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Abstract
The primary objective of this paper is the structural analysis of source-receptor air pollution problems in the EU region. Two views are provided for the analysis: an emission-driven view and a deposition-driven view. Different visual schemes are used to reproduce the global pollution network and identify the biggest sources and sinks of pollution. Visual modelling helps to understand the linkages and interconnections in the transboundary pollution network. Our interactive outputs give the options to zoom in to specific areas of the global source-receptor air pollution scheme and highlight the top emitters or receptors of pollution. Ranking of countries in decreasing order of pollution responsibility and/or vulnerability using graph metrics is a main result. Data sources are emissions-depositions (or source-receptor) tables of air pollutants, available online from the data repository of the European Monitoring and Evaluation Program (EMEP) of the Long-Range Transmission of Air Pollutants in Europe. In our computer-based visual analysis, we employ solely open software.

Keywords: source-receptor air pollution; network analysis; heatmaps; free open-source software.

JEL Classification: C63; C88; Q53; Q58.

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1. Introduction

The awareness of the pollution responsibility and the pollution dispersion is the first step to combat damage and social costs associated with air pollution (Halkos 1992; 1993; 1994; 1996; Hutton and Halkos 1995, Anaman and Looi, 2000; Halkos and Tsilika, 2014; 2017; Fujii and Managi 2016; Halkos et al., 2018; Halkos and Papageorgiou 2016). In this paper, we introduce a visual framework that explores linkages and interdependencies in source-receptor (hereafter SR) air pollution. The calculation of pollution indicators and ratios along with the visualization of the source-receptor air pollution scheme are sine qua non conditions to estimate the environmental impact of major polluters and their severe consequences. These tasks are integrated in network analysis software Gephi (v. 0.9.2) and in several free visual interfaces. The computer input consists of yearly country-to-country source-receptor (SR) pollution data over the extended EU area, as reported in the source-receptor tabular information in the EMEP/MSC-W website. The main contributions of this paper are:

- A computer-based design and analysis of transboundary air pollution networks and
- Mapping the pollution interactions among countries of the EMEP extended domain

In the first part of the paper, we build graph models of pollutants exchange. By employing graph measures and metrics, pollution indicators are estimated in order to quantify 1) the responsibility of polluters and 2) the degree of exposure for pollution victims, in annual basis. Ranking of countries in decreasing order of pollution responsibility and /or vulnerability is a main result of network analysis.

We aspire to illustrate the relevance of our results with respect to policy making and potential economic consequences. Our computational approach provides useful information on air pollution mapping in the EMEP area, early warning, risk awareness in an eco-framework, in order to set the directions for pollution control policies. Moreover, policies that reduce the associated social costs, damage costs, climate change costs.

This paper is organized as follows. Section 2 briefly presents the software and the data overview. The visualization tasks are described in section 3 followed by a detailed discussion of our structural analysis of transboundary pollution data in Section 4. Section 5 concludes the paper.

2. Software and data availability

Gephi is a cross-platform application, as it is developed in Java (Bastian et al., 2009). It is successfully tested on many different architecture, OS and graphical configuration. Gephi requires Java version 7 and later (https://gephi.org/). Gephi can import several standard file formats of data files (among them CSV and spreadsheets).

Data sources are emissions-depositions (or source-receptor) tables of air pollutants (see table 1), available online from the data repository of the European Monitoring and Evaluation Program (EMEP) of the Long-Range Transmission of Air Pollutants in Europe. Access to the source-receptor relationships by country of sulphur and nitrogen, ozone and particulate matter (PM) for period 2004-2016 is possible through the EMEP database[1]. The data are generated by source-receptor calculations, where emissions for each emitter of one or more precursors are reduced by 15%. For oxidized sulphur, oxidised nitrogen and reduced nitrogen, the results have been scaled up to represent the entire emission from an emitter. The calculations are based on a consistent series of model runs, all using the EMEP/MSC-W model

[1] http://emep.int/mscw/index_mscw.html

version rv4. The data files are given in a semicolon separated CSV format. Data used throughout this paper concern 49 land areas from the extended EMEP domain.

3. Visualization Tasks

There are different visualization tasks for SR data analysis, which can be classified into four categories:

- Pinpoint air pollution emitters and receptors,
- Report the variation of rankings for polluters and pollutees according to 13 different pollutants.
- Compare different regional pollution blocks (e,g, in different geographical zones). Similarities and differences between different regions are always of great interest.
- Reveal the blame and/or damage of a country to another, in terms of transboundary air pollution. This is a way of assessing distributional impacts of transboundary air pollution.

4. Visualization Modules

In the existing literature and the EMEP reports, transboundary air pollution data are presented in the form of maps, pies and bar charts (EMEP report, 2016). Here we exploit two popular graphic methods for visualizing high dimensional data: networks and heatmaps. Other innovative visualizations for air quality data have been reported in (Orudjevet al., 2016; Qu et al., 2007; Kanemoto et al., 2014; Carslawa et al., 2012).

Table 1: Data Attributes included in SR table, all in the extended EMEP domain

Pollutant / indicator	Unit
Deposition of OXS (oxidised sulphur)	100Mg of S
Deposition of OXN (oxidised nitrogen)	100Mg of N
Deposition of RDN (reduced nitrogen)	100Mg of N
PM2.5 Effect of a 15% reduction in PPM emissions	ng/m^3
PM2.5 Effect of a 15% reduction in SOx emissions	ng/m^3
PM2.5 Effect of a 15% reduction in NOx emissions	ng/m^3
PM2.5 Effect of a 15% reduction in NH3 emissions	ng/m^3
PM2.5 Effect of a 15% reduction in VOC	ng/m^3
$AOT40_f^{uc}$[2]. Effect of a 15% reduction in NOx emissions	ppb.h
$AOT40_f^{uc}$. Effect of a 15% reduction in VOC emissions	ppb.h
SOMO35[3]. Effect of a 15% reduction in NOx emissions	ppb.d
SOMO35. Effect of a 15% reduction in VOC emissions	ppb.d

4.1 Graph modelling

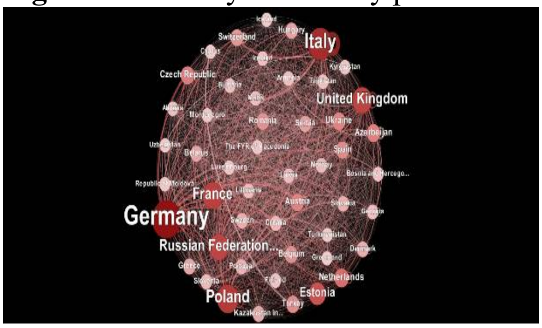
Our visualization module is based on graph theory. The countries can be interpreted as nodes and pollution relationships among them as edges in the network, thus to have the whole system transferred into an Input-Output network, which could quantify the interdependency among differed countries. The network visualization and exploration software is good at revealing the underlying structures of associations between EMEP countries (known also as "link analysis"). It permits the user to estimate and visualize the degree of responsibility of polluters and create the country-to-country blame network (figure 1 a,c). The user can also estimate and visualize the degree of exposure of pollution victims (figure 1b,d). By considering the strength of the interrelations, we indicate air pollution hotspots. Outcoming edges represent emitters' output and incoming edges represent receptors' input. The edge weights used are the levels of pollutants. The weighted degree and the weighted in- and out-degree (Barrat et al., 2004; Newman, 2001; Opsahl et al., 2010; Jiang et al., 2019) is calculated to investigate the structure of the network. Countries responsibility for pollution is measured by weighted-out degree of each node. Countries exposure in

[2] Accumulated amount of ozone over the threshold value of 40 ppb
[3] Sum of Ozone Means Over 35 ppb

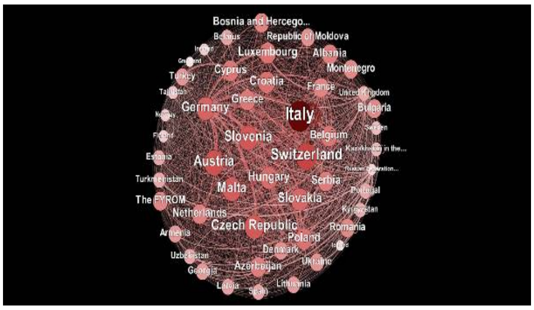
pollution is measured by weighted-in degree of the pollution network. The possibility to rank countries in order of increasing responsibility (in terms of their weighted-out degree) or vulnerability (in terms of their weighted-in degree) to air pollution is always an option (figures 5-6).

Gephi provides an interface for filtering nodes and edges (Heymann, 2015). The degree filter matches nodes with a degree that falls within the given minimum and maximum values, inclusive. A user can choose whether the filter operates on the in-degree, out-degree or overall (in + out) degree (see indicatively figure 2). Narrowing filters are applied to the entire network (figure 3b), and are used to select a subset of nodes or edges in a network based on user-specified constraints (figure 4a-f). Filtering options in figure 4 bring out the distribution of the top 9 pollutees per geographical zone.

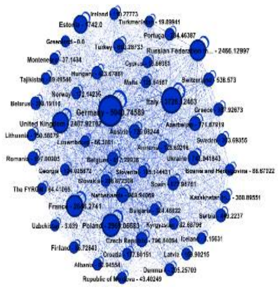
Figure 1: Country-to-country pollution network (pollutant: AOT40NMVOC, 2013)



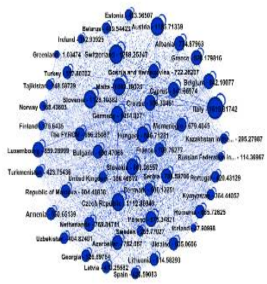
(a) Size of node, name and color intensity is analogous to emitters' responsibility



(b) Size of node, name and color intensity is analogous to receptors' exposure

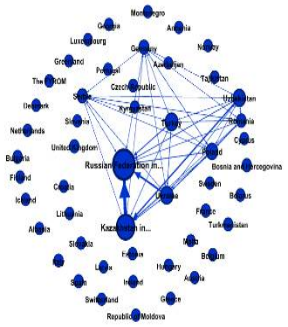


(c) Emitters' responsibility in numbers

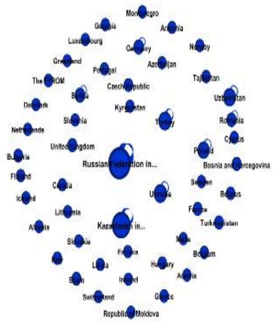


(d) Receptors' exposure in numbers

Figure 2: Filtered pollution network (pollutant: SOx, 2013, metric: weighted-out degree). Size of node and name is analogous to polluters' responsibility

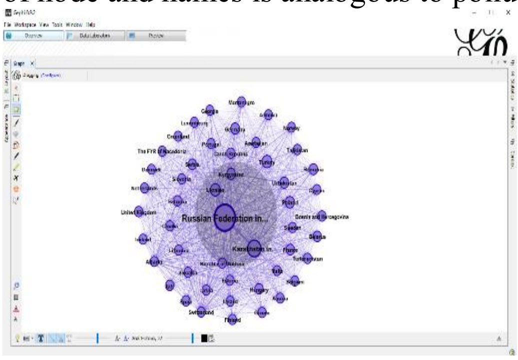


(a) Pollution interactions among top 9 polluters in the global pollution network

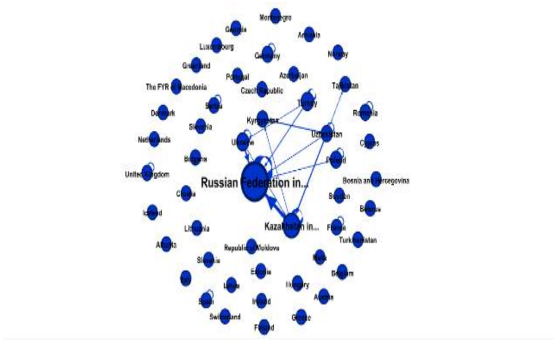


(b) Self-loops are used to depict pollution exposure of top 9 polluters. Numbers denote oxidised sulphur depositions in 100 Mg of S

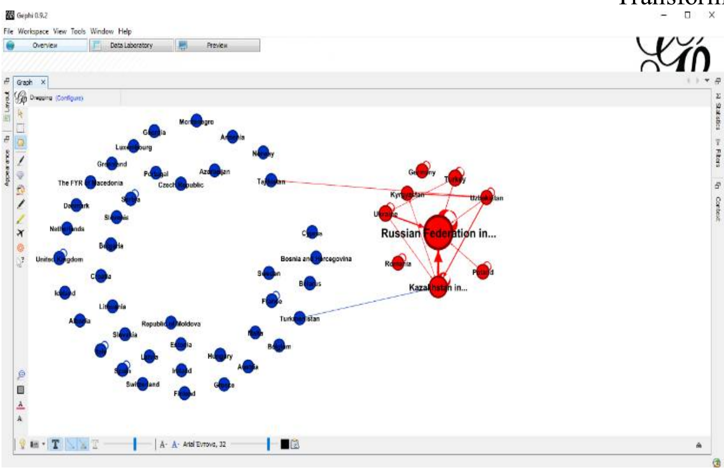
Figure 3: Gephi options to make the global pollution network more manageable**.** Size of node and names is analogous to pollutees' SOx exposure.



(a) Focusing on a certain area of the global source-receptor SOx pollution scheme

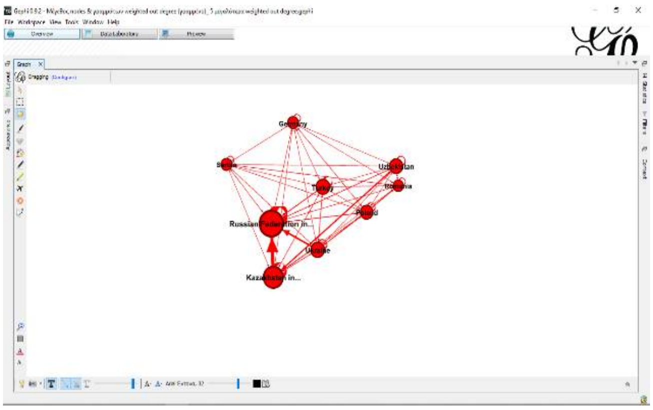


(b) Filtering the SOx pollution network: selecting edges with weight≥300 (units: 100 Mg of S) with Edge Interaction Transformer

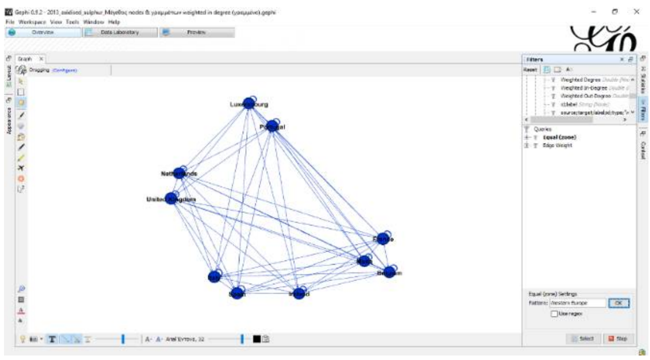


(c) Isolating a subset of nodes based on user-specified constraints (here the top 9 pollutees)

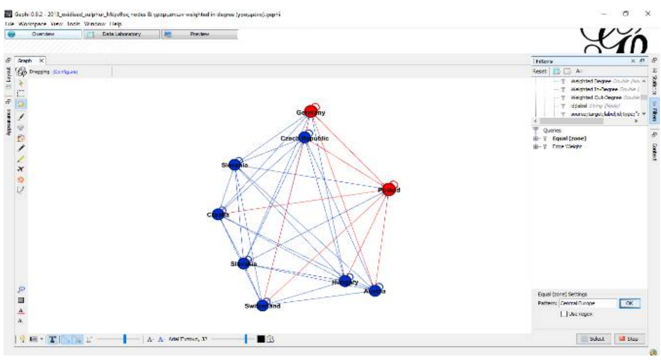
Figure 4: Disconnecting the global pollution network. Size of node and name is analogous to pollutees' SOx exposure for 2013



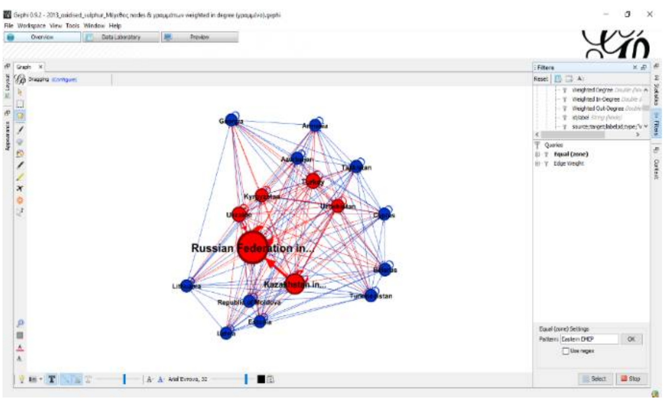
(a) top 9 pollutees in red



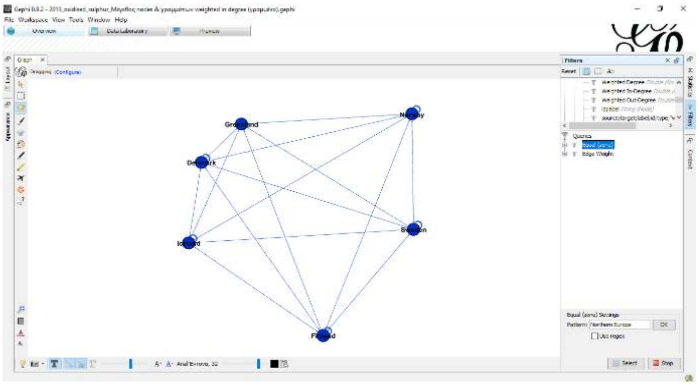
(b) Western Europe



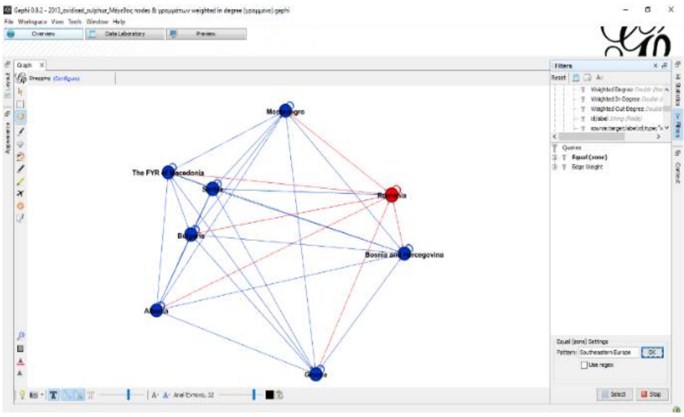
(c) Central Europe



(d) Eastern EMEP area



(e) Northern Europe



(f) Southeastern Europe network

Figure 5: Ranking the emitters of the extended EMEP area (metric: weighted-out degree). Horizontal bars chart was obtained using Tableau (Tableau, 2014)

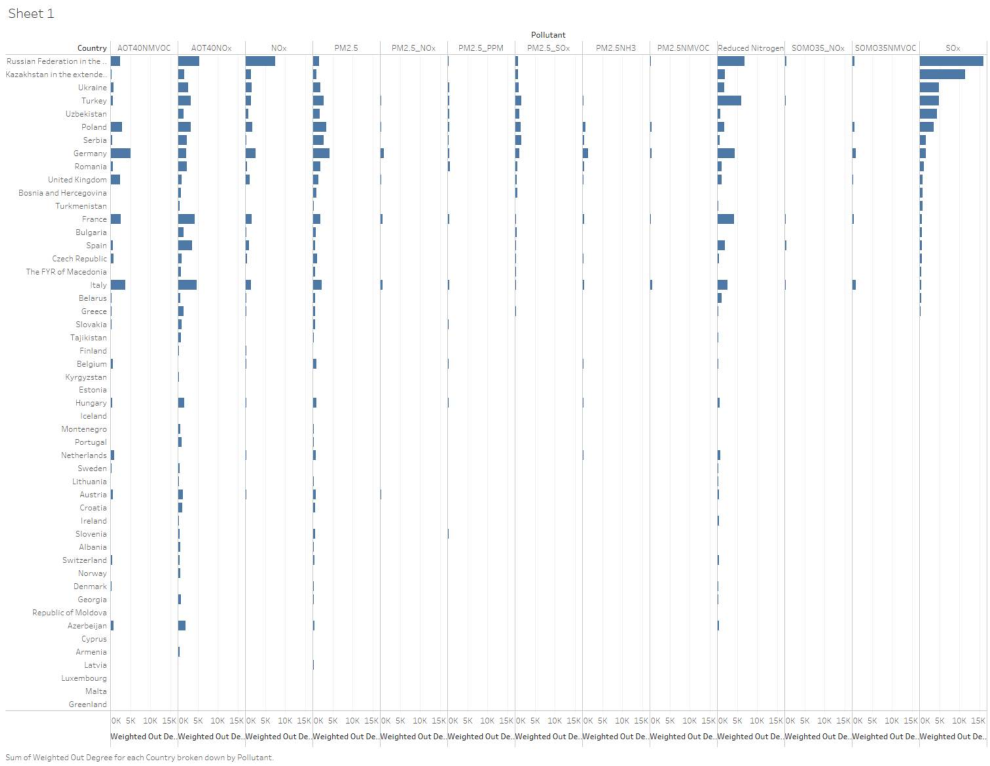
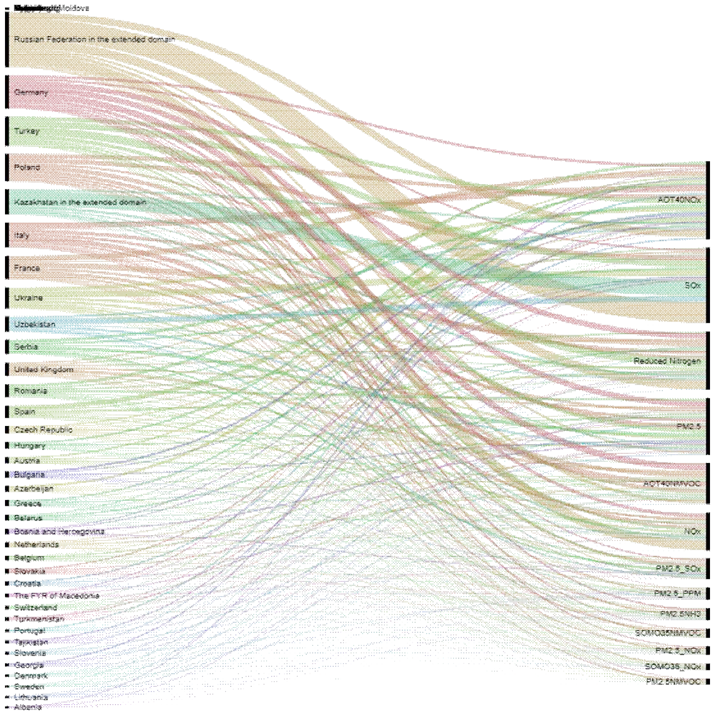


Figure 6: Ranking polluters and pollutants of the extended EMEP area (metric: weighted-out degree). Alluvial diagram was obtained using RAWGraphs (Mauri et al., 2017)



5. Conclusions

This paper mainly focuses on how countries interact within the SR pollution scheme and how the pollution providers spread their pollution. EMEP data are adopted to establish inter-country input–output tables and create graph models and tabular representations. The SR transboundary air pollution system for any pollutant are so interconnected that the polluters affect almost all countries. The SR tables are presented in a way to indicate the major pollution effects in the global pollution tabular scheme. For central planners, graph modelling could be a tool for policymaking. For governments and regional planners, ranking lists provide concise directions on which countries to blame and which to protect.

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