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# EXPLORING EFFECTIVE STRATEGIES: AN ANALYSIS OF EUROPEAN AVIATION NETWORK AND RESTRICTIVE MEASURES TO CONTROL PANDEMIC OUTBREAKS


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# 1. ABSTRACT

During the COVID-19 pandemic, governments faced immense pressure as they implemented drastic measures to combat the spread of the virus. One urgent issue that emerged was the reopening of borders between countries. This need arose due to a variety of reasons, including economic, social, humanitarian, and diplomatic considerations. This study aims to delve into the role of the aviation network in the spread of epidemics, with the goal of determining the most effective restrictive measures to prevent a pandemic outbreak.
To achieve this objective, a SEIR-ABM is applied. The model examines five distinct scenarios, comparing them to the baseline scenario where no restrictions are imposed. By doing so, the study aims to comprehensively analyze the impact of various restrictive measures implemented in order to effectively understand their effects on the overall dynamics of the pandemic.
The findings reveal that implementing a full lockdown is the most effective measure in combating the spread of the new epidemic followed by the implementation of quarantine for symptomatic individuals, probably a more viable solution, also from an economic and social perspective. Moreover, this study will show that the starting airport where the first infected individual is placed does not seem to be relevant and, in addition to this, it will also show that promptness in taking actions is crucial to prevent a pandemic from spreading.

# 2. KEYWORDS

SIR Model, SEIR Model, Agent-Based modelling, air traffic network, pandemic, interventions to prevent disease's spreading over aviation network.

# 3. INTRODUCTION

The aviation network allows people to travel quickly over long distances. As a matter of fact, with just a few hours, one could potentially travel across any two cities on the European continent. This connectivity improves people's quality of life and enables them to live several memorable experiences. Though, in the case of a pandemic or a contagious disease in general, this easiness of movement could be a severe risk. Indeed, as people can move faster from country to country also viruses can, and, hence, spread easier between them. This is why, in the modern era, pandemics cannot be considered as a rare phenomenon: SARS, EBOLA and COVID are just few examples of the pandemics people have experienced in past years.
The interdependence and the interconnectivity of different countries can cause the escalation of an epidemic born in one part of the world into a global health crisis. Therefore, international collaboration, data sharing, and coordinated response efforts are crucial to effectively manage and mitigate the spread of contagious diseases. This is only possible if governments can rely on strong studies and accurate models able to simulate prospects of spreading the epidemic according to different containment measures. The purpose of this project is to try to fill this need: a structured epidemic-spreading model for the European aviation network is proposed and several different scenarios will be analyzed to better understand the entity of possible containment measures. The aim is to define a model which, even under necessary assumptions, gives a view as complete as possible about the specific role of the flights network on the spreading of an epidemic. A combined SEIR-ABM model fits the described purpose since a variation of the classic compartmental model is extended considering the mobility factor of the agents and the possible interactions between the latter. Hence, in the following discussion, all agents will be divided into four mutually exclusive compartments (Susceptible (S), Exposed (E), Infected (I), and Recovered (R)) so as to better model and understand the progression of

the disease under analysis. Then, as will be later explained, ABM components will also be added so as to account for spatial-temporal dimensions.

The aforementioned interconnectedness of economies involves the movement of people, products, and resources. COVID-19 has shown how restrictions on international travel and trade can have economic, social and psychological impacts. As a matter of fact, the global supply chain can be disrupted since the international trade may face challenges in accessing inputs or reaching their customers. A good balance between implementing necessary restrictions and minimizing the adverse effects on different aspects of society and economy is a complex challenge for institutions and governments. This makes the proposed paper worthy of an in-depth study and of further analysis.

For all the aforementioned reasons, the research questions that this paper seeks to answer are: which is the role and the contribution of the flight network in epidemic spreading and how can this effect be mitigated by governmental restrictions? In particular, which are the most effective measures and why?

Therefore, the following study tries to fill a gap in the literature by analyzing the role of a complex network, like the aviation one, in the epidemic spreading in the European area trying to capture the effect of both symptomatic and asymptomatic agents. In the context of previous literature, it brings a new note to the discussion on the topic since many studies have been made to answer a similar question but using different approaches or setting the discussion on a different world area (mostly India and China). Also, the inclusion of symptomatic and asymptomatic agents and the development of an entire scenario on the possible quarantine measure for the former, is an element of distinction with respect to the studies prior to the COVID-19 outbreak, since this specific health condition is strictly related to this latter pandemic experience.

## 4. BACKGROUND AND LITERATURE REVIEW

This paper aims to define a model that can be a source of comparison with the real flow of last pandemics trends but also a starting point for future policies in case of new epidemic outbreaks. The purpose is a consequence to the need of a good organization within and across countries, essential to cope with a COVID19-like new epidemic outbreak. Knowing the spreading characteristics of a possible epidemic and the effect of an eventual restriction on population movements is crucial for policymakers, healthcare systems and communities to give a planned and conscious contribute to the definition of a coordinated response. Understanding the potential flow of a pandemic could permit to deal in advance with resource allocation, implementing contingency plans and communicating clear and accurate information to the public. With reference to the latter, COVID-19 has shown how much interpersonal and institutions trust is relevant to implement restrictive measures that would affect everyone's ordinary life and for the scope of this paper, the reference is to the travel restrictions in an aviation network. A scientific-based study could help to plan the fight against the epidemic, leading to a more moderate political debate during the emergency period and consequently to a more efficient and timely-stance making for what concerns the protection of public health and the impact of the pandemic. The latter consideration gives credits to a central trade-off, the one between the need of time and the pressing need for the economy to operate; indeed, travel restrictions on communities could be a good tool to address the epidemic spreading, giving to the scientific enterprise time to find solutions to the health crisis. However, meanwhile a total travel ban could not be a wise solution for the good of the economy since it could deteriorate the supply chain, leading to an additional crisis other than the health one: the economic one.

This study aims to help developing a good basis for further decisions taken by institutions and governments about flights restriction in case of a new epidemic, providing already-planned

scenarios for which consequences are already known and do not need more time for investigation, in order to reach a good balance between the two mentioned needs.
For this reason, it could be useful to know in advance the contribution that the flight network could give to the epidemic spreading and to perform a risk estimation of reducing flights restrictions according to the magnitude of their effects to the epidemic fight.
Since the strong political and economic pressure for governments to lift the air travel restrictions and to reopen borders during the COVID-19 pandemic, it is easy to understand the cruciality of the topic.
Different, but few, studies have been made on the epidemic spreading in an aviation network; they were fundamental to push the analysis even deeper to create a model as complete and as realistic as possible.
One main challenge was to understand the relation between the start of the spread of a new epidemic and the travels, and to estimate the likelihood of an outbreak caused by imported cases (Incorporating dynamic flight network in SEIR to model mobility between populations" Xiaoye Ding et al., 2021). The main purpose of the just mentioned paper was to answer to those questions in a dynamic Flight-SIR modeled environment considering flights to and from Canada.
According to the great impact vaccines had in the fight to the pandemic, Brooks Bulter et al (2021), in "The effect of population flow on epidemic spread: analysis and control", tried to evaluate the effects of a combined strategy including the restrictions on travel flows and the vaccine distribution, assuming fixed sub-populations in a SEIR model.
Richard J. Post et al (2021) with the paper "How did governmental interventions affect the spread of COVID-19 in European countries?" also introduced the distinction between tested and non-tested agents, since a COVID similar infection could cause a person to be infectious even without any symptoms. The following study shows a little variation from the just mentioned according to the characteristics of patients affected by COVID and the related distinction between symptomatic and asymptomatic agents. Here, the significant challenge was to capture the impact of these two different groups in the epidemic spreading.
To develop a model able to consider the spatial aspects of the spread and to track movements and contacts between individuals in different geographic groups, different studies were based on some kind of variations of the SIR model. Raul Goel et al (in "Mobility-based SIR model for complex networks: with case study of COVID-19 ", 2021) took into consideration connectivity and mobility factors among various regions of the world in a SIR model to study a fully-mixed and a complex network models which take into account real-life interactions. Compartmental models alone are insufficient to capture the intricate interconnectivity between various regions worldwide and the distribution of the population (Chinazzi et al. 2020).
Liliana Perez et al. proposed "An agent-based approach for modeling dynamics of contagious disease spread" (2009) in which an agent-based model is combined with the geographic information system (GIS-agent-based model) to simulate an epidemic spreading in an urban environment. The result confirmed the role of the dynamic-spatial interaction within different agents in the spreading of the disease. Indeed, extensive evidence shows that the dynamic spatial interactions within the population result in a significant concentration of exposed individuals in specific geographical locations, such as schools and universities, where they engage in stationary activities after commuting.
Nabil Iqbal reached some interesting qualitative findings related to the role of the travel network in the spreading of a disease. The study showed that the dynamics of the network only affect the rate of onset of the disease, while the magnitude of the infection does not depend on the connectivity network but on the internal dynamics characterizing each node. This leads to the conclusion that imposing travel bans altering the structure of the air connections could not be useful to fight the disease propagation, while a good and quick treatment of the infectious

people might turn out to be a more useful measure. ("Disease Propagation on a Network: Pandemics in the Era of Air Travel", 2009).
A different study was also conducted by David Diener, Rafael Dubach, Layla Husselman, and Kevin Kindler at Zurich University in 2022. They analyzed the spread of a pandemic over a flight network using network science techniques, with the goal of identifying the most critical airports for controlling the spread of a pandemic. A spreading simulator allowed to mimic the real-world situation in case of the more critical airports would be closed for a while.
The findings presented in the aforementioned papers open up avenues for additional analysis and potential new discoveries. This paper aims to employ a combined SEIR-ABM approach to simulate the real-world phenomenon of epidemic spreading through air travel. The primary objective of this study is to build upon previous research in the literature and delve deeper into its main findings, introducing a fresh approach and novel study outcomes.
The assumptions, the detailed structure of the model, and its main findings will be better defined in the next sections.

## 5. THE MODEL

As mentioned in the previous sections, this paper aims at modeling the contribution of the aviation network towards the diffusion of a new COVID-like pandemic and exploring different intervention scenarios. To do so, the spread of a new infection will be analyzed, over the 49 most crowded European airports, for the period January-April 2023.
For the sake of this analysis, a SEIR model with Agent-Based Model components will be used. As a matter of fact, combining compartmental models with an ABM framework allows for a more detailed and dynamic representation of individual behavior and interaction within the network. Indeed, having single agents which move and interact on a network grid enables to track some of their attributes such as current location, travel pattern, and infection status. This allows for a better modelling of human behavior and, thus, of the pandemic overall. On top of this, using a SEIR-ABM gives the possibility to incorporate both temporal and spatial heterogeneities. When dealing with the aviation network, both time and place are fundamental variables. As a matter of fact, connections within cities are variable, not every airport is connected and, even if two airports are linked, there could be days in which they are not. If the final goal is to model the spread of a pandemic through the aviation network, it is thus important to know precisely which routes are operated on a certain day and which are the agents who can potentially travel from a specific source to a specific destination.
Moreover, ABM are highly flexible and hence can be useful when running scenario analysis, as will be in this paper's case. Indeed, both the model and the agents' classes can be modified and adapted so to account for possible interventions and measures. In this study, in particular, six different scenarios concerning various interventions will be tested. A brief summary can be found in the table below, though they will be deeply explained in the results section in which a focus for each scenario is presented.

| Scenario | Description |
|---|---|
| 1 | Baseline, no intervention |
| 2 | Quarantine for symptomatic infected individuals |
| 3 | Quarantine for symptomatic infected individuals and closure of the most connected airports |
| 4 | Closure of the most connected airports |
| 5 | Quarantine for symptomatic infected individuals and introduction of an obligation to wear protective face masks in public |
| 6 | Total lockdown |

Table 1: scenarios analysed in the paper

In all the scenario cases, the introduction of the restrictive measure will take place only after the percentage of infected and symptomatic individuals surpasses the threshold of 0.05% and after an "adaptation week". As a matter of fact, the WHO has established this percentage as an alert threshold (Ding X. et al, 2021). Still, introducing restrictions may take a bit of time due to bureaucratic reasons and, hence, the real day of the beginning of the containment measures of the particular scenario will start a week after the surpassing of the threshold (the "adaptation week"). Here, there is the assumption that, given the recent experience with COVID-19, governments and institutions may act more rapidly in response to a possibly new threat compared to the time they took back when the first cases of COVID-19 were spreading.
Additionally, Agent-Based Models can well incorporate real world data. As a matter of fact, by utilizing available data on air travel patterns, population distributions, infection rates, and other relevant variables, the proposed model can be grounded in empirical observations, making the model outcomes more reliable and applicable to real-world situations.
On its hand, the SEIR component of the model allows to analyze agents as belonging to distinct compartments, thus enabling a clear understanding of the progression of the disease. Moreover, having the Exposed compartments allows for a better approximation of reality. Indeed, most contagious diseases have an incubation period in which the individual is nurturing the disease and hence, even if he/she/they already contracted it, he/she/they cannot yet transmit it to other individuals.
From a mathematical point of view, the model will be characterized by the following equations, which concern the dynamics of the pandemic for every airport $i$ under analysis. The first set is for scenario 4, and for scenarios 2, 3, 5, and 6 until the introduction of the restrictive measure, whilst the second one is for scenarios 2, 3, and 5 after the imposition of the restrictive measure. Indeed, when there is no imposition of quarantine, as in the case of scenario 4, there will still be the possibility to travel for all agents, irrespective of the compartment they are in. Moreover, in the case of scenario 6, after the imposition of the full lockdown, no agent will be allowed to travel or to infect others, agents will indeed only be allowed to recover if they have been previously infected whilst the measure was not yet in place. In the case of scenario 1 instead, given that no intervention is taken, the split between symptomatic and asymptomatic infected individuals was not performed. Hence, in this scenario, equations are the same as the first set of equations if not for the fact that there is no split in the I compartment and, hence, there is only one equation for it (there is no split according to ρ).

$$\frac{\partial \mathrm{S_i}}{\partial \mathrm{t}} = -\frac{\beta}{\mathrm{N_i}} I_{A_i} \mathrm{S_i} + \sum_{\mathrm{j}} \mathrm{S_{ji}} - \sum_{\mathrm{j}} \mathrm{S_{ij}}$$

$$\frac{\partial \mathrm{E_i}}{\partial \mathrm{t}} = +\frac{\beta}{\mathrm{N_i}} I_{A_i} \mathrm{S_i} - \delta \mathrm{E_i} + \sum_{\mathrm{j}} \mathrm{E_{ji}} - \sum_{\mathrm{j}} \mathrm{E_{ij}}$$

$$\frac{\partial \mathrm{I_{A_i}}}{\partial \mathrm{t}} = \rho\delta \mathrm{E_i} - \gamma \mathrm{I}_{A_i} + \sum_{\mathrm{j}} \mathrm{I_{A_{ji}}} - \sum_{\mathrm{j}} \mathrm{I_{A_{ij}}}$$

$$\frac{\partial \mathrm{I_{S_i}}}{\partial \mathrm{t}} = (1-\rho)\delta \mathrm{E_i} - \gamma \mathrm{I_{S_i}} + \sum_{\mathrm{j}} \mathrm{I_{S_{ji}}} - \sum_{\mathrm{j}} \mathrm{I_{S_{ij}}}$$

$$\frac{\partial \mathrm{R_i}}{\partial \mathrm{t}} = \gamma\left(\mathrm{I_{S_i}} + \mathrm{I_{A_i}}\right) + \sum_{\mathrm{j}} \mathrm{R_{ji}} - \sum_{\mathrm{j}} \mathrm{R_{ij}}$$

Equations 1: SEIR model for scenario 4 at any time and 2, 3, 5, and 6 until the introduction of the restrictive measure

$$\frac{\partial S_i}{\partial t} = -\frac{\beta}{N_i} I_{A_i} S_i + \sum_j S_{ji} - \sum_j S_{ij}$$

$$\frac{\partial E_i}{\partial t} = +\frac{\beta}{N_i} I_{A_i} S_i - \delta E_i + \sum_j E_{ji} - \sum_j E_{ij}$$

$$\frac{\partial I_{A_i}}{\partial t} = \rho\delta E_i - \gamma I_{A_i} + \sum_j I_{A_{ji}} - \sum_j I_{A_{ij}}$$

$$\frac{\partial I_{S_i}}{\partial t} = (1-\rho)\delta E_i - \gamma I_{S_i}$$

$$\frac{\partial R_i}{\partial t} = \gamma\left(I_{S_i} + I_{A_i}\right) + \sum_j R_{ji} - \sum_j R_{ij}$$

Equations 2: SEIR model for scenarios 2, 3, and 5 after the imposition of the quarantine for symptomatic individuals

In the equations above, on top of the standard elements of SEIR equations, there are the summation terms as well as the inclusion of a distinction between symptomatic and asymptomatic within the infected compartment, hence, the model at hand is an extension of a SEIR model. Summation terms indicate the incoming and outgoing flows from the specific airport under analysis. As a matter of fact, given that individuals can travel in between airports, it was necessary to account for shifts of chucks of individuals from one place to another. It has to be noted that, for the sake of this analysis, the unit of interest are the single airports, and not the whole city in which they are located. This is a common assumption also in the literature as modelling inflows and outflows from airports would require modelling the city at large. As a matter of fact, some agents may leave the airport and stay in the city forever, some may move to other cities without entering an airport again, or some can stay just for few days and then go back home via the aviation network. Because of this, an extensive tracking of individuals into cities would be necessary. Thus, to simplify the problem at hand without scarifying the reliability of the analysis, airports have been considered as microenvironments which should, in a way, mimic what is happening at large in a city or state. Moreover, it was also assumed that there is neither birth nor death rates. This was done since including birth rate would have meant to allow inflows from cities to airports, with the problems it brings as mentioned before. When it comes to the death rate, as also seen from literature, the effect would be marginal in such a short window of time and, moreover, introducing a death rate without having a birth one would have led to some consistency issues.
To sum up, a baseline case will be defined and then several intervention scenarios will be tested so as to assess which one seems to perform better given the particular characteristics of the epidemic. Moreover, more different starting points for the pandemic will be considered as a way to verify whether this is significant in determining its evolution or not.

## 6. DATA ACQUISITION AND PARAMETERS USED

To carry out the aforementioned analysis, it was necessary to obtain flight data for the period under analysis, namely January-April 2023. To do so, web scraping was applied and, in particular, the FlightLabsAPI was used as it was found to be the best performing one amongst the ones tried. This web API provides data about flights and their status. More in depth, a list of the 50 most crowded passengers was taken as reference (Top 100 Biggest and Busiest Airports in Europe | GetToCenter, 2022) and all the flights departing from those airports were

obtained via the above-mentioned API. It was deemed appropriate to consider only the top 50 airports in Europe as these represent the vast majority of all passengers flows within the continent (in the final analysis only 49 will actually be considered as the API did not have any information for Berlin's SFX airports). Data scraped include the departure day, the departure time, the arrival time, the source airport, the destination airport, and other flight specific information such as the company operating the flight.
The data obtained via several API requests was then filtered out according to the specific needs of the analysis. More in detail, cargo flights were removed as they do not carry any passengers and hence are not meaningful for the analysis of this paper. On top of this, it was also necessary to remove all the code-shared flights. As a matter of fact, the FlightLabs API returned multiple data points for the same flights if it was in codeshare. Codesharing is a practice in the airline industry where two or more airlines jointly market and operate a flight under their own airline codes (typically referred to as the IATA airline codes). This means that passengers can book a flight with one airline, but the actual flight may be operated by another airline. Given that, for the sake of the analysis, it was necessary to identify the total number of flights in between two airports, as this will be used to compute the probability of moving from one airport to another as will be later explained, having duplicate flights would have biased results and, hence, all duplicate flights were removed and only the main flight operated by the true company (meaning the one whose plane was actually used) was kept.
Thanks to the data collected in this way, it was possible to create a scheme of the aviation network in which nodes represent airports and edges connect airports if there is a direct flight between them. This network, displayed in the picture below, was then used inside of the MESA Model's class as grid over which agents move and perform their steps.

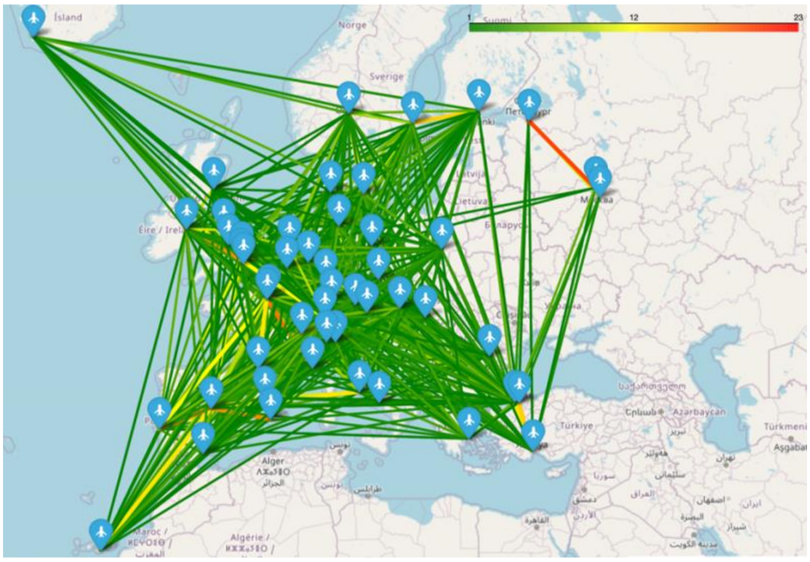


Figure 1: Network of top 50 European airports on the 1st of January 2023

When it comes to the parameters governing the overall epidemy, some were determined via the collected data on flights while others were obtained from previous literature. The main reference of analysis are parameters calibrated on COVID-19 as this was the most recent epidemy and was the one that paralyzed Europe for several months. The choice to take parameters directly from literature and not recalibrating them was taken since precise data on spreading of epidemies via the aviation network was not available. Hence, using parameters calibrated by experts on several thousands of data seemed a more viable solution. This approach was taken for values, like the average duration of the disease or the effectiveness of face masks, which tend to be more stable across applications and much more disease dependent. For the infectivity rate, a much more application-specific parameter, a different approach was taken. In particular, given that, when it comes to the aviation network, no precise indication about the values concerning the infectivity rate of COVID-19 were available in the literature, it was deemed appropriate to experiment more values and see how results changes with a varying infectivity rate. As a matter of fact, as this rate largely depends on the average number of contacts individuals have, taking an infectivity rate from another environment (e.g., another continent or social situation) would not lead to significant results. On top of this, COVID-19 data related to the aviation network were not available in an open-source format and hence it was not possible to calibrate this infectivity rate via techniques such as MCMC or MLE. As a starting reference value, the one by Barnett et al (2022) was used. In particular, they estimated what is the percentage of infections which happened on flights in the domestic US airplane routes. Even if this value is not an infectivity rate as intended in a standard SEIR model, it was used as a starting point as was the only available reference in the literature when it comes to transmission rate in the context of the aviation network. Moreover, domestic US flights display several common characteristics with European ones. For instance, they have approximately the same average duration. Passengers' flows are also comparable. Still, this remains an approximation given that the US implemented different restriction policies compared to the EU. It is also for this reason that several infectivity rates were tested in this paper's analysis. Even if they might seem too contained, it must be considered that contacts, when it comes to airports and aircrafts, are not so extensive as they might be in other environments such as schools or workplaces. Moreover, in the airports' case, the assumption of homogeneous mixing quite well matches reality.

A summary of the parameter used in the different scenarios of the model and of how they were obtained is presented in the table below:

| Parameter | Value | Source |
|---|---|---|
| **β (Infectivity Rate)** | Values ranging from 0.0001 to 0.1 | Values from "Covid infection risk on US domestic airlines" (Barnett A. et al, 2022) are taken as a proxy of the infectivity rate |
| **γ (Recovery Rate)** | 1/6.6 | Average recovery rate from an epidemiological investigations detected over 500 cases (Cereda D. et al, 2021) |
| **δ (Incubation Rate )** | 1/3 | European Centre for Disease Prevention and Control, 2022 |
| **ρ (Probability of becoming symptomatic)** | 75% | Average of several different papers, one of which is "Asymptomatic versus symptomatic SARS-CoV-2 infection: a cross-sectional seroprevalence study", El-Ghitany et al, 2022 |
| **Movement to specific airport** | Day dependent vector of probabilities | Devised from flight data |
| **Compliance with wearing facemasks** | 61% | Average of compliance in 35 European countries (Spira B., 2022) |
| **Infectivity reduction due to facemasks** | 25% and 55% | 25% (Leech et al, 2022)<br>55% is the average from (Ueki et al, 2020) |

Table 2: Parameters used in the analysis

In particular, the vector of probabilities governing the movement of agents between airports is computed for every day of the simulation as the number of flights going from the particular source airport to the particular destination airport over the total number of flights departing from the source airport. So, for instance, if on the 1st of January there are 10 flights departing

from MXP (Milan Malpensa) and 3 of which are for FCO (Rome Fiumicino), then the probability of moving from MXP to FCO for an agent which is at MXP is equal to 30%. In this respect, a further adjustment has been made. Indeed, in real life it is very likely that people fly to one particular city and, after some days, return to their airport of origin. To account for this in the model, before drawing a destination from the list of connected airports with probability governed by the aforementioned vector of probabilities, each agents has an 80% probability of moving home (if he/she/they is not already there). If this does not realize, and hence it falls it the 20% of cases, then a draw from the entire list is performed. The percentage of 80% was set arbitrarily since no precise indication was available in the previous literature. Moreover, each agent, upon inclusion in the model, was assigned a random time sleep drawn from a normal distribution with mean 3, which represents the average stay in a European city. This was done to account for the fact that, usually, individuals do not take flights everyday, but rather spend some time in a destination once they reach it before moving again.
As it can be seen from the table, parameters governing the reduction in the infectivity of the disease due to the introduction of face masks take two different values. Every scenario simulation will be run with both values of the parameters. This choice was taken since identifying a unique value in previous literature was a though challenge. Indeed, most states introduced mandatory face masks as an additional containment measure on top of other measures (such as vaccines or quarantine for infected individuals) and, hence, it is a hard task to isolate the effect generated by the usage of face masks alone. The two papers mentioned in the table try to do it, but provide two very different measures, thus, it was deemed appropriate to run the scenario analysis with both these values.
On top of the above, initially, each airport was allocated a number of passengers equal to the average flights departing from that airport in the period under analysis (computed from the data scraped above) multiplied by 170 (which is the average capacity of an Airbus320 and a Boeing737, the two most used planes to perform intra-Europe flights) multiplied by the average occupancy rate of an aircraft which was set to be 70%, as many different researches list it to be within 65% and 75%. The above, in formula, translates to:

$$Capacity = Avg\_Flights \cdot 170 \cdot 0.7$$

This number will then be scaled by diving the capacity of each airport by 5. This is done just for computational efficiency as having the model with the full sets of agents requires a long time to run. Still, results should not change that much because of this as the approximate shape of the curves, and hence the dynamics of the epidemic, should remain relatively stable. Clearly, the provided code is general and hence can be rerun adjusting this scaling parameter. Though, having attempted more than one of them (always keeping fixed the ratio between initial number of susceptible individuals and initial number of infected individuals) has proven not to change the relative results regarding the efficiencies of the various interventions.

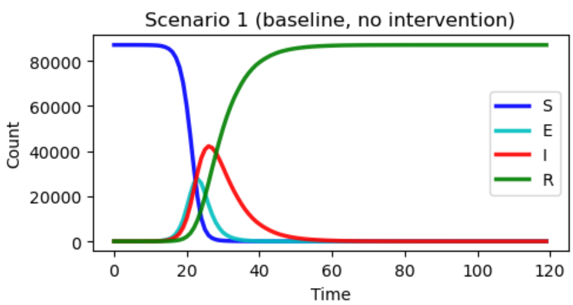
## 7. RESULTS

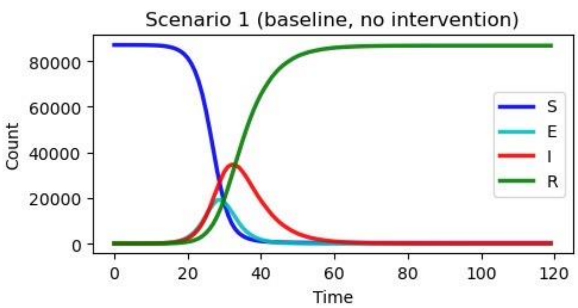
In this section, results obtained in the different scenarios under analysis are presented and compared so as to properly identify which are the most suitable measure to reduce the impact that the aviation network could have on the diffusion of a new pandemic in the European continent as the value of the infectivity rate varies.
When it comes to the infectivity rates tested, the values 0.01, 0.005, 0.001, 0.0005, and 0.0001 were used. In the results' discussion below, though, only 0.001 and 0.0005 will be taken into consideration and discussed. Indeed, on the one hand, using 0.01 or 0.005 makes the pandemic spread too quickly and all the measure hypothesized in this paper have no effect and the disease

reaches the entire population sooner or later. Clearly, this is also due to the fact that the "adaptation week" was included and the measures were not introduced immediately after the surpassing of the alert threshold. Still, this "adaptation week" was left since it is unrealistic to assume fewer days for governments/institutions to react. On the other hand, using 0.0001 makes the infection rate too low for the infection to scale and move between individuals. Therefore, if the infectivity rate is that low, there is no need for any intervention.
In all the scenarios, the epidemy started with a single infected individual positioned in Frankfurt Airport, an averagely connected location. Still, results, as will be later discussed, proved not to be sensible to the starting airport.

## 7.1. SCENARIO 1 – NO INTERVENTION

In this scenario no action is taken by governments or institutions. Therefore, the epidemic is free to evolve and spread from agent to agent without any particular measure being taken to stop it. In this context, the model applied is the standard SEIR model augmented with the fact that agents are allowed to move within airports and hence enter/exit the subpopulations of the specific units under analysis. In this case, as foreseeable, the epidemic starts and spreads until it reaches the entire population. Hence, the final configuration of the population after the 120 days of simulation is one fully made up of recovered individuals, irrespectively of the beta used. Using different values for the infectivity rates, indeed, causes a shift of the peak of infected individuals, both in terms of time and in terms of absolute values, but does not change the final result of the epidemy, as can be seen from the graphs below which refer, for completeness reasons, to the whole population under analysis, hence to the sum of the 49 final airports. Graphics for each separate airport, which are characterized by curves with very similar shapes, are clearly available in the code for this scenario as well as for all the scenarios below.



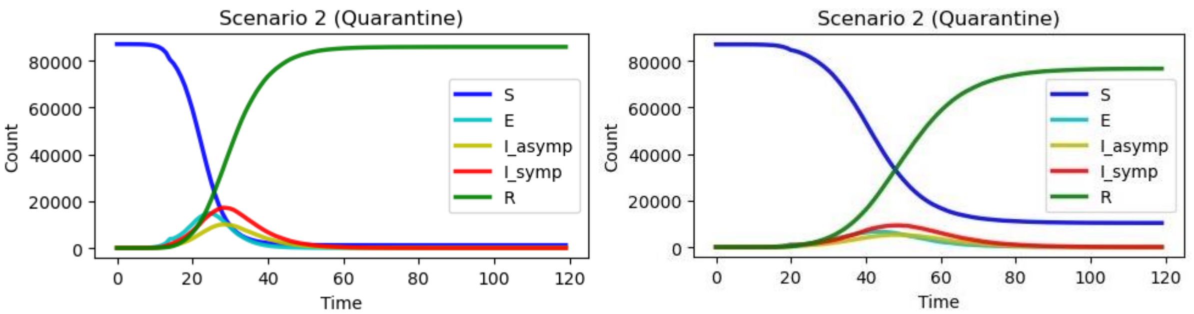




Figures 2 and 3: SEIR dynamics in scenario 1, respectively for β=0.001 (on the left) and β=0.0005 (on the right)

As it can be seen from these graphs, the peak in the case of a most infectious disease (so β=0.001) is reached sooner in terms of time (at day 26 precisely, compared to day 32 for the second case) and is represented by a higher number of infected individuals (approximately 42,000 compared to the approximately 34,500 of the second case). This is as expected even before the simulation, as the infectivity rate of the epidemy is twice as high as the first case, thus leading to a quicker spread of the virus.

## 7.2. SCENARIO 2 – QUARANTINE FOR SYMPTOMATIC INDIVIDUALS

In the second scenario, after the "adaptation week" following the surpassing of the alert threshold, quarantine was imposed to all the symptomatic individuals. This implies that they were subject to isolation and hence could neither travel nor infect others anymore. Here, it was assumed that all agents would comply with the imposed quarantine, and none would purposely decide to violate it. Quarantine has been imposed on symptomatic individuals only as these represent, likely, those individuals who get tested and hence can be forced to undertake an isolation regime until they recover from the disease. In this case, the obtained dynamics were as follows:




Figures 4 and 5: SEIR dynamics in scenario 2, respectively for β=0.001 (on the left) and β=0.0005 (on the right)

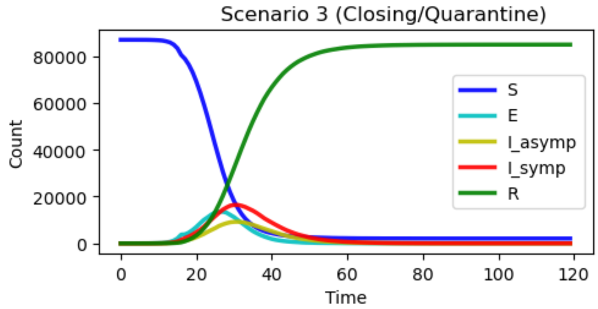
As it can be seen, epidemic's dynamics were affected by the introduction of the intervention under analysis. Indeed, compared to scenario 1, for both values of the infectivity rate the peaks of the infected individuals (summing both symptomatic and asymptomatic) are significantly lower and are happening at a later stage. In particular, now the peaks are respectively at 27,200 agents for the higher β while at 14,600 for the lower one. Moreover, these values are attained after 28 days in the first case and after 48 days in the second one. On top of this, it is possible to see that with the introduction of a quarantine, not all individuals eventually contract the disease. Indeed, in both graphs, the Susceptible' curve does not reach a value of zero. Hence, introducing a quarantine after the "adaptation week" could help to both slow down the pandemic and to reduce the overall effects it has on the population as a whole.

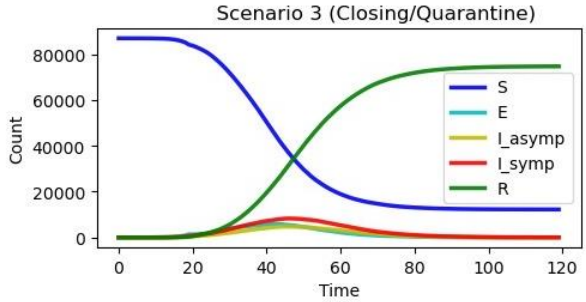
### 7.3. SCENARIO 3 – QUARANTINE FOR SYMPTOMATIC INDIVIDUALS AND CLOSURE OF 5 AIRPORTS

In this scenario, on top of quarantine, the most connected airports have been closed. If an airport was closed, then agents who were in that specific airport were not allowed to travel anymore, though, they were allowed to interact with each other and, hence, transmit the disease. This is the case since the goal of this scenario is just to restrict mobility without affecting individuals in their own behavior, which, in case of scenario 3, is already impacted by the quarantine for symptomatic individuals.

Here, the most connected airports were determined via the use of three measures: degree centrality, betweenness centrality, and clustering coefficient. More in depth, degree centrality quantifies the number of connection one node has with the other nodes, betweenness centrality, which quantifies the number of shortest path that pass through a specific node, captures the ability of nodes to connect different parts of the network and hence their ability to act like "bridges", whilst clustering coefficient measures the degree to which the neighbours of one node link to each other, put differently, it identifies which fraction of the neighbours are connected. Given that these three seem all relevant measures for the problem at hand, all three were considered when determining the most connected airports.

The graphs that follow are obtained with the closure of the top 5 most connected airports. Attempts were also made closing more than 5 airports, but results obtained were almost the same, the only relevant differences were obtained when closing a great share of the total airports, more than 20 in particular, but this was deemed to be too much restricting and out of the scope of this scenario and, rather, being closer to scenario 6.



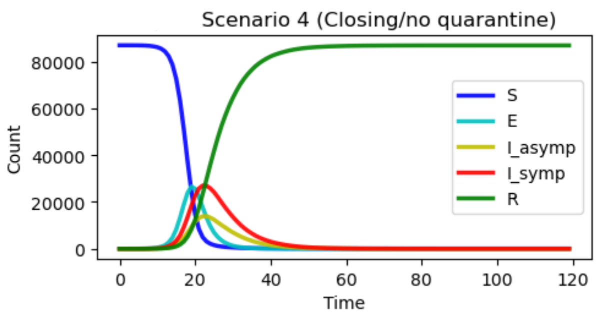


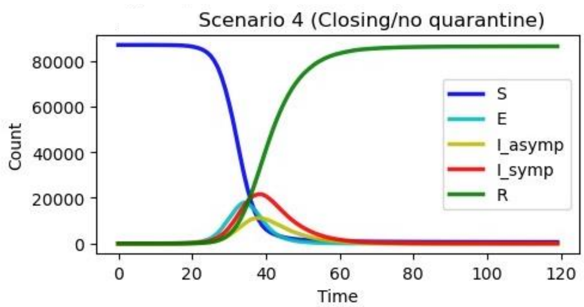

Figures 6 and 7: SEIR dynamics in scenario 3, respectively for β=0.001 (on the left) and β=0.0005 (on the right)

The obtained results mimic very closely the ones from scenario 2. The only differences are that the peak seems, in both cases, to be characterized by a smaller number of infected individuals and also the number of individuals not reached by the infection is slightly higher (still the numbers are very close to the one obtained in scenario 2). Nabil Iqbal (2009) already demonstrated in his paper that closing airports has only a limited effect on the overall dynamics of the epidemic if not combined with other containment measures. This is even more true in the network under analysis. Indeed, the top 49 European airports are largely interconnected within each other, there are no big hubs or airports with very few flights. Indeed, the network is not sparse, indicating a significant level of connectivity. To further confirm this observation, various statistics were obtained, and mathematical properties of the graph were analyzed. The network exhibits a diameter of 3, representing the maximum distance between any pair of nodes. Instead, the average shortest path in the network is approximately 1.22, indicating efficient connectivity. Furthermore, the average clustering coefficient is found to be 0.88, highlighting a high degree of local clustering. Examining the betweenness centrality distribution reveals that the majority of nodes have a low betweenness centrality, with the highest values not exceeding 0.040. This analysis clearly demonstrates that the major airports in Europe are well connected, without the presence of airport clusters. This characteristic makes closing specifying airports less effective in slowing down a pandemic if the overall dynamic of the whole population is considered. Still, some marginal effects are identifiable on the airports that have been closed, AMS (Amsterdam Schiphol) for instance, but their magnitude is very low and varies across simulations.

### 7.4. SCENARIO 4 – CLOSURE OF 5 AIRPORTS

In scenario 4, the intervention of closing the top 5 most connected airports is adopted as a standalone measure, no quarantine is imposed. As for what happened in scenario 3, logically one would expect that this fourth scenario mimics closely what happens in scenario 1.



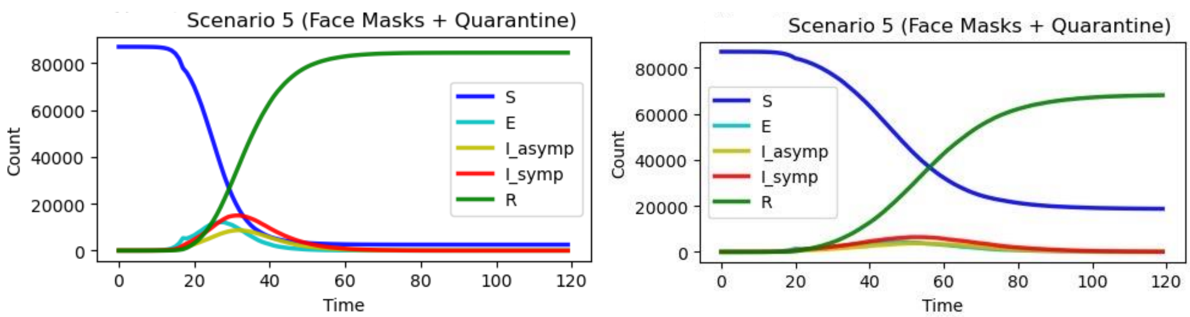



Figures 8 and 9: SEIR dynamics in scenario 4, respectively for β=0.001 (on the left) and β=0.0005 (on the right)

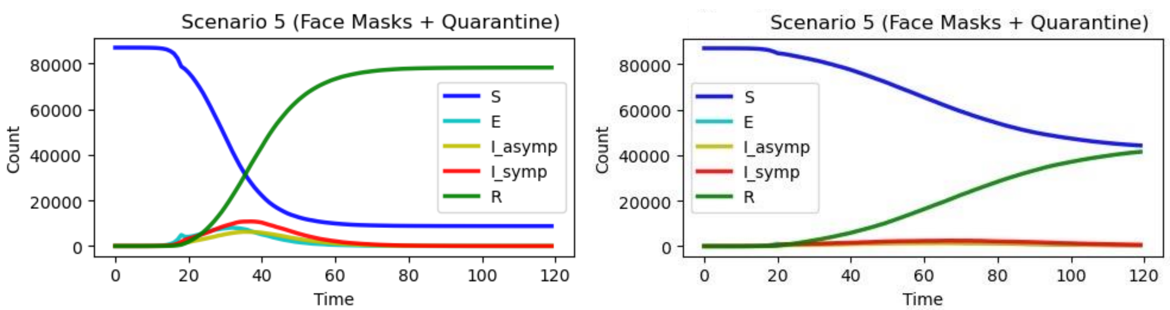
The curves indeed closely mimic the ones of scenario 1 as expected. Though, with β=0.0005, the epidemy does not reach every single individual in the population and, after the 120 days, some susceptible individuals are still present. Also, the peaks are attained at a slightly lower level than in the case with no intervention, but still the effects are very limited. This might, once again, be due to the fact that the European flight network is highly connected.

### 7.5. SCENARIO 5 – QUARANTINE FOR SYMPTOMATIC INDIVIDUALS AND MANDATORY MASK WEARING

This scenario is characterized by the introduction of quarantine, as in scenarios 2 and 3, but also by the introduction of mandatory face masks. In particular, after the "adaptation week", every individual is obliged to wear a protective mask. Empirical evidence shows that, during the COVID-19 pandemic, not every individual complied with this obligation. For this reason, each individual was initialized either as a complier (with 61% probability, corresponding to the average compliance rate across 35 European countries (Spira B., 2022)) or as a non-complier (with 39% probability). On top of this, in the literature there is debate on the actual level of effectiveness of facemasks in protecting from contracting an infection. Because of the uncertainty in this measure, both 25% and 55% were used as reduction rates in infection probability if at least one of the two agents coming into contact is wearing a protective mask (thus if either of the two is a complier). Clearly, both these figures average between different kinds of face masks. As a matter of fact, protection granted by a surgical mask is way lower than the one granted by an FFP2 mask. Still, it is assumed that the intervention entails the mandatory use of a face mask but does not impose any specific one. As a consequence, the average protection across different models has been considered.
Results obtained in this scenario are as follows:




Figures 10 and 11: SEIR dynamics in scenario 5 (with protection=25%), respectively for β=0.001 (on the left) and β=0.0005 (on the right)

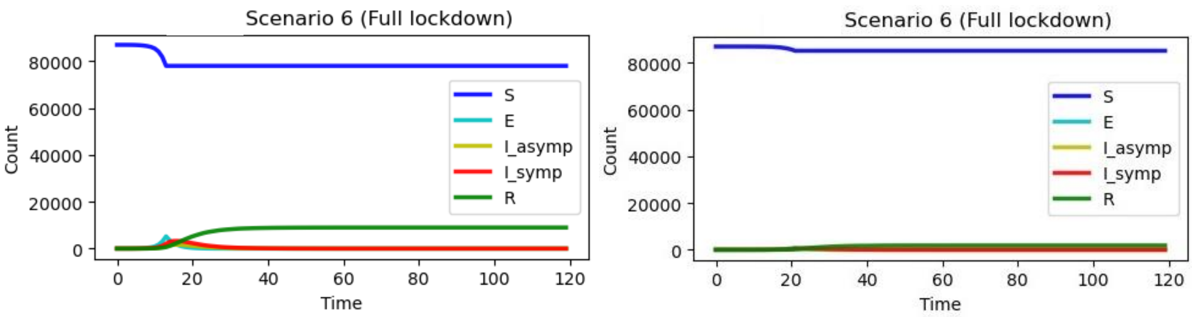



Figures 12 and 13: SEIR dynamics in scenario 5 (with protection=55%), respectively for β=0.001 (on the left) and β=0.0005 (on the right)

Compared to the scenario with just quarantine, the epidemy slows additionally down. Indeed, the peak was achieved at a later stage (day 32 and 37 for the larger β respectively for 25% and 55% reduction rate, while 52 and 67 for the smaller β) and its magnitude was significantly lower. More precisely, peaks were distinguished by approximately 4,000 less infected individuals when the reduction rate used was 25%, irrespective of the β, and 10,000 less when it was 55%. Moreover, the number of individuals who did not contract the disease, and hence are still in the susceptible compartment after the end of the 120 days of simulation, increased with respect to scenario 2. This clearly makes sense also logically as in this scenario an additional restriction has been imposed. Also, the fact that in the case in which the reduction rate is higher the effects are more pronounced is logical, indeed, the infection loses contagion power and hence the epidemy displays lower peaks and the number of individuals not contracting the disease is way higher.

## 7.6. SCENARIO 6 – FULL LOCKDOWN

In scenario 6, a total lockdown was imposed. In particular, after the "adaptation week" individuals were not allowed anymore to move from their current location and, on top of this, were subject to isolation and hence were not able to pass the disease anymore. This last assumption was made as the unit of reference are airports and not cities, hence identifying households of agents living together which could still interact within each other was neither possible given the data availability nor sensible. Clearly, this restriction is the most invasive one among the ones presented and analysed in this paper, though, as proven by results, is also the most effective one.




Figures 14 and 15: SEIR dynamics in scenario 5 (with protection=55%), respectively for β=0.001 (on the left) and β=0.0005 (on the right)

In this scenario's case, the epidemy starts but the intervention is so strong and happens so quickly that it does not give the time to the virus to spread and reach a significant part of the population. Indeed, most of the individuals remain in the susceptible compartment after the 120 days of the simulation. Evidently, this result is even sharper when β=0.0005, which was foreseeable as the epidemy already starts with a lower infective power.
Other attempts were also made to introduce the lockdown at a later stage of the epidemy. Though, for comparative reasons, here results are presented with the introduction of the intervention made at the same point in time. Still, the introduction of the lockdown cannot happen after approximately the $20^{th}$ day in the case of β=0.001 or the $35^{th}$/$40^{th}$ day in the case of β=0.0005. Indeed, if more time is taken to introduce this restriction, then the epidemy would reach a point in which the effect of the lockdown would be only marginal as many individuals already have contracted the disease.

# 8. CONCLUSIONS

The analysis conducted in this paper shows how some interventions seem to work better than others when it comes to reducing the impact of a COVID-19-like epidemy considering the contribution of the aviation network. Unsurprisingly, it was found that effectiveness and strictness are closely correlated. As a matter of fact, the strictest the containment measure applied is, the greatest the positive impact on the epidemy is. Given the above, the full lockdown seems to be the better option followed by the combination of quarantine for symptomatic individuals plus the obligation to wear a face mask. Though, as seen during the recent COVID-19 epidemy, health concerns are not the only drivers for governments/institutions. Indeed, even if imposing a full lockdown may be the best choice from a sanitary perspective, it might not be so from an economic or social one. The study at hand shows that, if the infectivity rate is not that high (as in the case of $\beta$=0.0005), more moderate measures, for instance quarantine only for symptomatic individuals can be a viable solution. As a matter of fact, this measure allows to reduce the overall impact of the disease without affecting mobility of individuals, unless they are ill, thus reducing the effect on the economy and on the socio-psychological sphere of individuals.

Moreover, the analysis confirmed the relatively small effect that closure of single airports has on the overall pandemic's spread over the entire aviation network. Once again, this is likely due to the high degree each of the nodes of the network under analysis has. Because of this, removing single nodes seems not to have a significant effect on the epidemy in general as agents can still travel in between almost every airport.

On top of this, the analysis also showed as acting in time is fundamental to prevent the spread of a new epidemy and reduce the contribution of the aviation network. During the simulation, different "adaptation" periods, following the surpassing of the alert threshold, have been experimented to conclude that a week is the best trade-off between the need to act promptly and the need to approve special measures. Clearly, for certain interventions a week may prove to be too short, and times might be diluted. Still, given the parameters of the epidemy under analysis, any delay risks to compromise the situation beyond a point after which no action is further beneficial. Therefore, the sooner the government intervenes the lighter the containment measures have to be. As a matter of fact, it was proven that the effect of introducing quarantine for symptomatic individuals after the "adaptation week" was more beneficial that introducing a full lock down after a longer period of time. Hence, this paper verifies that the sooner the intervention takes place the better it will be overall.

Last but not least, because of the high degree of each of the nodes in the network, the starting point of the epidemy seemed not to impact the overall obtained results. As a matter of fact, different starting points were tested but results remained almost constant in all cases. This is further proof that high interconnectivity might be a valuable asset in many situations but also brings risks associated to it.

Obviously, this is just an introductory analysis at a basic level. Better and more reality-proof results could be achieved with an increased availability of data. Indeed, scarcity of open-source information and data about diseases spread over the European aviation network reduced the overall ability of the proposed model to effectively analyse possible intervention measures. Still, results obtained in this paper confirm previous literature findings and also logical intuitions associated to the introduction of different kinds of interventions.

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