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A Multiregional Impact Assessment Model for disaster analysis

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ABSTRACT

This paper presents a recursive dynamic multiregional supply-use model, combining linear programming and input–output (I–O) modeling to assess the economy-wide consequences of a natural disaster on a pan-European scale. It is a supply-use model which considers production technologies and allows for supply side constraints. The model has been illustrated for three floods in Rotterdam, The Netherlands. Results show that most of the neighboring regions gain from the flood due to increased demand for reconstruction and production capacity constraints in the affected region. Regions located further away or neighboring regions without a direct export link to the affected region mostly suffered small losses. These losses are due to the costs of increased inefficiencies in the production process that have to be paid for by all (indirectly) consuming regions. In the end, the floods cause regionally differentiated welfare effects.

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1. Introduction

A vast amount of research has been done to assess a wide variety of disaster losses, ranging from direct and indirect losses, tangible and intangible losses (see Meyer et al., 2013 for an overview of existing literature), to short-term (e.g. Li et al., 2013; Hallegatte, 2014; Koks et al., 2015; Santos et al., 2014) and long-term losses (e.g. Skidmore and Toya, 2002; Coffman and Noy, 2012). Nevertheless, disaster impact analysis is often still focused on the effects to only one single country or region. Natural hazards and their economic consequences, however, do not stop at administrative boundaries. In a world with increasing economic relations between regions and countries, it can be expected that areas which are not directly hit by a disaster will suffer economic losses via cascading effects (Okuyama and Santos, 2014). In this study, a novel methodology is introduced which simultaneously allows for production limitations, production inefficiencies and cascading effects in an assessment of the short-run multiregional economic effects of a natural disaster in Europe.

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The economic losses due to the use of inefficient production technologies have, to our knowledge, not been taken into account so far.

In this paper we introduce a new model that takes available production technologies into account, includes both demand and supply side effects and includes multiregional tradeoffs via trade links between the regions. This model, further referred to as the MRIA (Multiregional Impact Assessment) Model, is a dynamic recursive multiregional supply-use model in the tradition of input–output (I–O) modeling combined with linear programming techniques. The model can be solved sequentially (one period at a time) where behavior depends only on current and past states of the economy. Such a framework provides the simplicity of I–O modeling but also allows for some more flexibility, which is available in computable general equilibrium (CGE) modeling (Oosterhaven and Bouwmeester, 2016). Several scholars have already shown the possibilities of combining (non-)linear programming with I–O modeling (Duchin, 2005; Rose and Wei, 2013; Baghersad and Zobel, 2015; Tan et al., 2015; Oosterhaven and Bouwmeester, 2016). Furthermore, the MRIA framework allows for modeling supply constraints endogenously in a demand-determined model. This characteristic makes it possible to find (i) the production losses in the affected regions and other regions, (ii) the required production in other regions necessary to take over lost production in the affected regions, (iii) the required production in Europe to satisfy reconstruction demands from the affected regions and (iv) the regional welfare distribution effect of the increased production inefficiencies in the economic system due to the disaster. Consequently, when knowing how much production is lost (or gained) in each region, the total economic consequences can be assessed.

The remainder of the paper proceeds as follows. In Section 2, a brief literature overview on disaster impact modeling is provided, followed by an explanation of the model in Section 3. Section 4 explains the data used. In Section 5, the model is illustrated by preliminary results of an application of this model to a (hypothetical) flood in the Netherlands. We also perform a simple sensitivity analysis to analyze the robustness of the model outcomes to several crucial parameters and the size of the shock. This sensitivity analysis improves the knowledge on possible weaknesses of the model and will help us to obtain a better understanding of the general model outcomes. In Section 6, we draw some final conclusions about the ability of the model to assess the indirect losses of a natural disaster based on the results of this exercise.

2. Disaster impact modeling

A natural disaster can be broadly defined as an impact of the natural environment upon the socioeconomic system (Alexander, 1993). Correspondingly, in economic modeling, a natural disaster is often translated into an exogenous shock affecting the economic system. When applying such an exogenous shock in an economic model, it is important to understand the consequences for the economy after the occurrence of a (natural) disaster. In this respect, we can assume the following direct consequences to the economy due to a disaster (Rose and Wei, 2013):

- Less production in the affected regions due to damaged buildings and infrastructure;
- Less supply and demand to other (non-affected) regions due to reduced production in the industries in the affected regions;

- Additional import demand from the affected regions to other regions to satisfy the demand for products that cannot be satisfied by the affected regions;
- Additional demand from the affected regions for reconstruction needs.

In general, literature that focuses on the economic impacts of natural disasters distinguishes between two types of losses: stock (direct) losses and flow (indirect) losses (Okuyama, 2003; Rose, 2004; Bockarjova, 2007; Okuyama and Santos, 2014). Stock losses can be defined as the direct damages as a result of the natural disaster, which consists of the destruction of both physical and human capital. The estimation of stock losses is often the main focus in the engineering community (e.g. Bouwer et al., 2009; Jongman et al., 2012; Rojas et al., 2013). Flow losses, or more generally the indirect effects, are considered to be the business interruption losses of the affected industries and the so-called ripple effects toward other (initially non-affected) economic actors, such as firms, households and governments (Okuyama and Santos, 2014). In contrast to the engineering community, flow losses are often the main focus in economic literature (e.g. Hallegatte, 2008; Rose and Wei, 2013; Okuyama, 2014). In addition, the flow losses are commonly subdivided into short-term (up to three years) and long-term (more than three years) effects (Cavallo and Noy, 2009).

The most commonly used and well-documented approaches in disaster impact analysis are I–O and CGE models. Short-term effects are often analyzed with I–O based approaches, while long-term effects require more (price) flexibility with, for instance, a CGE-based approach (Thissen, 2004). Both I–O and CGE models are considered to be well suited for assessing the propagation of an initial shock resulting from a (natural) disaster into the economy (Okuyama and Santos, 2014). I–O models, on the one hand, are mainly praised for their simplicity and ability to reflect the economic interdependencies between industries and regions within an economy through intermediate supply and final demand for deriving higher order effects. CGE models, on the other hand, include supply side effects and allow for much more flexibility due to their non-linearity as a consequence of substitution effects following relative price changes. As a result of the different economic mechanisms, the outcomes often differ as well. Due to their linearity and lack of substitution possibilities, I–O models are often considered to overestimate the impacts of a disaster. CGE models, on the contrary, have the potential to underestimate the impacts because of possible extreme substitution effects and price changes (Rose, 2004), especially in the short run.

Numerous studies have developed models to assess the short-run economic effects that occur from a natural disaster within an affected area (e.g. Santos and Haimés, 2004; Steenge and Bočkarjova, 2007; Hallegatte, 2008; Barker and Santos, 2010; Rose et al., 2011). Recently however, more research focuses on assessing the indirect losses outside the affected region in more detail as well. A few studies have emphasized the multiregional effects of natural disasters in general (Okuyama et al., 2004; Okuyama, 2010; Bierkandt et al., 2014; Ciscar et al., 2014; Wenz et al., 2014), floods (In den Bäumen et al., 2015) and earthquakes in specific (Cho et al., 2001; Kim et al., 2002; MacKenzie et al., 2012; Arto et al., 2015). These studies that took multiregional effects into account show that substantial losses, but also benefits, can occur outside the affected regions.

Although much progress has been made over the past years in the development of disaster impact models, many of the more traditional (multiregional) I–O models used

in disaster impact analysis still insufficiently tackle three major issues in disaster impact modeling: (i) the fact that a disruption caused by a (natural) disaster is most often a disruption in the supply side of the production chain; (ii) modeling the potential positive effects of a disaster due to substitution capabilities of other regions and/or other industries; (iii) the potential additional costs for other companies when taking over some of the production. In this paper, the first issue is tackled by using optimization techniques to solve the model. The use of optimization techniques allows for taking endogenous import and supply constraints into account in an essentially demand-determined model. This overcomes two potential concerns: (i) the need of translating the supply side shock into a demand-side shock and (ii) the need of using a supply driven I–O model, often criticized in the scientific literature (Oosterhaven, 1996; Dietzenbacher, 1997).

When taking a traditional I–O modeling approach and not considering substitution effects, all other industries and regions will always be negatively impacted by a disaster. As can be interpreted from In den Bäumen et al. (2015), for instance, traditional multi-regional I–O modeling may result in overestimation of the effects in the non-affected regions when not considering substitution possibilities between the imports from different regions. In this paper, we therefore introduce (multi-regional) substitution possibilities by allowing for products being produced by different industries in the same or other regions. This approach allows for an endogenously determined new post-disaster optimum with shifts between main suppliers within the boundaries of the existing (trade and) production structure of the (regional) economy. This also directly relates to the third issue of additional costs occurring when other companies take over some of the production. Other companies use different technologies, which may result in (potentially) inefficient production. In this paper, we aim to account for these costs of inefficient production, by introducing the possibility of inefficiencies in production and applying the Leontief price model (Dietzenbacher, 1997) to determine the interregional costs for the (regionally) different consumers.

Moreover, an important concept in disaster impact modeling which is often touched upon is the concept of economic resilience, which can be subdivided roughly into two main types of resilience: static and dynamic resilience (Rose and Wei, 2013). In this respect, static resilience can be interpreted as the ability or capacity of an economic entity to maintain functionality after a shock has occurred. Dynamic resilience, on the other hand, refers to the ability to increase the speed at which an entity or a system recovers from a severe shock to achieve a (new) desired state (Rose and Wei, 2013). While it proves difficult to model all aspects of resilience, and especially the estimation of it (Rose and Liao, 2005), we try to touch upon a few aspects of resilience in the proposed modeling framework of this paper. In the MRIA Model, the most prominent resilience measure considered is the substitution between purchases from suppliers from within and outside the region. However, this substitution comes at additional costs. In this respect, little additional costs in the region imply a resilient regional economy, while little additional costs over all regions imply a resilient economic system.

3. Methodology

3.1. The MRIA Model

The MRIA Model is a tool to assess the short-run economic effects of a natural disaster for the European economy, using a linear I–O programming approach, based on a supply

and use framework (see Section 4). The MRIA Model is able to (i) reproduce the base line situation and (ii) to assess the impact of an economic shock due to a disaster. In line with standard I–O modeling, the model is based on the assumption of a demand-determined economy. In other words, demand from all European regions and the rest of the world has to be satisfied by total supply in all separate regions and the rest of the world. Although this will hold for the total European economy, we introduce the possibility of supply restrictions at the regional level. Industries in the different regions face a short-run maximum capacity. If the demand exceeds this maximum capacity, imports to this region should increase to satisfy demand.

The industries in each region minimize their costs given the demand for products and the available technologies to make these different products. These technologies describe how industries can make a mix of products out of a specific set of inputs. These technologies are ‘owned’ by the different industries in the different regions and are therefore only available to them. The mix of inputs that each industry requires to make its specific mix of products represents its production technology and is described by the use table. The mix of products that each industry can make using this technology is described by the supply (or make) table.

The complete MRIA Model can be described by the following set of equations, with $t = \text{time}$, with $p = 1, \dots, P$ ($P = \text{number of products}$), with i and $j = 1, \dots, I$ ($I = \text{number of industries}$), with $r = 1, \dots, N$ and with $s = 1, \dots, N$ ($N = \text{number of regions}$). A full list of all variables and their description can be found in Appendix B in the supplementary material.

$$\text{Min } z_t = \sum_r \mathbf{i}' \mathbf{x}_{r,t} = \sum_{i,r} x_{i,r,t}, \quad (1)$$

$$\mathbf{s}_{r,t} \geq (\mathbf{I} - \hat{\boldsymbol{\eta}}_r)(\mathbf{u}_{r,t} + \mathbf{f}_{r,t} + \mathbf{v}_{r,t}) - \boldsymbol{\omega}_{r,t} + \mathbf{e}_{r,t}^{\text{EU}} + \mathbf{e}_{r,t}^{\text{world}}, \quad (2)$$

$$\boldsymbol{\omega}_{r,t} = \text{Max}[\mathbf{0}, (\mathbf{I} - \hat{\boldsymbol{\eta}}_r)(\mathbf{u}_{r,t} + \mathbf{f}_{r,t} + \mathbf{v}_{r,t}) + \mathbf{e}_{r,t}^{\text{EU}} + \mathbf{e}_{r,t}^{\text{world}} - \delta \mathbf{s}_{r,t}^{\text{max}}], \quad (3)$$

$$\mathbf{e}_{r,t}^{\text{EU}} = \sum_s \mathbf{T}_s \boldsymbol{\mu}_s (\mathbf{u}_{s,t} + \mathbf{f}_{s,t} + \mathbf{v}_{s,t}) + \sum_s \mathbf{T}_s \boldsymbol{\mu}_s \boldsymbol{\omega}_{s,t}, \quad (4)$$

with

$$x_{i,r,t} \geq 0, \quad x_{i,r,t} \leq x_{i,r,t}^{\text{max}}, \quad \omega_{p,r,t} \geq 0, \quad v_{p,r,t} \geq 0,$$

$$\mathbf{s}_{r,t} = \mathbf{C}_r \mathbf{x}_{r,t}, \quad \mathbf{s}_{r,t}^{\text{max}} = \mathbf{C}_r \mathbf{x}_{r,t}^{\text{max}},$$

$$\mathbf{u}_{r,t} = \mathbf{B}_r \mathbf{x}_{r,t},$$

$$\boldsymbol{\eta}_r = (\hat{\mathbf{m}}_r^{\text{EU}} + \hat{\mathbf{m}}_r^{\text{world}})(\mathbf{u}_r^{\text{base}} + \mathbf{f}_r^{\text{base}})^{-1},$$

$$\boldsymbol{\mu}_r = (\hat{\mathbf{m}}_r^{\text{EU}})(\mathbf{u}_r^{\text{base}} + \mathbf{f}_r^{\text{base}})^{-1}.$$

The supply of products in all regions should be equal to or larger than demand for these products from all regions. This is described by Equation 2. The production in all regions will take place at the lowest possible costs (industries minimize costs) given demand, the available technologies and the maximum capacity of industries. The objective function of the model is therefore the minimization of the value of total production over all regions

(Equation 1) given that supply should be equal to or larger than demand (Equation 2).¹ The base model exactly replicates the baseline situation without inefficiencies and with supply exactly equal to demand. The possibility of supply to be larger than demand is a crucial element in our model. It enables us to model inefficiencies in the economy due to limits in the production capacity in the disaster-affected area. This modeling of inefficiencies is discussed below. These inefficiencies make the model different from I–O and CGE models that impose equality between demand and supply.

The MRIA Model includes supply constraints $x_{i,r,t}^{\max}$, which describe the maximum capacity of industries. A specific event that represents an economic disruption is modeled by reducing such a maximum capacity, which will become binding for the affected industries in the affected regions. Additionally, the demand will increase in the affected region due to the introduction of reconstruction demand vector \mathbf{v} (see Equation 2 in the model). The event therefore initially causes demand for certain products to be larger than the maximum production capacity in the affected regions (excess demand). In our model, there are two ways in which the supply for products can be increased to satisfy this excess demand. First, the production is increased in industries in the affected region that are not at their maximum capacity but can produce the demanded product as a by-product. Obviously, this causes inefficiencies in the economy because these products are no longer made by the best possible technology. Second, imports to the region with an excess demand can be increased. The option to increase imports of a certain product is only used when the total of all industries that can produce this product in a region is approaching their combined maximum capacity (Equation 3). The distribution of imports from other regions is determined using fixed proportions, which is in line with standard multiregional I–O models. Please note that large disasters may result in large additional imports, which may cause exporting regions not directly hit by the disaster to also reach their maximum capacity for certain industries. This is endogenously determined in the model.

The parameter δ (< 1) in Equation 3 ensures that the additional imports start to emerge before all industries are at their maximum capacities and all supply capabilities of the region have been exhausted.² This parameter prevents products from being made with extremely inefficient technologies. The model therefore makes a distinction between an industry's maximum capacity and the region's maximum capacity. Let us illustrate this by an example. A carpenter not only makes furniture (main product) but also transports it to deliver it to his/her customers (byproduct). When demand for transport increases dramatically in a region, the carpenter may start using his little van to transport goods provided by other suppliers. However, considering his available production technology and his productive human and physical capital, this would only take place at high costs. As a consequence, this would only be possible to a limited extent. The introduction of δ prevents that too many byproducts will become the main product of industries at very high costs. It should therefore help us to get more reasonable results.

This brings us to one of the key new elements of the MRIA Model. The MRIA Model is based on technologies 'owned' by industries and used to make products. Products are produced at the lowest costs, and together with the demand for products in every region

¹ The value of total production equals total costs in a supply and use framework.

² Please note that these additional imports are determined by a maximum function. The derivative of the maximum function is non-smooth in the point zero. We therefore use a non-linear optimization routine to solve the MRIA model.

this determines which technologies are being used and to what extent. It implies that inefficient technologies are being used to produce products when production with the ‘optimal’ technology is limited due to supply constraints. In our model, these inefficiencies result in unnecessary byproducts supplied to the market that are not demanded. It is clear from the example of the carpenter that we should interpret them as extra costs because the carpenter is inefficient in transporting goods using his carpenter technology to produce transport. The furniture he could make using this technology as a byproduct of transport is an estimate of the costs of using this inefficient technology.³ It should be noted that these inefficiencies occur at the regional level and not at the industry level; they are caused by the limited available technologies and associated machinery given the demand for products in a region after a disaster. This limitation in the number of available technologies increases the inefficiencies in the economy. In line with I–O modeling, we have a fixed production technology without the possibility of substitution between inputs. Consequently, the estimate of efficiency losses can be interpreted as maximum estimates. The MRIA Model is specifically designed to capture these inefficiency losses. As stated above, Equation 2 ensures that supply is equal to or larger than total demand. The vector $\omega_{r,t}$ defines the required additional import (‘disaster imports’) of the affected regions from other regions to satisfy the demand for products which cannot be satisfied due to lost production capacity in the own region (Equation 3). The last term in Equation 3 consists of the maximum regional capacity of a region to produce goods given the available production technologies. It is determined by the maximum capacity of the industries ($\mathbf{x}_{r,t}^{\max}$) multiplied by the regional supply matrix of available technologies (C_r). Factor δ describes to what extent the regions will exhaust all of its technology to produce a demanded product before it starts to import additional products.

The maximum possible capacity $\mathbf{x}_{r,t}^{\max}$ is included because one may assume that industries cannot increase their production indefinitely. In contrast to, for instance, Hallegatte (2008), the maximum possible capacity is not modeled dynamically due to differences in model properties. In this study, it is assumed that capacity is possible directly from the beginning. This overproduction in the first time periods after the disaster can be interpreted as the usage of inventories in combination with slack capacity of the industry. Overproduction has proved to be an important factor in disaster modeling (Hallegatte, 2014; Koks et al., 2015). Finally, the crucial Equation 4 closes the model by ensuring that additional imports due to limits in regional production capacity or increased production are produced by the exporting regions.

3.2. Implementing the MRIA for disaster impact analysis

To assess the disaster disruption, the model will be solved for a series of time periods with different reconstruction demand and supply limits, until the pre-disaster economic situation is reached again. By using this recursive dynamic approach, we allow for a more ‘realistic’ recovery period. A multi-period approach is necessary as it is expected that for large-scale disasters, the affected area does not fully recover in a single time period. The duration of the recovery period can be influenced both by financial reasons (e.g. it takes

³ Alternatively, one could loosely interpret this as the cost of owning machinery for making the main product that is idle when making byproducts.

time for economic actors to direct money to reconstruction activities) and a shortfall in production capacity. For instance, after storms in France in 1999, it took several years to reconstruct because there was a shortage of roofers (Hallegatte et al., 2007). However, due to the lack of empirical data, it proves to be challenging to determine ‘correct’ estimates of the recovery path and time. Therefore, in our empirical illustration shown below (Section 4), an approach similar to the Dynamic Inoperability Input–Output Model (DIIM) (Barker and Santos, 2010) will be taken. In the DIIM, it is assumed that industries decrease their inoperability in each specific time step. For the MRIA Model, the inoperability decreases each time step, based on the remaining reconstruction demand.⁴ The vector of (remaining) capital losses ($\Psi_{r,t}$) for each industry is used to determine the inoperability vector per industry ($\sigma_{r,t}$). Following Hallegatte et al. (2007) and Hallegatte (2008), we assume that the amount of capital required to produce one Euro of value added is approximately four Euros. This allows us to convert the incurred capital losses into a loss in value added (loss vector $\iota_{r,t}$). The next step is to translate this into an inoperability vector. Following Santos et al. (2013), we assume a fixed relationship between industry value added ($y_{r,t}$) and its gross output ($x_{r,t}$) during the recovery period, shown in the second part of Equation 5. This allows us to translate the changes associated with losses of value added into a measure of industry inoperability.

$$\sigma_{r,t} = \hat{\iota}_{r,t}(\hat{y}_{r,t}\mathbf{x}_{r,t}^{-1}). \quad (5)$$

The loss vector $\iota_{r,t}$ is determined as $\iota_{r,t} = (\mathbf{I} - \frac{1}{4}\hat{\Psi}_{r,t}(\mathbf{y}_{r,t}^{-1}))$. By using the inoperability vector from Equation 5, we allow ourselves to assess the maximum production capacity for any given industry in any given time period. As shown in Equation 6, the maximum production capacity without any disruptive event (\mathbf{x}_r^{\max}) is multiplied by one minus the inoperability vector. This provides us with the maximum production capacity for each industry in any given time period ($\mathbf{x}_{r,t}^{\max}$).

$$\mathbf{x}_{r,t}^{\max} = \mathbf{x}_r^{\max}(\mathbf{I} - \hat{\sigma}_{r,t}). \quad (6)$$

In each time period, the remaining demand for reconstruction commodities and the new maximum production capacity in the affected regions should be calculated. The new reconstruction needs can be calculated as shown in Equation 7, where $\mathbf{v}_{r,t}$ is the reconstruction demand to be satisfied in the current time period and $\sum_t \mathbf{v}_{r,t}$ the sum of the reconstruction demand over all time periods. The reconstruction demand for each time period is based on the maximum possible recovery (ρ) for that specific time period. Equation 8, required to assess ρ , models a similar curve as commonly used in the DIIM. The maximum recovery time (t^{\max}), however, is often declared rather arbitrary. Due to limited availability of empirical data, this arbitrary approach is currently unavoidable. In our approach, the maximum recovery time will vary between a few months for a small-scale disaster up to several years for a large-scale disaster (see Table 1). To solve some of this uncertainty in the model assumptions, we will work with a range of possible recovery times based on the severity of the flood in the sensitivity analysis (see Section 4.2).

$$\mathbf{v}_{r,t} = \sum_t \mathbf{v}_{r,t} \times \rho_t, \quad (7)$$

⁴ For simplification purposes within this simulation, we assume that the total capital losses are equal to the total reconstruction demand for each sector over all time periods.

$$\rho_t = \sqrt{\frac{t}{t^{\max}}} - \sqrt{\frac{t-1}{t^{\max}}}, \quad (8)$$

$$\psi_{r,t+1} = \psi_{r,t} - \nu_{r,t}. \quad (9)$$

Finally, to determine the new capital losses to be used in Equation 5, the reconstruction demand should be subtracted from the capital losses, as shown in Equation 9. This gives us the remaining capital losses in the new time period. From here, Equations 1–9 can be repeated again, until we reach the pre-disaster situation. As can be implied from Equations 8 and 9, the reconstruction demand in each time period and the related recovery path are determined exogenously.

As soon as the total reconstruction needs are satisfied (i.e. the whole area is reconstructed and no additional goods are required), the additional import (ω) from the affected regions will also equal zero, as zero reconstruction needs implicitly mean that the production capacity is back at its pre-disaster level and the affected region does not require any additional imports.

3.3. Assessing the total economic consequences

When the economy is back at the pre-disaster situation, the total economic effects of the disaster can be determined. Next to the commonly assessed output losses, in terms of loss in value added, the MRIA Model also allows us to determine the economic losses due to the use of inefficient production technologies. It is important to note that the output losses (θ_r), as determined in Equation 10, can either be negative or positive. If a specific industry is not affected by a reduction in demand for products from the affected region, but is ‘affected’ by an increase in demand due to additional import and reconstruction needs, value added will increase. As such, the loss or gain in value added can be computed as the total difference in value added for each industry over each time period compared to the initial value added.⁵ In mathematical notation, this can be expressed as

$$\theta_r = \sum_t (y_r^{\text{base}} - y_{r,t}). \quad (10)$$

The second type of economic losses, due to the increased inefficiencies in the production process, results in the rise of production costs. The multiregional supply and use framework gives us all the information needed to precisely determine how these costs will trickle down through the economic system and who will have to pay for these costs. To determine the regional impact of this increase in costs, we therefore use the cost-push I–O price model (Oosterhaven, 1996; Dietzenbacher, 1997; Miller and Blair, 2009, pp. 41–51). We can explain the use of the cost-push I–O price model as follows. First, we determine the multiregional commodity–industry matrix (G_t), which is the same as the previously defined matrix B_t over all regions, with the only difference that the products are specific to the region of production. G_t has therefore the dimension ($p:j:r$) and can be calculated by dividing the use of commodities by industries (U_t) with the same dimensions by its gross

⁵ Value added itself is determined as a fixed proportion of production and is commonly derived from in the use table.

output (\mathbf{x}_t):

$$\mathbf{G}_t = \mathbf{U}_t \hat{\mathbf{x}}_t^{-1}. \quad (11)$$

Second, the multiregional market share matrix \mathbf{D} with commodity output proportions can be calculated by dividing the industry's commodities output (\mathbf{V}) by its total commodity output (\mathbf{q}):

$$\mathbf{D}_t = \mathbf{V}_t \hat{\mathbf{q}}_t^{-1}. \quad (12)$$

By adopting "Model D" (using the "fixed commodity sales structure" assumption), we can find the total requirements matrices for commodity demand-driven models (Miller and Blair, 2009, p. 209) as:⁶

$$\mathbf{L}\mathbf{D}_t = (\mathbf{I} - \mathbf{A}_t)^{-1}\mathbf{D} = (\mathbf{I} - \mathbf{D}_t\mathbf{G}_t)^{-1}\mathbf{D}_t. \quad (13)$$

In order to determine the losses due to the inefficiencies in the various industries, we turn to a variant of the cost-push I-O price model. As such, we can write our variant of the cost-push price model for the commodity demand-driven model as:

$$\mathbf{p}'_t = \mathbf{w}'_t(\mathbf{I} - \mathbf{D}_t\mathbf{G}_t)^{-1}\mathbf{D}_t. \quad (14)$$

\mathbf{p}'_t is the commodity vector of the changed price indices and \mathbf{w}'_t is the price vector of inefficiencies equaling the amount of products not demanded. Now we have all the information we need to calculate the inefficiency loss per region. With the final demand vector \mathbf{f}_t in every region, we get the economic cost ζ_r per region, over all time periods, as defined in Equation 15.

$$\zeta_r = \sum_t \mathbf{p}'_{r,t} \mathbf{f}_{r,t}. \quad (15)$$

This methodology implies that we distribute these production inefficiencies over the demanding regions proportional to their (indirect) use for (inefficiently produced) products of these regions. The costs ζ_r represent therefore the extra costs needed to obtain the same utility effect. It therefore represents the welfare effect of the inefficiencies in income equivalents, given demand. This implies that we used the following complementary utility function in the model:

$$v_r = \text{Min}[\gamma_{r,p1} f_{r,t,p1}, \dots, \gamma_{r,t,p} f_{r,t,p}]. \quad (16)$$

In this equation, n stands for the number of goods. Substitution effects in demand are assumed to be non-existent. Finally, by adding up the outcomes of Equations 10 and 15, we will find the total economic losses for each region. This total effect represents the income

⁶ Please note that model D is the only approach available to use since we work with a non-symmetric supply and use system with more commodities than industries.

lost in (or earned by) a region due to the decrease of (or increase of) production and the additional costs of inefficiencies.

4. Multiregional data

The multiregional data used in the model are based on the PBL dataset on multiregional supply and use tables (Thissen et al., 2013), including bilateral trade between 256 European NUTS2 regions for the year 2000. The PBL multiregional supply and use tables contain 59 product categories, which cover both goods and services, following the European Classification of Products by Activity (Nace 1.1 – CPA 2002). The data sources used to construct the dataset are (1) the national accounts of 25 EU countries, (2) international trade data on goods from (Feenstra et al., 2005) and services from Eurostat (2009a; 2009b), (3) regional information on production, investment and consumption made available via Cambridge Econometrics (2008), (4) information on freight transport among European regions from the Dutch Ministry of Infrastructure and the Environment (2007) and (5) first and business class airline ticket information from SEO (2010). Regional trade flows are consistent with statistics on production and consumption by region, which, in turn, are in line with the national accounts data on production and consumption. These regional flows are not only consistent with national accounts and international trade statistics at the national level but also mutually consistent (after corrections for c.i.f./f.o.b. inconsistencies).⁷ Exports from a region or country A to a region or country B thus equal the opposite flow of imports received by region or country B.

The main strength of the dataset is in its multiregional trade flows. These trade flows were based on actual data and not estimated using a model based on behavioral equations. The PBL dataset is constructed to fit to the information available, but no structure has been imposed on the data. This makes it possible to use this data in economic models or other economic analysis. Cross-hauling, the simultaneous trade of the same product category between two regions was also explicitly taken into account. We have chosen the 2000 dataset since more recent tables are simply an update of the 2000 table without additional information on multiregional trade flows. See the appendix in Thissen et al. (2013) for an extensive discussion of the construction of the data.

5. An illustration of the model: a flood in Rotterdam

To illustrate the proposed model, we take the case of a flood occurring in the port area of Rotterdam, located in the Netherlands. Rotterdam is one of the largest ports of the world and the Netherlands is a country largely below sea level, with several of the main rivers in Europe. Therefore, the Rotterdam port area seems to be an interesting case to show the results that can be obtained with the proposed MRIA Model. We simulate three floods in the region of South-Holland, which encompasses the Rotterdam area. We have chosen this larger region because of limited information on regional trade on a lower spatial scale.

In our simulation analyses, we set the maximum capacity of the industries ($\mathbf{x}_{r,t}^{\max}$) at 110% of the pre-disaster production capacity (a form of adaptive economic resilience). We also differentiate between local and non-local products with respect to the endogenous

⁷ Cost insurance freight/free on board price concepts.

Table 1. The three flood events considered in this study.

| | Mean sector inoperability in South-Holland (%) | Duration of recovery (months) | Stock losses | Flow losses | Ratio flow/stock |
|----------|--|-------------------------------|--------------|-------------|------------------|
| 1/100 | 0.7 | 6 | 442 | 282 | 0.64 |
| 1/1,000 | 1.2 | 12 | 761 | 659 | 0.87 |
| 1/10,000 | 2.9 | 24 | 1,880 | 1,616 | 0.86 |

Note: The total stock and flow losses for the region of South-Holland are in millions Euro.

disaster imports.⁸ In practical terms, this means that, for instance, services provided by the public sector can only be sourced from regions in the same country (local products). Goods produced and services provided by any of the manufacturing industries, the agricultural industries, construction industry or market services industries can be bought from any region in the EU already having trade relations with the affected region (non-local products). See Table A2 in supplementary material for an overview of the local and non-local products. In the general model outcomes, as shown in Section 3.1, the maximum use of regional capacity δ is set at 0.98.

5.1. General model outcomes

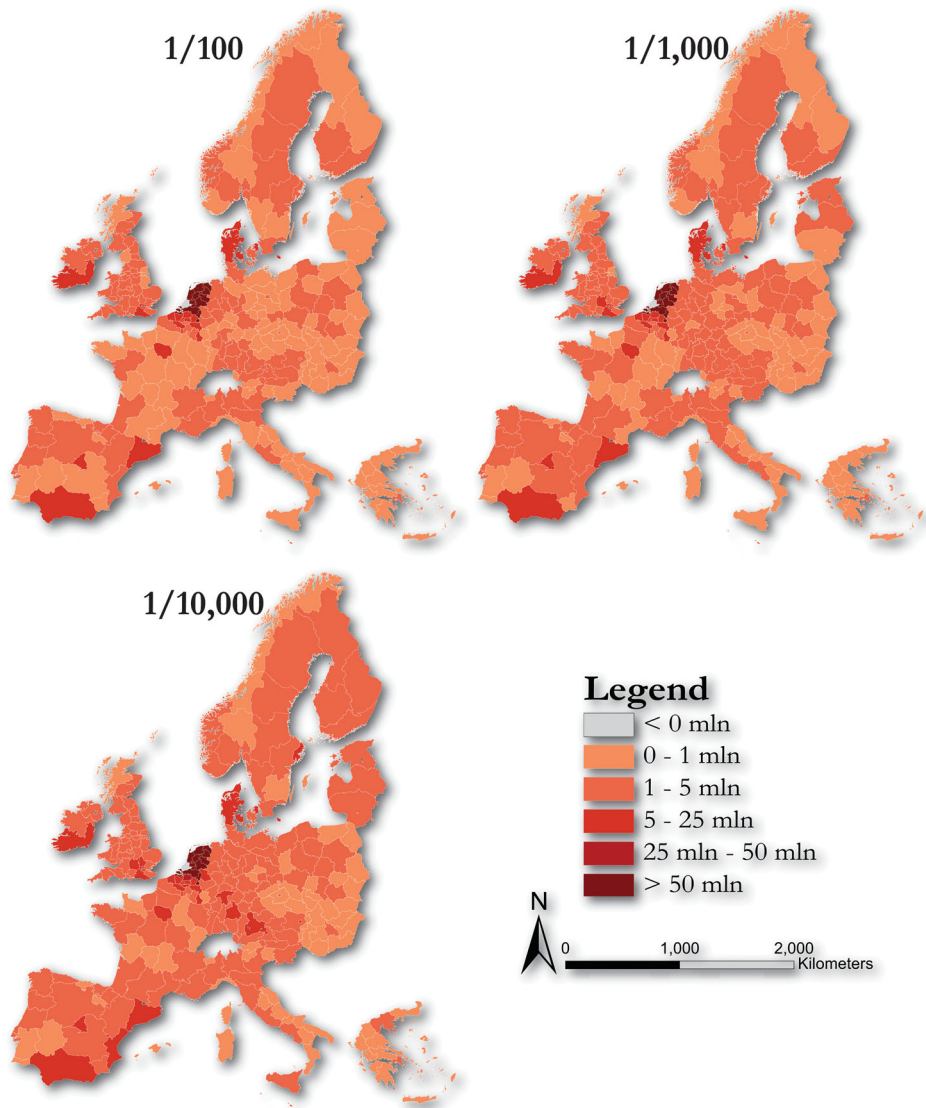
Table 1 shows the main characteristics of each flood and the modeling results. We assume that the affected region is back at its pre-disaster situation within six months for the small flood, one year for the intermediate flood and two years for the large flood. Interestingly, the flow losses for the 1/10,000 flood⁹ are substantially lower to those in Koks et al. (2015), which are computed by using a single-region model for the same area without multiregional substitution possibilities. This means that the substitution possibilities between regions limit the negative effects of a disaster by, for instance, reducing the need for rationing.

In Figure 1 the increase in production after each flood is shown. We see in this figure that other regions in the EU and the rest of the world can take over the loss in supply of the affected region such that total final demand is satisfied. This results in a ‘redistribution’ of the effects due to the flood. For all floods, around 25% of this total increase in production in the EU is caused by the disaster imports (ω), which is the direct increase in production demand for the non-affected regions (first-order indirect effect). This implies that 75% of the total production is a higher-order indirect effect of the disaster. Of this 75%, around 4% can be explained by the reconstruction demand. The remaining (unexplained) increase in total production can be interpreted as the increased inefficiencies in the production process due to the use of non-optimal technologies to satisfy demand (i.e. the carpenter using his van for transportation demand) and the increased demand in the supply chain. Hence, this total increase in production cannot be fully interpreted as a gain since there is an additional cost for the consumer of the inefficiently produced products.

⁸ Although all products are internationally traded according to the actual dataset, we limit international trade for several product groups to compensate for limited production capacity after the flood. The reason is largely data-related. For instance, imports of the hotel industry refer in our dataset mainly to tourists living in South-Holland going on holiday abroad. However, this has little to do with any replacement of hotel demand in South-Holland after this area has been hit by a flood and extra demand for hotels is occurring due to reconstruction demand.

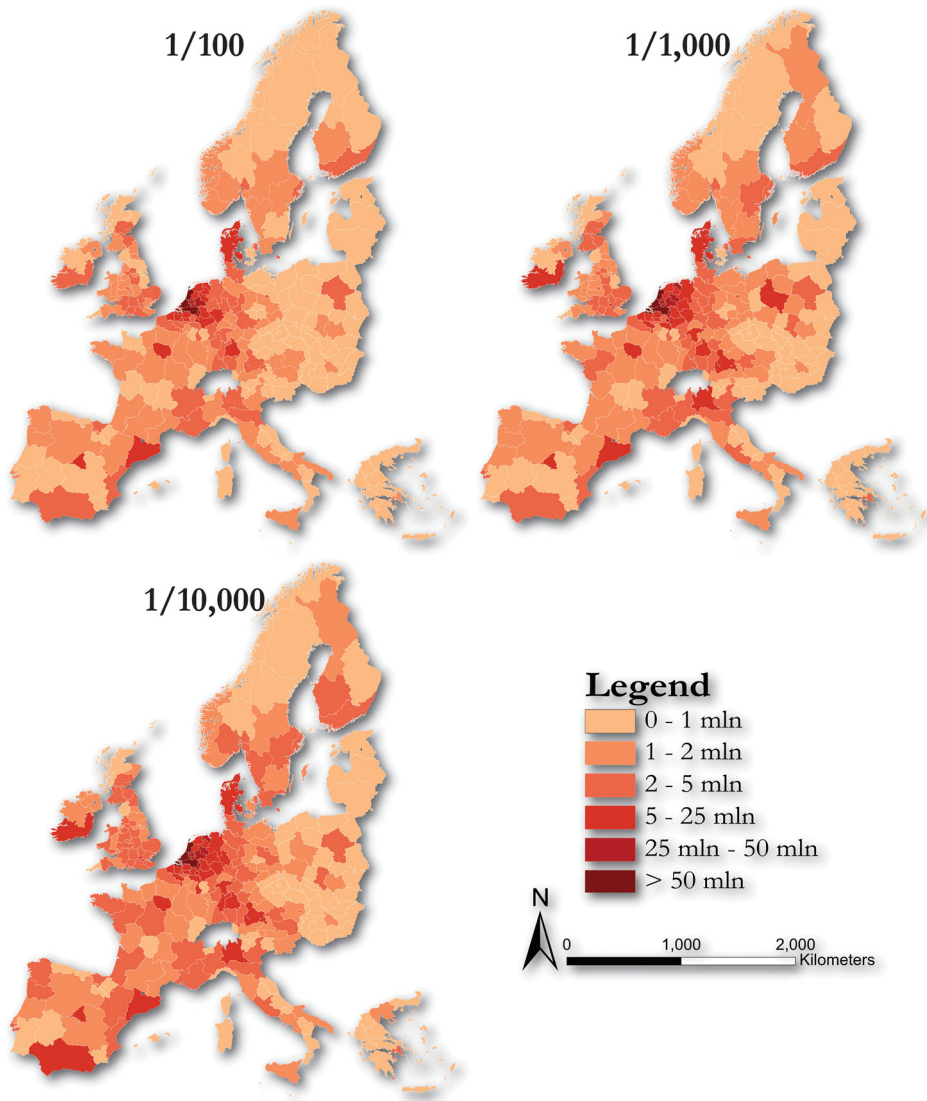
⁹ A 1/10,000 flood corresponds to a flood with a return period of 10,000 years, which represents an annual probability of occurrence of 1/10,000.

Figure 1. Production change per region in the EU for each flood in the region of South-Holland (in millions Euro).



Therefore, as explained in Section 3.3, to come to a more ‘correct’ interpretation of the economic consequences of the disaster, we determined the extra production costs in each region to satisfy demand. This correction can be interpreted as the cost-push price effect due to the economic disruption in the affected region. Due to this increase in costs, several regions throughout Europe show (small) losses, as illustrated in Figure 2. Regions with the highest increase in production show, expectedly, also the highest increase in costs. Nonetheless, the redistribution effect, as shown in Figure 1, also clearly demonstrates the potential of the European Union (EU) and the rest of the world to satisfy demand for products when a specific region is partly out of business, albeit that this satisfaction comes with a higher cost compared to the pre-disaster situation.

Figure 2. Production costs per region in the EU for each flood in the region of South-Holland (in millions Euro).



Interestingly, approximately 75% of the disaster imports come from within Europe, while (by construction) 100% of the local goods come from within the Netherlands, causing substantial extra production in the other regions of the Netherlands.¹⁰

¹⁰ Important to note is that the MRIA Model is not able to capture transit trade, as this is not included in a supply and use framework. Such trade can be considered to be an important part of a harbor's activities and may result in increased positive (substitution) effects for other European ports when parts of the port of Rotterdam are out of order. Nonetheless, the losses (or benefits) of the disaster are captured by looking at the change in value added for each industry. With transit trade, a firm does not add (much) value added to a product. In that respect, ignoring transit trade in the model is assumed to have a relative small effect on the total economic consequences of the disaster.

Figure 3. Indirect effects per region in the EU for each flood in the region of South-Holland (in millions Euro).

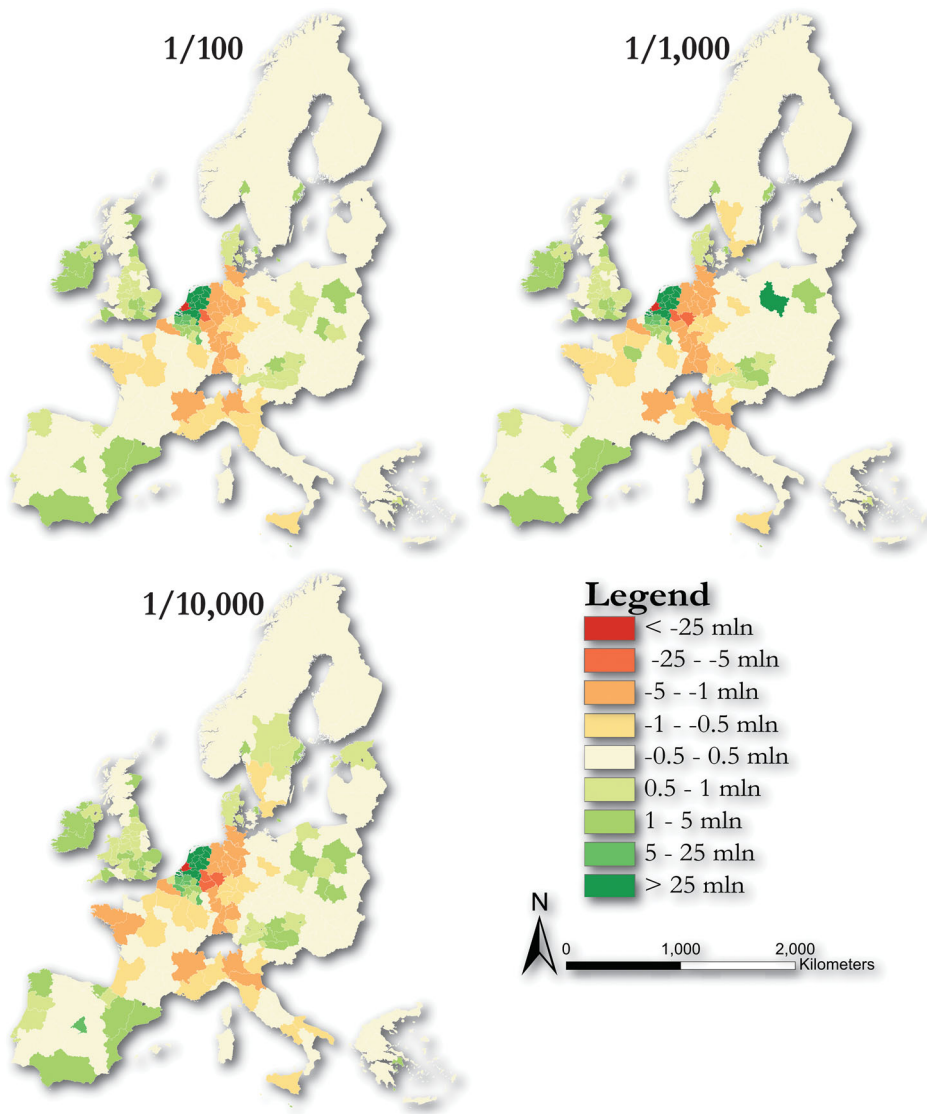


Figure 3 shows the total losses and gains for every region in the EU over the entire recovery period, defined as the total change in value added minus the additional production costs. These gains and losses, therefore, include the additional use of resources (labor and capital) and the loss due to inefficiencies in production. The figure shows that most of the direct neighboring regions benefit strongly from the flood in South-Holland (the rest of the Netherlands, Belgium and Luxembourg are clearly positively colored in the figure). Germany, however, suffers losses. This effect increases when the flood becomes more severe. The difference between a benefit and a loss can be explained by the tradeoff between extra exports and the higher costs of used products: more export to the affected region can

offset the effects of lower demand for products and higher costs for production. Regions which are already more export-focused toward the affected regions can see an increase in trade because they take over some of the production from the affected region due to existing export-oriented trade relations. More import-focused regions, on the other hand, see a reduction in demand for products from the affected region and an increase in ‘price’ for products due to the increased inefficiency of production caused by natural disaster, resulting in a loss.

5.2. Parameter sensitivity

Two important model assumptions are required to solve the MRIA Model. The first assumption concerns the maximum use of regional capacity (δ), which influences when and by how much products will be imported from other regions if the production in the affected region cannot satisfy demand. The second assumption concerns the recovery period amount and the amount of reconstruction demand for a specific industry in every time period. As stated in Section 3.2, there is almost no empirical data available on the reconstruction process of different industries in the post-disaster period. To overcome some of the uncertainty in these assumptions, this section will discuss the results of the model with alternative parameter settings for these assumptions, *ceteris paribus*.

Table 2 shows the total amount of disaster imports and inefficient production in the affected region for different settings of parameter δ over the entire recovery period of the 1/1,000 flood. The value of 0.98 (in bold) is the default setting, used in the calculations of Section 4.1. The default value gives the lowest amount of inefficient production, while a value of 0.99 results in the lowest amount of imports from other regions. The default setting is chosen as the most conservative setting, with the least inefficiencies. As expected, a lower value of δ is associated with less inefficiencies in production and higher additional imports because a lower value of δ implies that a region that is confronted with excess demand will not exhaust all its inefficient production possibilities and turn to imports earlier. However, this may trigger second-order effects where these higher imports result in high inefficiencies in the exporting regions. The combination of these effects results in a value of 0.98 for δ , which results in the lowest amount of inefficient production. There is a different second-order effect related to imports: high inefficiencies are a sign for a high amount of intermediate goods used in production. This may trigger more imports to satisfy the intermediate demand. This effect causes the optimal value of 0.99, where we have the lowest imports. When the parameter δ is set to 1, the production technologies will be

Table 2. Sensitivity of parameter δ for the region of South-Holland for the 1/1,000 flood (default values in bold).

| δ | Disaster imports | Waste production |
|-------------|------------------|------------------|
| 0.95 | 4,249 | 797 |
| 0.96 | 3,211 | 389 |
| 0.97 | 2,394 | 347 |
| 0.98 | 1,633 | 286 |
| 0.99 | 1,023 | 382 |
| 1.00 | 1,073 | 1,268 |

Note: Values of the disaster imports (Ω) and the waste production are in millions Euro.

Table 3. Variation in recovery duration for the region of South-Holland (default values in bold).

| Return period | Recovery duration (months) | Indirect losses |
|---------------|----------------------------|-----------------|
| 1/100 | 3 | 141 |
| | 6 | 282 |
| | 12 | 564 |
| 1/1,000 | 6 | 330 |
| | 12 | 659 |
| | 24 | 1,318 |
| 1/10,000 | 12 | 808 |
| | 24 | 1,616 |
| | 48 | 3,232 |

Note: Values are in millions Euro.

used to their maximum capacity before any additional imports will take place. Clearly, the waste-production substantially increases and interestingly, the disaster imports are high as well. This high amount of disaster imports can be explained by the additional amount of intermediate goods needed in the inefficient production process.

Table 3 shows the results when varying the recovery duration. As can be clearly observed, a change in recovery time can substantially change the total indirect losses. This is also in line with results found in Koks et al. (2015), where it is shown that when it takes considerably long for the affected area to start reconstructing (e.g. due to a long period of inundation), the losses increase significantly. This is not surprising: if a business is out of business for a longer period, obviously its production losses are higher. Improving recovery speed can be interpreted as a measure of dynamic economic resilience. As the results show that losses can change substantially between different recovery durations, more research should be done in determining the recovery duration. This will allow for a more accurate indirect loss assessment to be used in policy analysis. Nonetheless, even though the magnitude of the losses might change, the dynamics and patterns in the model outcome will remain similar and we showed that our model can be used in such an analysis.

In addition to these two important model assumptions, the size of the economic disruption is also varied, next to the three floods considered in the case study. This shows the sensitivity of the model to the difference in the size of the shock. The initial economic disruption of the floods considered in the case study is ‘small’ (a maximum of 8% for the largest flood). Hence, it is unknown what the consequences will be when a more extreme disaster hits the affected region. When increasing the disaster impact by up to a factor 10 compared to the disaster impact of the 1/10,000 flood, the indirect losses still remain smaller compared to the direct losses. This result can be attributed to the possibility to replace the increased limitation in production capacity with an increase in inefficient production and disaster imports from non-affected regions to satisfy the demand from the affected region. This is in contrast with the results of, for instance, Hallegatte (2014) and Koks et al. (2015), the models which lack the regional substitution possibilities, and where it is found that the indirect losses eventually become larger than the direct losses due to high levels of rationing. In the MRIA Model, there is no additional reduction in final demand because rationing is not needed. In an extreme disaster (i.e. multiple neighboring regions hit by a very large disaster), however, rationing may be necessary. In that extreme case, the results may become more comparable to the high indirect effects in the studies of Hallegatte

(2014) and Koks et al. (2015). In general the MRIA Model results are more comparable to a CGE approach like Carrera et al. (2015), where the output losses remain substantially lower compared to the asset losses. Carrera et al. (2015) also contributes this to substitution effects between regions that dampen the negative effects.

6. Concluding remarks

This paper presented a recursive dynamic multiregional supply-use model, combining linear programming with elements of I–O modeling, to assess the effects of a local natural disaster on the EU regional economy. By combining a linear programming approach with multiregional I–O modeling, we have created a framework that takes available production technologies into account, includes both demand and supply side effects and includes multiregional tradeoffs via trade links between the regions. The separate use of production technologies made it possible to estimate the efficiency loss due to a constraint in available production technologies due to a disaster. The model was illustrated with an analysis of a flood event in the port of Rotterdam.

The MRIA Model helps us to understand the indirect effects of a disaster. It shows how these cascading effects over the different regions may lead to substantial indirect losses and strong distributional effects between regions. These effects should therefore not be neglected when assessing the (economic) consequences of a disaster. The Rotterdam case shows clearly that many regions outside the affected area are indirectly affected by the natural disaster. Most of the neighboring regions benefit from the flood by increased reconstruction demand or taking over some of the production from the affected region. Regions that are located further away without a direct export link to the affected region mostly suffered small losses. These losses are due to the costs of increased inefficiencies in the production process that have to be paid for by the other (indirectly) consuming regions. In the end, consumption does not increase and the flood mainly causes a regionally differentiated welfare effect.

By allowing for substitution between suppliers and by increasing production capacity of industries, some measures of economic resilience have been incorporated in the model. The results show that by timely changing between suppliers, waste production and losses can be reduced substantially within an affected region. Nonetheless, in this paper we have only briefly touched upon economic resilience. In further developments of the MRIA Model, incorporating more enhanced measures of dynamic economic resilience, such as alternative recovery paths and production technologies, should be explored.

Due to the relative few input requirements and a straightforward modeling approach, the MRIA Model proves to be a suitable tool for policy-makers to assess the indirect effects of a natural disaster. In this study, a large-scale flood is used as a case study to demonstrate the applicability of the model. With relative ease, however, this can be changed into any type of disruptive (natural) event. However, the sensitivity analysis showed that the duration of the recovery period influences the total losses substantially. As a result, one should take care when interpreting the absolute values of the indirect losses of a disaster and more research is needed to appropriately analyze these recovery periods. Finally, the model only analyses the short-run effects of a disaster. We did not consider the long-term effects of large disasters with strong price effects and the relocation of people. This limitation is common for models that are based on the fixed coefficients common for I–O models.

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