Graph Theory approach to COVID-19 transmission across adjacent municipals

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Introduction:

The spread of the "Severe Acute Respiratory Coronavirus 2" (SARS-CoV-2), responsible for the coronavirus disease (COVID-19), was first recognized as a pandemic by the World Health Organization (WHO) in March 2020, considering its rapid dissemination over the world in a short period of time, rendering it a global health emergency. [1,2]

Given the importance of understanding how this infection flows are represented in real life and how relevant COVID19 is on a global scale, represented in a conceptual model, this study used graph theory to try to understand it.

Graphs may be used to represent many different types of relationships and processes in physical, biological, social, and information systems. [3–5] Ultimately graph theory is about connections networks and thus it can be used to model and answer, different kinds of questions. In this work graph theory will be used to emulate COVID-19 virus transition chain between municipalities in the district of Aveiro.

Methods:

All COVID-19-related test results in ACES BV reported to the Public Health Unit (PHU) between January 30, 2020, and January 14, 2022 (N = 17.568) were used in this investigation. However, due to missing numbers and/or insufficient information in the data for 2022, only the first two years of data were considered. Since the study's focus was on the dynamics between municipalities, the database was filtered to contain just the IDs (person identification number) and each relevant ID county, as well as COVID results and test dates. The dataset was filtered to eliminate missing and repetitive items.

Contact matrices, being those matrixes that display the transmission between the infector (line) and the infected (column) [6], were created using the resulting dataset for the years 2020 and 2021. These matrices were then used to generate graphs. To each of these graphs, the following centrality metrics were applied: Closeness Centrality, Betweenness Centrality, Eigencentrality, Degree Centrality. Closeness centrality reflects how near a node is to all other nodes in the network. It is determined as the average of the shortest path lengths from the node to every other node in the network, and so indicates the transmission speed. Betweenness centrality quantifies how much influence a node has on the flow of information in a network. Eigencentrality is a measure of a node's impact in a network, but it excludes information about ego's changes and so evaluates the strength of each node's neighbors in the proximity network. The number of connections occurring at a node is known as its degree centrality (i.e., the number of ties that a node has). Some of these measures are based on the shortest paths between a vertex and all others, so the smaller the edge weight, the shorter the distance, and thus for the measures of Closeness Centrality and Betweenness Centrality the inverse of the matrices were used for the calculations.

The study of the dynamics of the COVID-19 disease was then understood by comparing the evolution of this measures across the calculated time periods.

Results:

The contact matrices (Tab.1) for the time intervals related to 2020 and 2021 are similar, having both the majority of transmissions within the diagonal, hence they occur within the municipality.

As for the measures of centrality (Fig. 1), it can be said that they all remained relatively constant between the two years.

Aveiro had the greatest value for Closeness Centrality, with Águeda and Ílhavo coming in second and third, respectively, in the first interval and shifting positions in the second interval. In both intervals of the
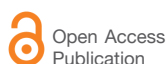
Table 1 – Contact matrices

Contact Matrix of 2020

	A. Velha	Águeda	Anadia	Aveiro	Estarreja"	Ílhavo	Murtosa	O. Bairro	Ovar	S. Vouga	Vagos
A. Velha	268	6	0	8	0	1	0	0	0	1	1
Águeda	2	517	16	13	2	0	0	6	1	0	0
Anadia	0	5	460	4	0	0	0	9	0	0	0
Aveiro	5	5	4	972	6	38	1	0	5	3	6
Estarreja	0	2	1	6	400	1	33	0	10	0	1
Ílhavo	1	2	0	46	0	472	0	2	1	1	2
Murtosa	0	0	0	2	54	0	236	0	3	1	0
O. Bairro	0	5	10	3	2	5	0	96	1	0	2
Ovar	0	0	0	10	5	0	4	0	1022	0	2
S. Vouga	0	3	0	0	0	0	1	0	0	160	0
Vagos	0	1	3	13	0	11	0	1	0	0	208

Contact Matrix of 2021

|	A. Velha	Águeda	Anadia	Aveiro	Estarreja"	Ílhavo	Murtosa	O. Bairro	Ovar	S. Vouga	Vagos
A. Velha	864	14	0	23	4	6	0	0	2	3	0
Águeda	36	1222	11	25	0	3	0	15	0	4	2
Anadia	1	15	873	11	0	3	0	20	0	1	0
Aveiro	32	19	16	2520	13	89	1	38	2	3	12
Estarreja	8	3	0	14	850	0	14	0	8	0	0
Ílhavo	5	6	2	104	2	1313	2	10	0	0	16
Murtosa	0	0	0	6	14	2	402	0	4	0	0
O. Bairro	6	23	11	37	0	3	0	528	0	0	2
Ovar	2	4	0	8	25	1	6	0	1841	1	0
S. Vouga	0	4	3	2	0	3	0	0	1	349	2
Vagos	1	4	3	34	1	12	0	4	0	1	630
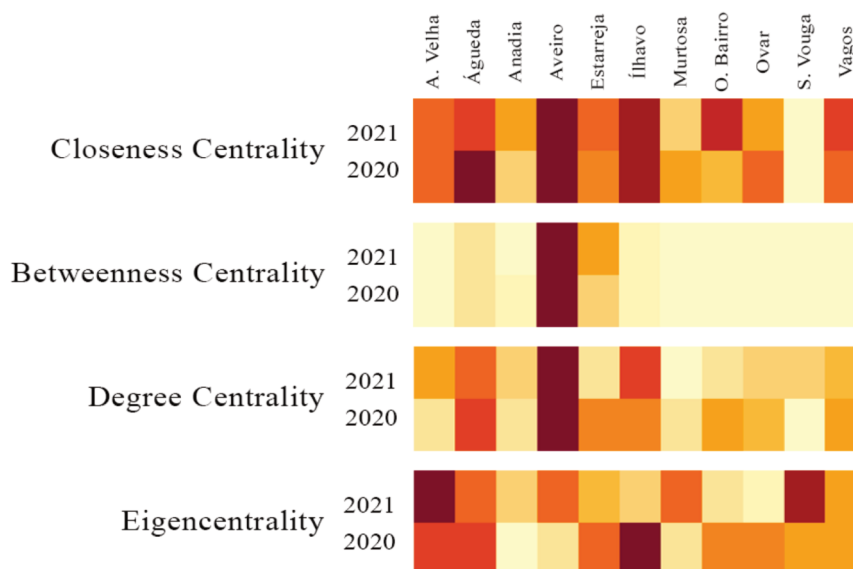
Figure 1 - Centrality measures heatmaps

betweenness centrality measure, the municipality of Aveiro is the strongest node, with Estarreja and Águeda coming in second and third, respectively. The nodes showed about the similar strength for the Degree Centrality measure (for both time intervals), with only the Aveiro node outperforming the others, although the general values are all high. In terms of Eigencentrality, the first interval is dominated by S.Vouga and A.Velha, whereas the second interval is dominated by Ílhavo, however, it still has A.Velha with high values.

Discussion:

The measurements of centrality were largely stable over the two years, showing that the COVID-19 dynamics were similar in these two periods, even while vaccination practically only occurred in 2021 and the prophylactic isolation of Ovar occurred in 2020. Analyzing the Closeness and Betweenness Centrality, it is concluded that in both years, Aveiro was the strongest node in both measures, and so, it was the municipality that infected other nodes the fastest and had the most influence. For the Eigencentrality, the time intervals appear to be shifting. A. Velha, on the other hand, has been shown to be the overall node with the strongest neighbors. Regarding the Degree Centrality, all the nodes appear to be linked to the majority of nodes.

Ethics committee and informed consent:

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