, which do not allow any flexibility in the economic system, and CGE models, which assume that substitution and markets make the economy highly adaptive, this paper proposes a middle-ground solution. Based on an IO structure, the ARIO-inventory model represents explicitly production bottlenecks and input scarcity, models a flexibility in production capacity in case of scarcity (measured with an explicit scarcity index where CGEs use the price as a scarcity indicator), and introduces inventories as an additional flexibility in the production system.

Importantly, this modeling strategy makes it possible to distinguish between (i) essential supplies that cannot be stocked (e.g., electricity, water) and whose scarcity can paralyze all economic activity; (ii) essential supplies that can be stocked at least temporarily (e.g., steel, chemicals), whose scarcity creates problems only over the medium term; and (iii) supplies that are not essential in the production process (e.g., pens, some business services) and whose scarcity is problematic only over the long run and are therefore easy to replace with imports. Since prices and substitution play a large role over the longer run, one major limit of this model is the assumption of fixed IO coefficients and the use of a scarcity index over both the short and long terms. These assumptions appear acceptable in the immediate disaster aftermath, but are more questionable over the entire reconstruction period. Ideally, a model should be able to model the continuum between the short-term, with fixed technologies and sticky prices, and the long-term with technological substitution and market mechanisms. Also, the model focuses on production and available consumption, but cannot assess explicit welfare losses in absence of a modeling of consumer utilities.

Using this model, we estimate the output losses due to Katrina around \$11 billion, for direct losses of approximately $63 billion. More interesting than this numerical estimate, which is found extremely sensitive to many model parameters, the model identifies two periods in the disaster aftermath: the first year during which cross-sectoral forward ripple-effects, i.e. production bottlenecks, are responsible for a larger loss of output; the rest of the reconstruction period, during which output losses are much lower and bottlenecks are inexistent.

Sensitivity analyses identify parameters that require a precise calibration and additional work, possibly at sector scale. For instance, a better understanding of qualified-worker migrations in disaster aftermath would help calibrate the overproduction capacity of the construction sector. Also, detailed analyses of how rationing takes place in disaster aftermath could improve our understanding of disaster consequences. The relative role of prices, of existing business relationship, and of public policy emergency decisions need to be better understood. In parallel, the sensitivity analyses also stresses policy options to mitigate disaster-related output losses, like increased openness to qualified workers and equipments during the reconstruction phase.

But most importantly, the model highlights the fact that heterogeneity within sectors has a large influence on production bottlenecks, and thus on total economic losses from natural disasters. Current models do not take this issue into account, and this limit is shared by IO and CGE models. Theoretically, however, heterogeneity can be taken into account in sector-scale models, through the type of modeling approach that is suggested here. But the calibration of the resulting model parameters requires analyses at the business scale, representing explicitly supply-chains and substitution possibilities. More research is needed to make progress on this issue. More generally, investigating the role of heterogeneity and substitution in the special conditions of disaster aftermaths may provide useful case studies to improve our understanding of economic mechanisms.

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