Implications of short-term Cargo Collapses on European Airports

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1. Motivation

In the aftermath of Iceland's Eyjafjalljökull volcano's eruption the Airspace in Germany and much of Europe was closed for days in mid April 2010. The major disruptions of the flight schedule, caused by the giant ash cloud emitted by the volcano, left thousands of passengers stranded at airports all over the world and turned out to be particularly damaging for European airlines. According to estimations of the International Air Travel Association (IATA) the widespread closure of European airspace in April came along with a loss in revenues of around €1.26 billion.

Clearly, economic damages could easily exceed airlines' losses. Since Europe's fragile economies are still recovering from 2008's and 2009's financial crises, any major disturbance of the production process might hamper the economic turnaround. This is particularly true for industries that rely heavily on air cargo such as Europe's car manufacturers. BMW, for example, was forced to halt production due to missing electronic components. The example highlights the dependency of manufacturer on a smooth running air transport system. A system that is highly dependent on the whole network of European airports and therefore very sensitive for any kind of disturbances.[1]

With regard to the frequent occurrence of temporary disturbances, such as severe natural events or potential terrorism, and having in mind the strong interdependence of economic production, trade and (air) freight transport, the main objective of the paper is to identify the importance of each airport for the entire (European) air cargo network and to model the impacts of disasters on Europe's airports.

1 Despite significant impacts of these temporary disturbances, there is hardly any evidence that they shall affect the major trend in air cargo development. In the past decades, this trend was characterized by growth rates well above worldwide GDP growth. In fact, freight tonnes transported by air rose by more than 5% per year between 1995 and 2007. Thus, air cargo volumes outpaced the growth of global GDP between 1.5 and 2 times. Things changed dramatically in the second half of 2008. The worldwide decline of industrial production and a strong reduction of international trade volumes hit the logistics business in general and the inter-continental/long-distance air cargo business in particular. The slump has affected all European airports but their magnitude differs significantly.

The structure of the paper is as follows. Chapter 2 defines, in a first step, the air cargo network as a matrix that accounts for freight volumes shipped from airport i to any other airport j. The matrix comprises 291 European airports, five artificial airports, representing the rest of the world, and each airport's hinterland. Flows assigned to the functional airports derive from the aggregated flows for the major airports in the regions of North America, South America, Africa, Asia-Pacific and Rest of Europe.

The derived matrix forms the starting line for the measurement of each airport's importance performed in chapter 3. For this purpose the air cargo network is interpreted as an input-output system with the 296 x 296 matrix as the intermediate part and the in- and outflows from and to the corresponding hinterlands as primary inputs and final demands respectively. Following the principles of input-output analysis, the next step foresees to calculate different linkage indices in order to reveal each airport's importance in the network.

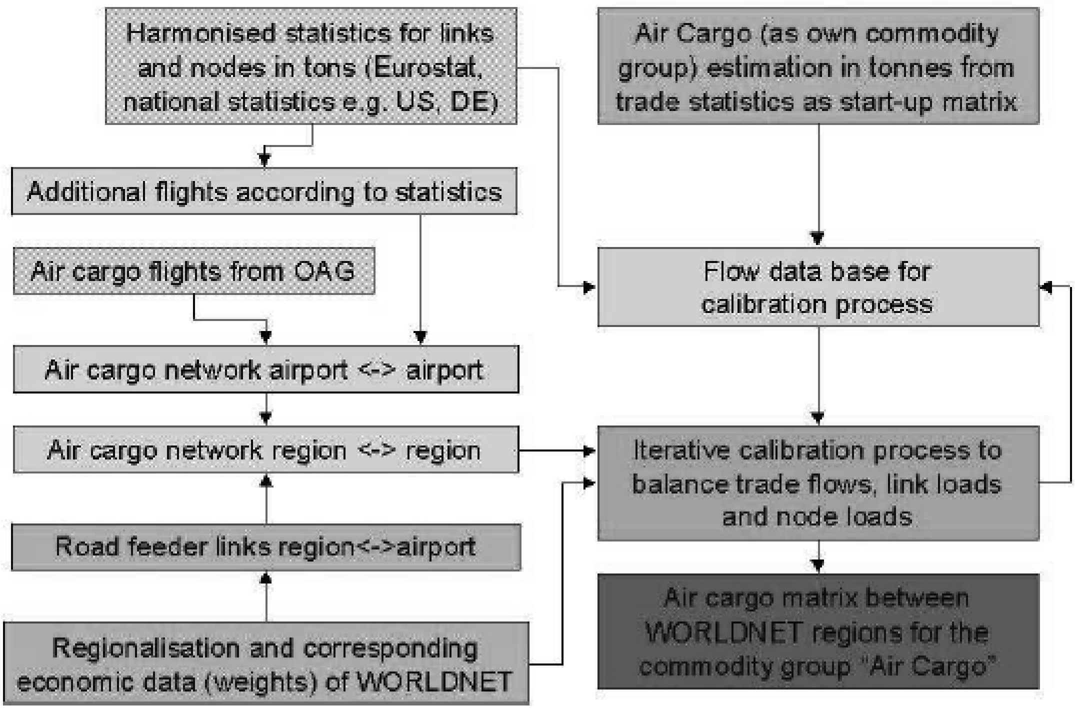
Chapter 4 quantifies the impacts of single (and multiple) airport closures on the entire European air cargo market. Such closures might accrue from natural disasters, terrorist attacks or technical breakdowns and might have far-reaching implications also for not directly affected airports. Therefore, the input-output philosophy is applied again.

Finally, chapter 5 presents the main conclusions drawn from this study.

2. Air cargo matrix

The set up of the European air cargo matrix requires comprehensive, homogenous and reliable data. These requirements are fulfilled by data that derive from the research project WORLDNET (2009a, 2009b).[2] Within the scope of this project air cargo is incorporated into a European transport network model. This, in turn, allows for setting up a flow matrix on the given regional level for the year 2005 covering air cargo within Europe and between Europe and

2 WORLDNET is a Framework 6 research project under the Scientific Support to Policies (SSP) initiative of the European Commission, Directorate General Energy and Transport.



Source: WORLDNET, 2009a

Fig. 1. Scheme of the developed approach for constructing the air cargo matrix

the world. Thus, the model copes with the dominance of intercontinental flow patterns - the underlying regionalization of WORLDNET, with about 500 traffic zones representing the world outside Europe and more than 1500 for Europe (NUTS3-level) form the base for an adequate detail. Figure 1 illustrates the developed scheme of the WORLDNET approach for air cargo flows.

The main approach consists of four major sequences (WORLDNET, 2009a, 2009b).

1. Build up an air cargo network, combining air links between airports and feeder links between regions and airports (nodes and links),
2. Enrich the build-up air cargo network with actually measured cargo volumes from statistics (airport and flow statistics),
3. Create from the available statistics a start-up freight matrix for air cargo,
4. Run an iterative calibration process to minimize the total sum of deviations between assigned (model results) and measured (observed) link loads as well as between start-up cargo flows adjusted according to the link statistics on country-level.

Data sources which have been used for the air cargo matrix include trade statistics (EU Trade Transport Data) to identify the air mode for extra-EU trade flows, transport statistics (e.g. Eurostat, national statistics) to gain information on the intra-European air cargo flows and socio-economic data (e.g. Eurostat, CIA World Factbook) for the purpose of matrix calibration.

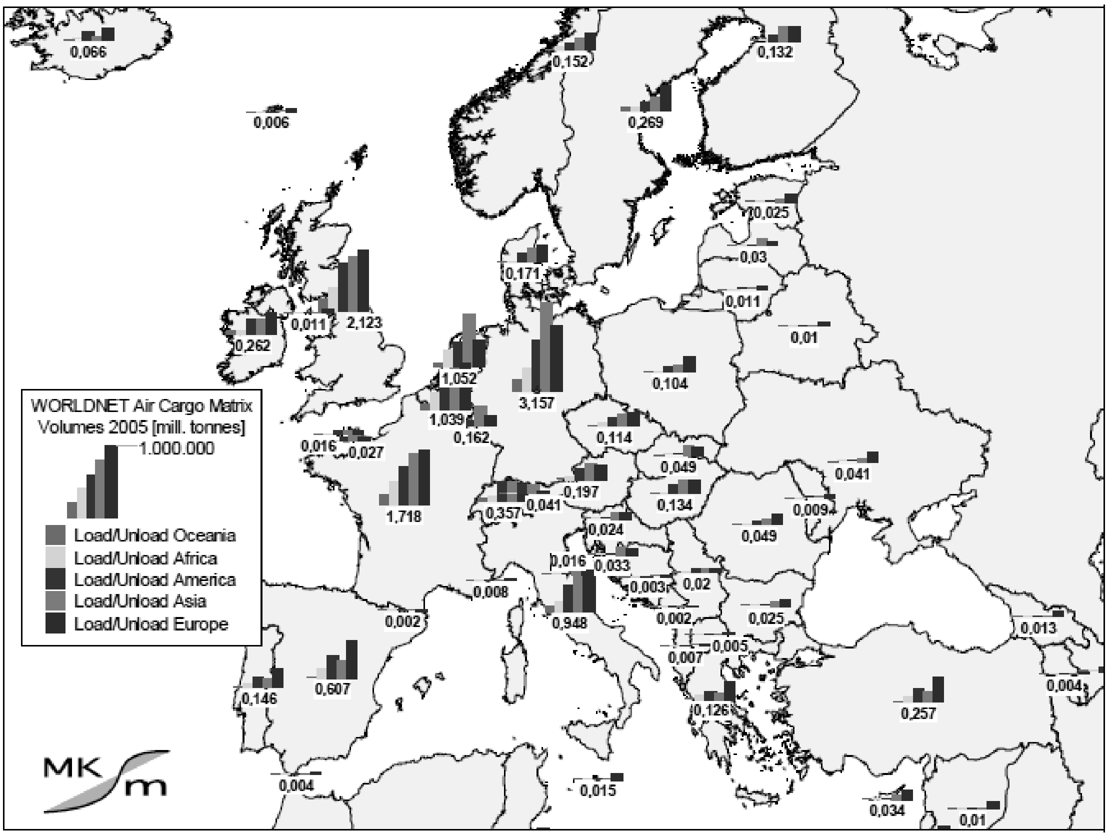
The iterative calibration process (assignment) grounds on a route choice model. In order to minimize the residuum of a linear system of equations, the model assigns flows of the start-up matrix to concrete routes (Furness algorithm). The linear-system consists of one line per air link and one column per origin-destination pair. The iterative process terminates when the deviation between statistics and link loads as well as between start-up matrix and adapted matrix have come to a minimum (WORLDNET, 2009b).

The developed air cargo matrix shows the cargo flows in tonnes for each pair of regions covered within WORLDNET. At least one of these regions has to be situated in Europe (the matrix covers all cargo flows to, from or within Europe). Cargo flows between two regions outside Europe are not covered, irrespective the routing touches Europe or not.

Figure 2 presents the cargo volumes in tonnes for the year 2005. The total air cargo flows to/from and within Europe including also domestic flows sum up to 11.25 million tonnes for the year 2005. Three fourth of this volume has been carried on intercontinental relations, while 20% were international, intra-European transport and less than 5% were of domestic nature.

Air cargo to or from Asia forms about 40% of all freight flows of this mode, while cargo to or from America makes about 25% of the total amount. Cargo to from Africa brings another 7% of the cargo volume, while the flows concerning Australia/ Oceania are minor building a share of just 3% of all air cargo flows. The remaining quarter is the intra-European air cargo demand.

Considering the country specific volumes, the top five



Source: WORLDNET, 2009a

Fig. 2. Cargo Volumes by European country

countries in Europe are Germany (3.2 mill. tonnes), United Kingdom (2.1 mill. tonnes), France (1.7 mill. tonnes), The Netherlands (1.1 mill. tonnes) and Belgium (1.0 mill. tonnes), which makes about 80% of all air cargo carried to, from or within Europe.

The WORLDNET matrix, which covers all freight flows to, from or within Europe, can be considered the core of the matrix applied for this study. However, to set up a complete air cargo matrix, the flows among the functional airports and the flows between the functional airports and their hinterland have to be estimated in a last step.

With regard to the missing flows among the artificial airports the “World Intercontinental Air Trade Forecast” which grounds its forecasts for the period from 2006 to 2010 on 2005 data gives sufficient information (Merge Global, 2006). For the estimation of the flows from and to the hinterland average European-Airport-Hinterland-Coefficients are calculated and then applied to the aggregated artificial airports (see annex for a detailed description of the procedure).[3]

The outcome of the described steps finally allows setting up the complete input-output matrix for air cargo. This complete matrix structure is needed for accomplishing the analyses to calculate the airports’ degree of interdependency and importance.

3 Clearly, this rather rough method hardly yields exact results. But since hinterland flows for the rest of the world airports hardly affect our analysis, which focuses on the identification of European airports’ relative importance, we prefer to go on with an educated guess rather than empty cells.

3. Importance and interdependency of European airports

3.1. Air cargo input-output table

In order to identify the importance and interdependency of European airports, the study at hand follows the input-output technique. Traditional input-output tables provide detailed information of industries inputs and outputs in matrix form. The core of the tables is the intermediate quadrant that gives an insight into the industries’ linkages. Under ceteris paribus restrictions, the input-output representation thus allows for analyzing the dependency of each industry on all other industries. Since the tables also account for the industries production of final goods and their absorption of primary inputs, they present a rather complete picture of an economy. This also implies that total inputs – generally measured in monetary units equal total outputs for each industry. If the tables are used for analytical purposes, the technology is assumed to be constant. While this is reasonable for short, and in some cases medium term analysis, the tool is (in its static version) less appropriate for the simulation of long term effects.

Table 1. General Structure of the input-output table for air cargo flows

Sector		AAL	AAR	ABZ	...	ZAD	ZAG	ZRH	AP	AF	NA	SA	EE	Hinterland	Sum
	Index	0	1	2	...	288	289	290	291	292	293	294	295	296	297
AAL	0														
AAR	1														
ABZ	2														
...	...														
...	...														
XCR	286						I							II	
XRY	287														
ZAD	288														
ZAG	289														
ZRH	290														
AP	291														
AF	292														
NA	293														
SA	294														
EE	295														
Hinter-land	296				III										
Sum	297														

Source: Vosen, 2011

For the study at hand, the input-output philosophy is transferred to the air cargo market. For this purpose the airports replace the industries as consumers of inputs and producers of outputs. Both inputs and outputs (henceforth inflows and outflows) are measured in tonnes. The point of departure for the analysis is a set of 291 European and 5 artificial airports (representing the rest of the world) where air cargo flows occurs in a certain period of time (base year 2005). Table 1 displays the general structure of the input-output matrix for air cargo flows.

Cargo flows between 291 European airports and between these airports and 5 world regions[4] (blue shaped) are incorporated into the matrix. Furthermore, feeder services to (green shaped) and from (orange shaped) the European airports are also considered ("Hinterland").

Following the input-output notation, the blue-shaped part can be considered the intermediate matrix. A typical element x_{ij} denotes the total freight tonnes shipped from airport i to airport j. The rows display the outflows of airport i whereas the columns illustrate the airports' inflows. The row "Hinterland" displays the air cargo outflows from airport i to its hinterland (by any other mode). In input-output notation this vector defines airport i's final demand. The column "Hinterland" (the primary input vector in the traditional tables) displays air cargo inflows to airport j from its hinterland (by any other mode).

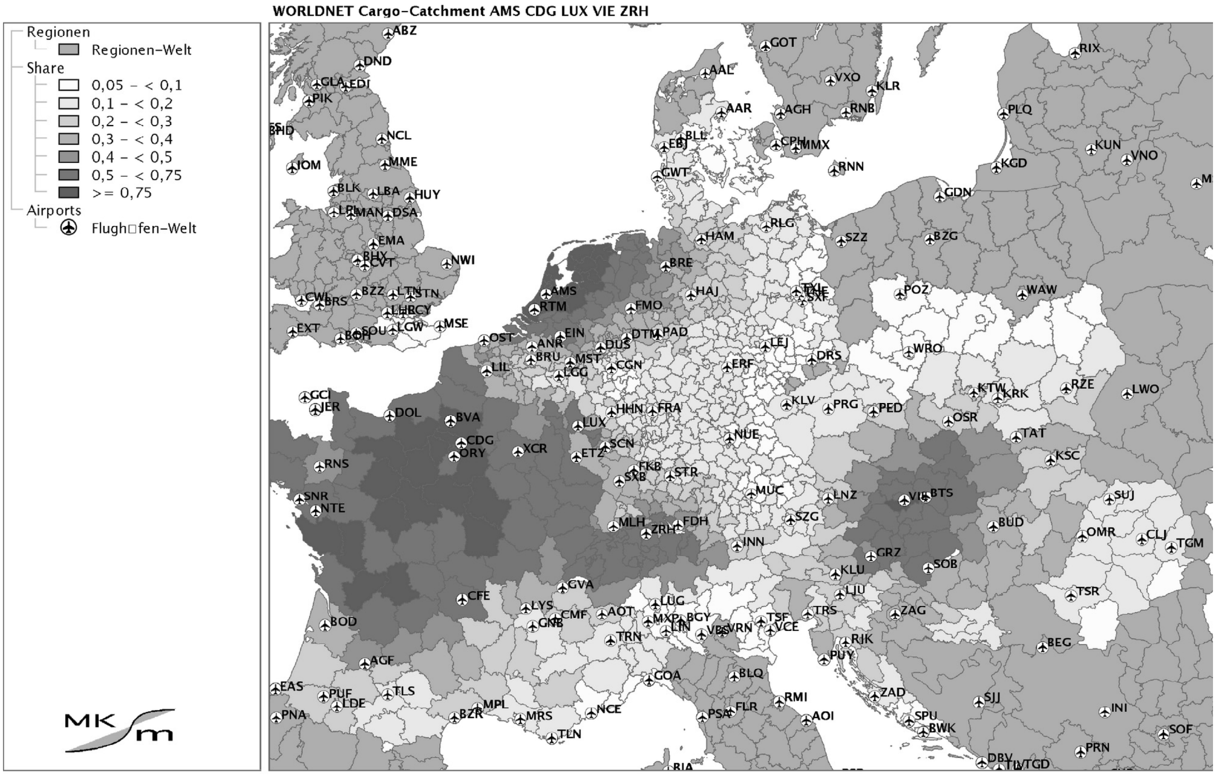
Each column sum ($\sum_{i=1}^{n} x_{ij}$) displays the inflows from all airports (including 5 rest of the world airports) to airport j. Each row sum ($\sum_{j=1}^{n} x_{ij}$) displays the outflows of airport i to all airports (including 5 rest of the world airports).

4 The five aggregated World Regions are: Africa (AF), Asia Pacific (AP) (Asia and Oceania), North America (NA), South America (SA), Rest of Europe (not considered in the detailed analysis of the WORLDNET project).

3.2. Measure of airport interdependency and importance

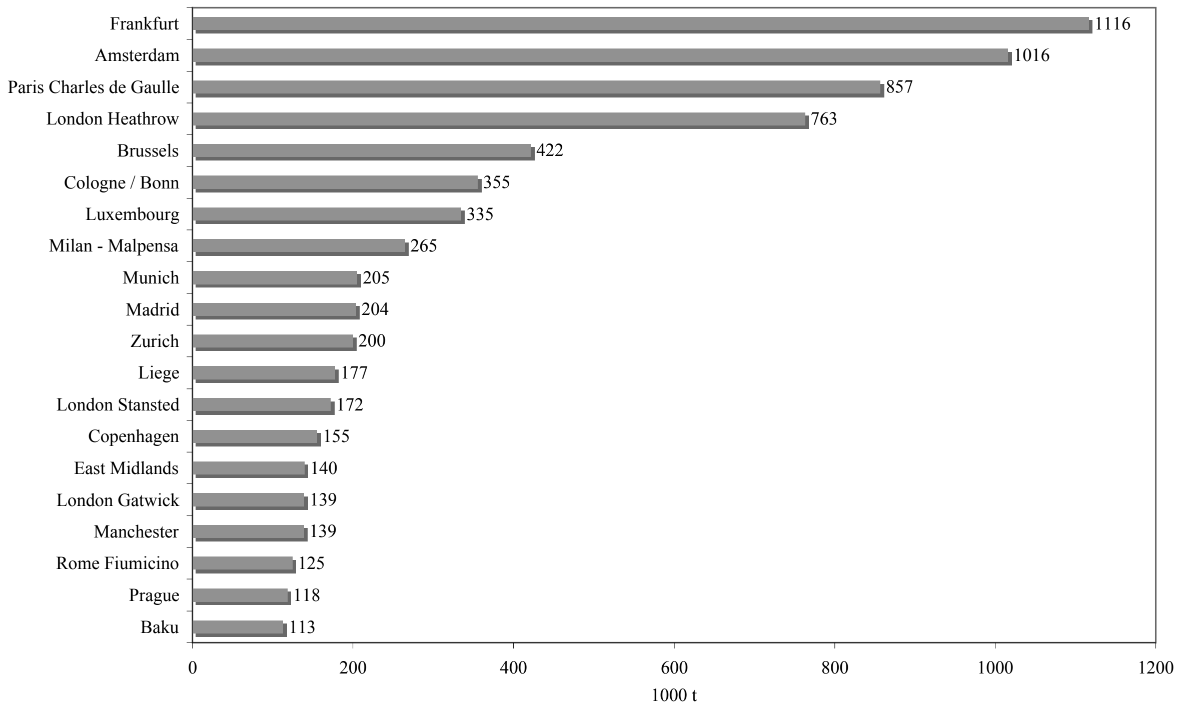
A smooth running air cargo network requires that each airport receives the inflows from other airports and its hinterland according to the planned scenario. In case this requirement cannot be met, as it was the case in the aftermath of the recent eruption of Iceland's Eyjafjalljökull volcano, the production of airports and clients in the respective hinterland might be severely limited. The production stop of BMW in Munich due to missing parts shipped by air is only partly due to the closure of Munich airport. Equally important was the closure of main European hub airports, which receive freight from all over the world and further distribute the goods to their final destination. Furthermore Munich manufacturers receive their air cargo not only from Munich airport but also from other nearby airports. Figure 3 depicts the combined cargo catchment of some selected airports addressing the market share they can attract from the regions. In fact the spatial coverage shows how strong industries are affected in case of an airport closure. So the industry around Munich would have been affected as well to a level of 10% despite the airport MUC would have been operating but the depicted ones would have been closed. In consequence risk assessment of production lines should consider this dependency.

Clearly the hinterland increases with airport size, which can certainly be considered a first indicator of an airport's importance. Figure 4 shows the 20 biggest European airports



Source: authors' own representation

Fig. 3. Hinterland of the airports Amsterdam, Charles de Gaulle, Luxembourg, Vienna and Zurich



Source: authors' own representation

Fig. 4. Cargo volumes shipped to other airports

in terms of freight volumes shipped to other airports. The volumes account for flows to the rest of the world airports but do not include flows to the respective hinterland.

In terms of absolute flows, the closure (or limited operation) of Amsterdam airport has more severe impacts for the network operability compared to a closure (or limited operation) of Paris Charles de Gaulle. However, the degree of a network's inoperability is further determined by the (supply driven) forward linkages of the affected airport(s).

The first step to identify the airports' forward linkage is the calculation of the output-coefficients a_{ij}:

(1) $$a_{ij} = \frac{x_{ij}}{x_i}$$

The coefficient measures the cargo volumes that are further shipped from airport i to airport j (outflows) in relative terms to the total inflows received by the airport.[5] Following one basic assumption of the input-output analysis, the a_{ij} are considered constant in the short term which is not an unrealistic scenario (e.g. see the Eyjafjalljökull volcano's eruption). A coefficient of 0.4 implies that for each 100 tonnes of cargo arriving at airport i (from other airports or the airport's hinterland), 40 tonnes are further shipped to airport j. If, for some external reasons, inflows received by airport i are reduced by 50%, or if the airport receives all inflows but can, due to internal defects, process only 50% of the volume, airport j just receives 20 tonnes.

In a second round, the reduction of 20 tonnes in the inflows for airport j causes further disruption of the system. Assume the as planned scenario of airport j foresees to ship a total of 100 tonnes to other airports, production is now limited to 80 tonnes. This effect continues, to an ever minor extent, in all subsequent rounds. Thus, the estimation of the cumulated effect follows an iterative process according equation (2):

(2) $$B = I + A + A^2 + A^3 + A^4 + ...$$

I: Unity matrix

$$A: \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \dots & a_{nn} \end{pmatrix}$$

(The A-matrix is often referred to as Ghosh matrix.[6])

The result of the iterative process given by equation (2) can alternatively be calculated according equation (3):

(3) $$B = (I-A)^{-1}$$

$$B: \begin{pmatrix} b_{11} & \dots & b_{1n} \\ \vdots & & \vdots \\ b_{n1} & \dots & b_{nn} \end{pmatrix}$$

(The B-matrix is often referred to as Ghosh inverse matrix.)

5 Note that total inflows equal total outflows for any airport.

6 A detailed review and interpretation of the Gosh-matrix can be found at Dietzenbacher (1997).

Taking into account the Ghosh inverse matrix, equation (4) describes the complete airport cargo network:

(4) $$x = (I - A)^{-1} f$$

x: n-element vector of airports' total inflows (= airports' total outflows)

f: n-element vector of airports' inflows from the corresponding hinterland (other inflows)

Furthermore, the Ghosh inverse matrix enables the calculation of input multipliers in line with equation (5) (West, 1988):

(5) $$L_i = \sum_{j=1}^{n} b_{ij}$$

In the context of the air cargo input-output system, the multiplier measures the cumulated effect on total outflows of all airports that come along with a unit change in the inflows of airport i. Thus, L_i measures how much more (or less) cargo is further shipped to any other airport when an additional unit (or a unit less) of cargo arrives at airport i. Cargo can arrive either from airport to airport relations or from the airport's hinterland. A multiplier for airport i of 2.50 means that in case of a sudden drop of inflows by 1,000 tonnes to this airport, the transported tonnes in the whole network is reduced by 2,500 units where 1,500 units occur at other airports (transfer freight).

A high multiplier value identifies a strong forward linkage and therefore points to a relatively high importance of the airport as a supplier of intermediate goods. The limited operability of such an airport, or in case of an extreme event the closure, has severe consequences for the whole network. Clearly, major hub airports can be assumed to come up with high multipliers. In contrast, we expect small multiplier for airports at the end of the logistic chain.

Table 2 shows the 20 airports with the highest multiplier but also gives some examples for well-known airports with medium and small multipliers.[7]

The results confirm the expectations in most instances. Major cargo hubs, such as Frankfurt (FRA), Amsterdam (AMS), Paris (CDG) and London Heathrow (LHR) are among the top 20. Milan Malpensa International (MXP) and Luxembourg (LUX) are just behind. In addition Madrid, Brussels and Cologne / Bonn and Rome show over-average multipliers, and lead the group of airports with medium multipliers. Since the multipliers are independent from the absolute flows shipped by the airport, results are not driven by the airports' size but their (forward) interconnectedness. This explains why smaller hubs of larger airlines (e.g. SAS/Copenhagen, Swiss/Zurich, Lufthansa/Munich, Cargolux/Baku) come up with similar or sometimes even higher multipliers compared to the leading European cargo hubs. Finally, some airports, such as Kristiansand airport Kjevik or Pisa emerge in the top 20 list by surprise. However, these airports have rather strong

7 The calculation of multipliers is based on the full cargo input-output table. However, since the focus of the presented study is on air cargo transport in Europe, airports are only considered for further discussion, if a minimum freight volume of at least 1000 t per year is processed at the respective airport. This restriction limits the analysis of airports' importance to a total of about 180 airports.

Table 2. Forward linkages of European airports

Airport	Multiplier	Airport	Multiplier
High multipliers		**Medium multipliers**	
Rovaniemi	2.81	Madrid	2.41
Baku	2.75	Brussels	2.34
London Gatwick	2.73	Cologne / Bonn	2.33
Coventry	2.65	Rome Fiumicino	2.33
Frankfurt	2.64	Innsbruck	2.21
Paris Charles de Gaulle	2.62	Berlin	2.18
Pisa	2.62	Dublin	2.16
Amsterdam	2.61	Split	2.16
Belgrade	2.61	Athens	2.16
Riga	2.60	Warsaw	2.15
Copenhagen	2.60	Vienna	2.07
Bucharest	2.58	Turin	2.06
London Heathrow	2.57	**Low multipliers**	
Kjevik	2.57	Friedrichshafen	1.73
Paris Orly	2.56	Klagenfurt	1.73
Munich	2.55	Tenerife	1.71
Strasbourg	2.53	Jersey	1.61
Basel Mulhouse	2.52	Heraklion	1.59
Stockholm	2.52	Cagliari	1.53
Zurich	2.51	Seville	1.44

Source: authors' own representation

linkages with major hubs (Copenhagen and Amsterdam in case of Kjevik, Rome Fiumicino and Malpensa International in case of Pisa) and benefit indirectly from the strong interconnectedness of those airports.

We further expected small multipliers for airports at the end of the logistic chain. Again, the results generally strengthen this hypothesis, since peripheral airports in touristic regions (without major manufacturing industries) largely form the group of airports with smallest forward multipliers.

Although the calculation of multiplier is technically independent of the airport size, a relation can still exist. An airport's strong interconnectedness could for example add to its attractivity as a cargo hub and therefore enhance the processed freight volumes over time. Figure 5 partly supports this reasoning, as airports' total outflows (without flows to the corresponding hinterland) increase with the multipliers. At the same time the trend is not very strong. Indeed low and high multipliers occur for any airport size.

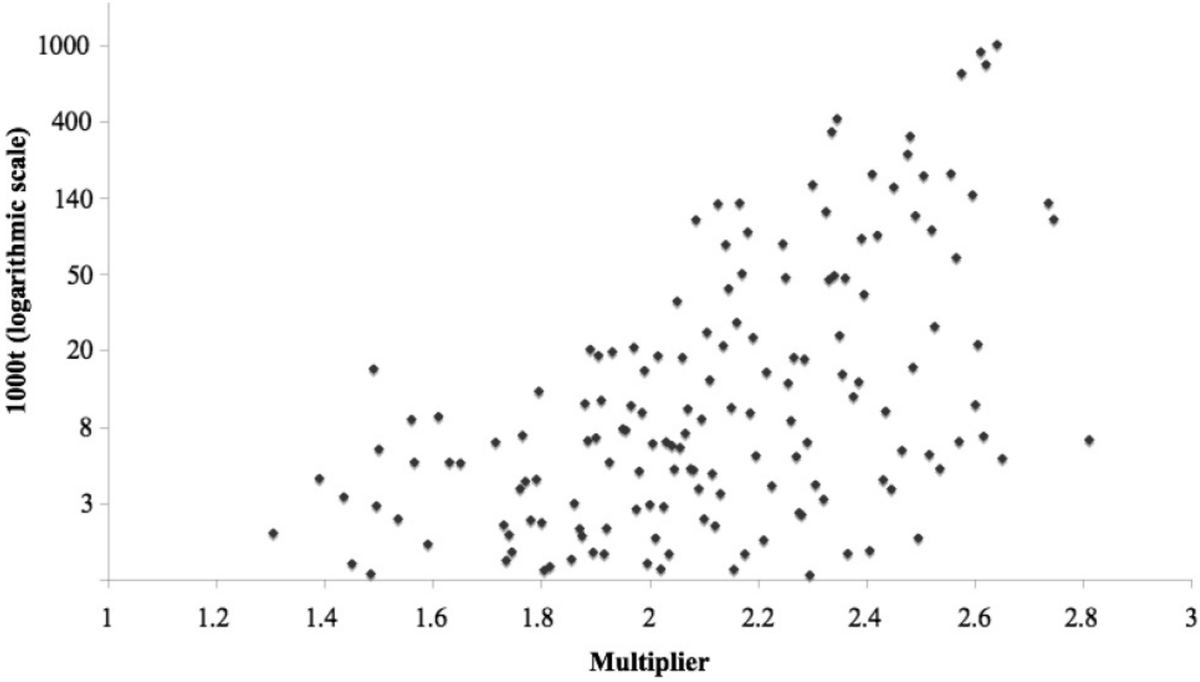
The final step foresees the identification of airports' importance by taking into account airport size and forward linkage. For this purpose a weighted (and this time normalized) linkage index is defined in the following way:

$$(6) \qquad L_i^{\omega} = \omega_i \frac{\sum_{j=1}^{n} b_j}{\sum_{i=1}^{n}\sum_{j=1}^{n} b_j}$$

ω_i : weight

Clearly the linkage is rather sensitive to the chosen weight. The presented study two different weights are proposed. First, the attached weight just equals the absolute cargo volumes (in tonnes) shipped from airport i to other airport. Since the multipliers are rather similar for the biggest airports, the linkage relies heavily on the airports' size and hardly any change compared to the ranking based on tonnes only can be expected. The second weight is also based on the processed cargo volumes, but instead of the absolute flows their logarithmic value is taken into account. Thus, the attached weights still increase with the absolute flows but at a much lower rate. Table 3 shows the airports with the highest forward linkages for both alternatives.

In case the weights are defined by the absolute flows, the rankings hardly change compared to the ranking based on



Source: authors' own representation

Fig. 5. Airports' total outflows (in 1000t logarithmic scale) and forward multipliers

Table 3. Weighted forward linkages with different weights

Airport	Weighted linkage	delta rank	Airport	Weighted linkage	delta rank
Frankfurt	22.51	0	Frankfurt	1.86	0
Amsterdam	20.25	0	Amsterdam	1.82	0
Paris Charles de Gaulle	17.14	0	Paris Charles de Gaulle	1.81	0
London Heathrow	14.99	0	London Heathrow	1.76	0
Brussels	7.51	0	London Gatwick	1.64	+11
Luxembourg	6.33	+1	Baku	1.61	+14
Cologne / Bonn	6.32	-1	Luxembourg	1.59	0
Milan - Malpensa	5.00	0	Munich	1.58	+1
Munich	4.00	0	Copenhagen	1.57	+5
Zurich	3.82	+1	Milan Malpensa	1.56	-2
Madrid	3.75	-1	Zurich	1.55	0
London Stansted	3.22	+1	Brussels	1.53	-7
Liege	3.11	-1	Cologne / Bonn	1.51	-7
Copenhagen	3.08	0	London Stansted	1.49	-1
London Gatwick	2.91	+1	Madrid	1.49	-5
Baku	2.36	+4	Prague	1.47	+3
East Midlands	2.30	-2	Stockholm	1.46	+5
Prague	2.25	+1	Paris Orly	1.44	+10
Manchester	2.23	-2	Liege	1.40	-7
Rome Fiumicino	2.21	-2	Milan Orio al Serio	1.40	+4

* delta rank: changes of ranking compared to the ranking based on cargo volume only (figure 4)

Source: authors' own representation

cargo volume only (compare figure 4). Some airports switch position, but with the notable exception of Baku airport no significant changes occur. In fact all of the biggest 20 airports in terms of cargo volume reappear in the top 20 list of airports with highest weighted forward linkages.

In contrast, the ranking changes significantly, if the weights are based on the logarithmic values. The airports of Baku, London Gatwick, Paris Orly, Copenhagen and Stockholm clearly rise in importance. At the same time, the airports of East Midlands, Brussels, Cologne / Bonn, Liege and Madrid lose 5 or more positions due to their comparatively smaller forward connectedness. The airports of East Midlands, Manchester and Rome Fiumicino even drop out of the top 20 list. They are replaced by the airports of Stockholm, Paris Orly and Milan Orio al Serio.

Due to their much higher volumes compared to all other airports, the biggest cargo hubs (Frankfurt, Amsterdam, Paris CDG and London Heathrow) remain at the top of the ranking, no matter which weight is attached.

4. Implications of airport closures on the entire air cargo network

4.1. Model definition and development

The introduced forward linkages give a first impression on Europe's central and most important airports. In a next step the impacts of network disruptions, such as airport or air space closures are quantified by applying an input-output model. The idea of the model is leant on the work of Jiang and Haimes (2004) who developed a framework based on Leontief's notation of input-output and applied it for an economic risk assessment. Jiang and Haimes (2004) use a steady-state approach which describes primarily the long-term, equilibrium relationship for the participating subsystems.

The present subsystem is the European air freight market and the model's main features are as follows:

- Airport (air space) closures (or disruptions) result in changes in the freight flows between the affected airport(s) and their connected airports (hinterland transports keep unchanged)
- Freight flow changes lead to an adaptation of the intermediate matrix, the A matrix where a typical element x_{ij} denotes the total freight tonnes shipped from airport i to airport j
- Cascading effects caused by the interdependencies and interconnectedness of the European air freight market intensify the impacts of the initial airport closures and will change the overall air freight network size

Disruption at the airport level is defined as the remaining capacity (percentage of the daily average capacity, disruption share) which still can be operated at the airport(s) after the disaster. Disasters might accrue from natural disaster, terrorist attacks or technological problems which impact the maximum capacity at the airport(s).

The approach grounds on the relationship of the input-output philosophy where input and outputs are linked together in the following way (introduced in chapter 3):

$$x = (I - A)^{-1} f$$

x: n-element vector of airports' total inflows (= airports' total outflows)

f: n-element vector of airports' inflows from the corresponding hinterland (other inflows)

The implemented approach and its three operation steps are introduced in the following:

Step 1 (recalculation of the intermediate matrix's elements x_{ij}):

- The disruption share (ρ_i) of all engaged airports of the European air freight system is to be determined first (disaster scenario definition). A disruption share of i.e. 0.4 implies that after the disaster 40% of freight tonnes can still be handled at airport i. The remaining 60% cannot be operated from/to airport i which might be due to runway closure due to damage, ice, etc., increased safety distances between aircrafts, de-icing of aircrafts, etc.
- The intermediate output-coefficient matrix A needs to be adapted based on the developed disaster. For each engaged airport i its row and column values x_{ij} are multiplied by its disruption share ρ_i. The adapted values x'_{ij} indicate the total freight tonnes which can be transported from the disrupted airport i to airport j caused by the disaster.

Step 2 (calculation of the "disaster matrix" A):*

- The adaptations of the matrix's elements (x'_{ij}) also change the structure of the original input-output table, the A-matrix. Therefore, a new "disaster matrix" A* is required which results from these adaptations and which is determined as introduced in chapter 3 for the original A-Matrix.
- Furthermore, a new Ghosh-Matrix as well as a new Ghosh-Inverse is determined which are based on A* ("disaster matrix"). The new Ghosh-Matrices describe the "new" interdependencies and interconnectedness between the system's airports which are limited by the present disaster.

Step 3 (recalculation of the steady-state)

- The impact of the disaster for each airport as well as for the entire airport system is now recalculated by applying the new Ghosh-Matrices to the original inflows of the system, the Hinterland transports.

$$x^* = (I - A^*)^{-1} f$$

Finally, the results (x*) can then be compared with the original, non disaster affected, results (x) of every airport.

Deviations indicate the disruption level at airport i which is due to the interdependency and interconnectedness of the air freight system where also not directly affected airports do perceive the disaster significantly.

4.2. Case-study application

The developed model can be applied to airport closures and capacity reductions at airports as well as to closures and capacity reductions of entire air spaces in Europe. A recurring challenge to Europe's air freight system is capacity constraints due to winter storms (including heavy and abrupt snowfall). Therefore, the vulnerability of the entire air freight system as well as the direct and indirect impacts of winter storms on airports will be analyzed in detail. Airports which are not directly but indirectly affected by the winter storm will be elaborated in detail (cascading effect).

The applied scenario is leant on the situation in December 2010 where a heavy snow storm affected airports in Germany, the Benelux, Great Britain and in North France. Besides a large number of smaller airports also the European air freight gateways have been affected by the storm significantly, such as Amsterdam Airport Schiphol (AMS), Paris Charles-de-Gaulle (CDG), Frankfurt International (FRA) and London Heathrow (LHR). The very high importance of the gateways for the European air freight system as already introduced by the forward linkages and therefore the high dependency of secondary airports on their operability underline the importance of such a scenario for the gateway airports but particularly for the dependent secondary airports.

The scenario "winter storm in Europe" is divided into two sub-scenarios which represent the spread of the winter storm over time[8]. Figure 6 illustrates the situation and colours the affected regions of the sub-scenarios. Scenario 1 (light shade) analyzes the beginning of the winter storm: First disturbances of the airlines' flight schedules are observed and one of the major air freight gateways, namely FRA, is already affected by the winter storm. Scenario 2 (dark shade) tightens the situation and the storm is spread over central Europe and more airports are affected (including AMS, CDG, FRA and LHR) and also the intensity of disruption has increased. Both scenarios constraint the air capacity of the system whereas hinterland connections to and from the airports keep unrestrained. Hence, a short- to medium-term perspective is applied in the present scenarios.

Detailed results of the scenarios are presented in Table 4 and Table 5. It becomes obvious that because of the interdependency and the interconnectedness of the air freight system, disruptions at selected airports (or regions) do impact the entire European air freight system. Disruptions at 10% of the European airports where still 80% of freight tonnes can be handled (scenario 1) lead to an average reduction of daily freight tonnes of only 2.02%. This result indicates that in scenario 1 especially smaller airports are affected by the disruption and that comprehensive airport alternatives exist. Contrarily, the impacts of scenario 2 (red) where the major European air freight gateways are directly affected (AMS, CDG, FRA and LHR) lead to an overall reduction of air freight tonnes of approx. 18% even though around 80% of airports are not directly affected by the winter storm.

The most impacted airports are the airports which are directly affected by the winter storm because capacity reductions at these airports are incorporated into the model for the air side exogenously[9] (intermediary matrix). The top 10 affected airports which are not located in the winter storm regions are presented in Table 5 for both scenarios. It becomes obvious that especially the interconnectedness with the major air freight gateways impact the disruption levels of not directly affected airports (and regions). Therefore, Polish, Italian, and Greece airports are the top affected airports of scenario 1 because international gateways to the major air freight market, such as Asia and North America, are either not located in these countries or freight is to a significantly share transported by feeder services to the major cargo airports in central Europe (e.g. AMS, CDG or FRA). Nevertheless, the top 10 airports which are primarily affected by scenario 1 are all of secondary importance for the entire European air freight market that only the first order impacts do count for this scenario (all Austrian, Czech and German airports are constraint by the winter storm). A different picture can be observed for scenario 2. The overall daily freight tonnes are reduced by approx. 18% which is already a significant reduction for the air freight system. Furthermore, approx. 20% of European airports are directly constraint by the winter storm including the air freight gateways and finally, more airports are significantly affected by the storm caused by secondary and tertiary effects. Especially, British and French airports are now present in the top 10 which can be explained by the fact that only some British and French airports are defined as directly affected by the winter storm. Due to the strong interdependencies and interconnectedness between airports of the same country and especially within Great Britain caused by its island position, also other airports are indirectly affected by the winter storm. As for scenario 1 it should be noted that the top 10 airports (by disruption level) are only secondary airports but the entire system disruption and especially the (partly) inoperability of the air freight gateways (AMS, CDG, FRA and LHR) affect the air freight system significantly.

5. Conclusions

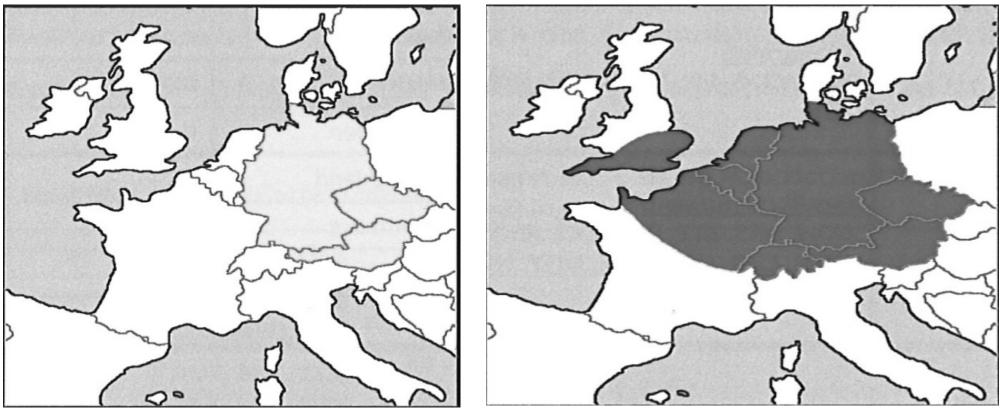
The eruption of Iceland's Eyjafjalljökull volcano eruption in April 2010 impressively demonstrated the dependency of the economy on a smooth running air cargo network. Though economic damages have been comparatively small, production came to halt due to missing parts in different locations all over Europe.

There is a lively debate going on whether the closure of the airports has been justified. While airlines are clearly sceptical, public authorities point to the safety aspect. No matter which side is right, the ash cloud illustrated that crises strategies are hardly mature.

The presented paper aims to add a small mosaic to the ongoing

8 It should be noted that the scenario "winter storm Europe" is only a fictive scenario. The events of December 2010 only serve as a orientation.

9 Because the hinterland connections to and from the airports keep unrestrained, the overall reductions at the airport (air side + hinterland capacities) are smaller.



Affected countries (all airports)	Austria, Czech Republic, Germany*	Austria, Belgium, Czech Republic, Germany, Luxembourg, the Netherlands, Swiss
Affected airports (additional airports)	-	**France:** (BVA, CDG, LIL, MLH, ORY, SXB, XCR) **Great Britain:** (BOH, BRS, BZZ, EXT, GCI, JER, LCY, LGW, LHR, LTN, MSE, NQY, NWI, SOU, STN)

* In sub-scenario 1 (left, light shade) a disruption share of 0.8 is assumed (80% of freight tons can still be handled at the airports). In sub-scenario 2 (right, dark shade) a disruption share of 0.2 is assumed.

Source: Vosen, 2011

Fig. 6. Regional disruption for the case-study "winter storm Europe"

Table 4. Overview of scenario results (aggregated level)

Scenario	Affected countries	Disruption share at affected airports	Average freight tonnes per day (without disaster)	Average freight tonnes per day (with disaster)	Change in freight tonnes per day
1 (light shade)	AUT, CZE, GER	0.8	156,137	152,986	-2.02%
2 (dark shade)	AUT, BEL, CZE, FRA*, GBR*, GER, LUX, NED, SUI	0.2	156,137	128,626	-17.62%

* Only partly (see Figure 6 for further details)

Source: authors' own representation

discussion in this field by setting up a European air cargo input-output table in the first step. These tables reveal the strong interdependence of the air cargo market and present the airports' absolute in- and outflows. In input-output notation, the airport to airport relations define the intermediate matrix. Flows from the corresponding hinterland to the airports are the primary inputs whereas flows to the hinterland are the final demands.

Since the table follows the main principles of the input-output analysis, indicators of airports' connectedness and importance can be estimated. Based on the Ghosh inverse matrix we first calculate forward multipliers which are independent of absolute flows but give a good idea of the airports forward linkages. Not surprisingly the main hub airports come up with rather large multipliers. In contrast, airports at the end of the logistic chain generally show small

Table 5. Top affected airports caused by the winter-storm scenarios according to their level of disruption

Scenario 1					Scenario 2				
Rank (affected -ness)	**Airport**	**Country**	**Disruption level**	**Freight tonnes before disaster [tonnes per day]**	**Rank (affected -ness)**	**Airport**	**Country**	**Disruption level**	**Freight tonnes before disaster [tonnes per day]**
1	LEI*	ESP	0.82	5.66	**1**	LEI	ESP	0.30	5.66
2	KVA	GRE	0.87	17.19	**2**	LSI	GBR	0.33	21.24
3	CFU	GRE	0.88	6.06	**3**	MJV	ESP	0.35	11.99
4	FLR	ITA	0.88	9.97	**4**	MME	GBR	0.43	7.80
5	KTW	POL	0.89	10.21	**5**	SVQ	ESP	0.43	42.96
6	TSF	ITA	0.90	41.30	**6**	TLN	FRA	0.46	0.59
7	POZ	POL	0.91	11.16	**7**	PUF	FRA	0.47	6.56
8	GDN	POL	0.91	10.14	**8**	KVA	GRE	0.50	17.19
9	SJJ	BIH	0.92	2.82	**9**	BES	FRA	0.51	1.95
10	AOI	ITA	0.93	4.40	**10**	TRF	NOR	0.53	32.59

* LEI: Aeropuerto de Almeria (Spain), KVA: Kavala International Airport „Alexander the Great“ (Greece), LSI: Sumburgh Airport (Great Britain), CFU: Corfu International Airport, „Ioannis Kapodistrias“ (Greece), MJV: Murcia-San Javier Airport (Spain), FLR: Florence Airport (Italy), MME: Durham Tees Valley Airport (Great Britain), KTW: Katowice International Airport (Poland), SVQ: Seville Airport (Spain), TSF: Tenerife South Airport (Spain), TLN: Toulon-Hyères Airport (France), POZ: Poznań-Ławica Henryk Wieniawski Airport (Poland), PUF: Pau Pyrénées Airport (France), GDN: Gdansk Lech Walesa Airport (Poland), SJJ: Sarajevo International Airport (Bosnia and Herzegovina), BES: Brest Bretagne Airport (France), AOI: Ancona-Falconara Airport (Italy), TRF: Sandefjord Airport (Norway)

Source: authors' own representation

multipliers. The second step foresees the calculation of a weighted forward linkage. For this purpose two alternative weights are suggested: the absolute cargo volume transported to other airports and the logarithmic value of these flows. In case of the first weight, the role of the connectedness is reduced in favour of the airports size and the airports with the highest linkages follow very much the same ranking as if the ranking is purely based on the volumes. In contrast, the application of the second weight seems to provide a linkage index with a sound balance of forward connectedness and absolute volumes. Interestingly the rankings differ significantly compared to the first alternative. In case a crises strategy is not only driven by the airport size but takes into account the dependency as well the latter index can be considered a better proxy for the airports' importance.

In a last step an input-output model is developed which quantifies direct and indirect impacts of disasters for the air freight system. Therefore, interdependency and interconnectedness between the airports is considered. Hence, cascading effects can be represented by the model which is extremely important for network systems, such as the air freight system where hub-and-spoke structures are the predominant network structures (Scholz, 2011). A case-study application which is leant on the winter storm of December 2010 shows the functionality of the model.

The present steady-state approach

- Elaborates the importance of the primary airports (gateway airports) for the entire air freight system
- Identifies the high interconnectedness of the air freight system which is a risk (dependency from gateway airports) but also an opportunity (alternative routing opportunities)
- Ascertains the vulnerability of the system in case of disruptions at gateway airports which is caused by the sophisticated hub-and-spoke systems of the market players (e.g. airlines, forwarders)

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Annex

Calculation of the hinterland outflows for the artificial rest of the world airports:

- Calculate the total tonnes for all European airports:

$$x_{sum} = \sum_{i=1}^{291} \sum_{j=1}^{296} x_{ij}$$

- Calculate the hinterland flows (other outflows) for all European airports:

$$e = \sum_{i=1}^{291} e_i$$

- Calculate the European-Airport-Hinterland-Outflow-Coefficient:

$$\delta = \frac{x_{sum}}{e}$$

- Apply the European-Airport-Hinterland-Outflow-Coefficient to the World Regions:

$$e_i = \frac{\sum_{j=1}^{296} x_{ij}}{\delta}$$

The determination of the inflows (hinterland) bases on the simulated outflows as the row sum of airport i (x_i) equals the column sum of airport i (x_i). This assumption can be justified because the air freight market is a closed system that every tonne of freight must have one specific origin as well as one dedicated destination. The inflows calculation passes the following procedure:

- Calculate the total outflow tonnes (incl. hinterland) for all airports (incl. World Regions):

$$x_i = \sum_{i=1}^{296} \sum_{j=1}^{297} x_{ij}$$

- Calculate the total inflow tonnes (excl. hinterland) for all airports (incl. World Regions):

$$x_{sum,i} = \sum_{i=1}^{296} \sum_{j=1}^{296} x_{ij}$$

- Determine the missing hinterland inflows for the World Regions:

$$i_i = x_i - x_{sum,i}$$

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