14th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP14
Dublin, Ireland, July 9-13, 2023

Rapid Resilience assessment of a Transport Networks for Medical Needs

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ABSTRACT: A healthy transportation network should be resilient in many ways and resilience for medical emegencies or needs are one of the important factors in this regard. This paper demonstrates for such resilieince can be rapidly assessed for existing transportation networks and considers the city of Dublin as an example. To assess the resilieince, a transportation network in Dublin is chosen, considering the locations of a number of medical facilities. The impact of removal of some parts of the networks are observed to assess the resilience of a network, especially in the context of connectivity with such medical facilities. Residential, tertiary and secondary roads were considered and various nodes were removed to observe the consequences. A number of scenarios were considered and the computations were carried out within a Bi-Objective Node Removal Impact Problem formulation. The outcomes demonstrate how extensive analyses in this direction can provide better information and decisions around planning, changes or even policy instruments on transport by keeping medical facilities and emergencies as a matter of priority. Resilient designs against uncertainties at this network level will lead to pragmatic and robust networks for the future and for evolving scenarios.

1. INTRODUCTION

The road network of Dublin City was considered for the purposes of understanding access to hospitals. Dublin has the highest population density and a large commuting network. The resilience is assessed by considering access to hospitals in case some areas were inaccessible and the critical areas were identified through simulated scenarios of such inaccessibility. The Bi-Objective Node Removal Impact Problem method (BO-NRIP) is considered for this (Grubesic et al., 2007).

Here, the road network consists arcs representing the streets and nodes representing the intersections of streets and locations with major traffic lights. The nodes and arcs have their attributes (properties) which give them an importance grade. Arcs have higher attribute values depending on the number of traffic lanes while node attribute is determined by how close it is to hospitals. The grading for nodes range from 1 to 5 where 5 is the attribute of a node closest to a hospital. The sum of all nodes and all arcs are related to two aspects. The first is where the maximum value is obtained if none of them are removed. They are also related to a binary variable which acts as a node or arc removal tool. The formulation has the form

$$Z_1 = \sum_j a_j y_j \quad (1)$$

$$Z_2 = \sum_i c_i x_i \quad (2)$$

where i is the indexing of nodes, j is the indexing of arcs, Ω_j is the node pair of an arc j, a_j is attribute of arc a_j, c_i is attribute of node i, N_i is the set of arcs connected to node i, n_i is the number of arcs connected to node $|N_i|$ and p is the number of nodes to be removed. The term $x_i = 1$ if node i is removed from the network and it is 0 otherwise. Similarly, $y_j = 1$ if arc j is in network and it is 0 otherwise.

To highlight the vulnerabilities of the network, four scenarios were considered in total, representing the different levels of inaccessibility for the network. The defined functions are maximized or minimised to determine which node/s are to be removed, based on the sum of attributes, which also maximises or minimises effect on arc flow. There are 4 scenarios:

Scenario 1: minimise both Z1 and Z2.

This scenario aims to remove the node with highest attribute which will have most impact on the network with will lead to reach significant reduction total value of attributes both of arc and node. If multiple node are moved then some of the arcs will be lost which will highlight vulnerability.

Scenario 2: maximise both Z1 and Z2.

This scenario has similar aim but in the opposite way with minimising impact on both arcs and nodes. It will show data about areas which have least impact and might not lead to loss of any arcs.

Scenario 3: maximise Z1 and minimise Z2.

While Scenario 1 and Scenario 2 are idealistic and represent the highest damage or very light impact damages, real life the situations are not so straightforward and inaccessibility may not maximise impact in those ways but can lead to a random disruption. The scenarios where one objective is maximised and another one is minimised can represent those cases. This scenario aims to remove the most important node with least amount of impact on the arcs.

Scenario 4: minimise Z1 and maximise Z2.

This represents a opposite situation to Scenario 3. To solve these scenarios, Pyomo environment of python was used. Different weights were assigned to each objective to obtain the most optimal solution. Assigning manually weighted sum is inefficient and a Pareto- optimal front of such function is used using an additional constraint (of a form $Z_2^{min} \leq \epsilon \leq Z_2^{max}, Z_2 > \epsilon$) which prevents one of the functions to stay at a high value while the other one is being maximised. Such method works well for Scenarios 1 and 2. However , for Scenarios 3 and 4 the objectives are not the same and to adapt the same method, equations 1 and 2 are multiplied by -1 which lets to to minimise or maximise both functions and find a non dominated front.

2. DATA

Arc pair matrix Ω_j is input to Pyomo along with matrix N_i with information of arcs connected to each node. If there is insufficient arcs to full all columns of N_i then the remaining elements are set to zero. Attribute arrays a_j and c_i for arcs and nodes, respectively are also taken. Data was obtained from open source Open Street Map (OSM) and primary, secondary and resident roads for Dublin were used. Nodes are the points where the traffic diverts, changes and requires traffic control. Hospitals for analysis were also located on this network. An example map is presented in Figure 1. The data from OSM is reshaped in python using Pandas and Geopandas, which allows working with larger amounts of data. The nodes for hospitals were found by considering the centroid of the polygon representing a hospital on a map.

Figure 1: An example network considered in Dublin

The arcs score are based on amount of lanes they have. Table 1 shows the attributes for first 20 nodes (out of 11000), along with those for arcs.

Subsequently, node and arc indices were connected to matrices Ω_j and N_i. First, the largest distance calculated between node pairs present on the street (obtained from its edges) was assigned as the node pair for arc in data frame. For N_i all streets connected to each node was found and then the corresponding indexes for them were computed. In order to do that, street data was normalised and cleaned for empty entries. It was checked if coordinate of each node was present on a linestring (geometry data type which is a line with several coordinate points). If this was less then the distance which was close to 0 that meant it was on the street and was added to a matrix. This also ensured that the arcs were not added twice due to the process of being enclosed in the loop. In Table 2 columns 1 to 5 are used for each node because maximum amount of arcs attached to node was 5. All arc indexes were collected as one variable called dictionary and all the arcs were separated and converted into integers

Residential, secondary and tertiary roads (Figure 2) were chosen and there were around 5000 arcs, after filtering for empty names and double names. Geometry, index and number of streets attached to nodes were noted with Efficient Frontier method for removing nodes in Scenarios 3 and 4 to eases the bi-objective programming. Here equation 1 becomes the constraint and only equation 2 is the objective function.

Figure 2: Types of roads in Dublin network

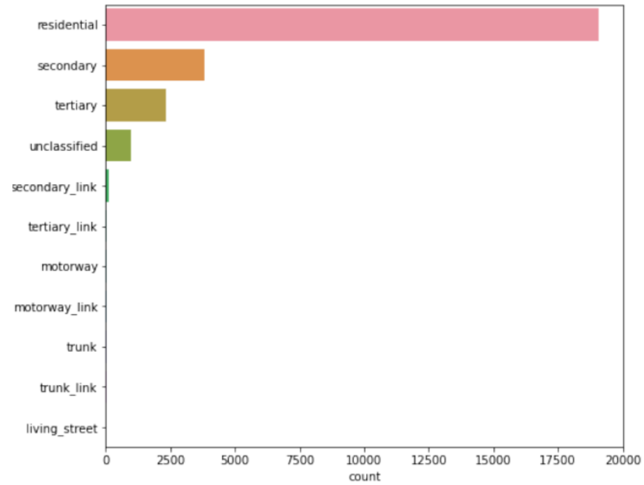

Table 1. Scoring of attributes

c_i	*score*	a_j	*score*
1	5	1	2
2	5	2	2
3	5	3	3
4	5	4	2
5	5	5	3
6	5	6	4
7	5	7	2
8	10	8	4
9	5	9	2
10	5	10	3
11	5	11	2
12	5	12	3
13	5	13	1
14	5	14	1
15	5	15	2
16	10	16	3
17	10	17	4
18	3	18	1
19	5	19	1
20	3	20	2

Table 2 presents the node pairs corresponding to the arc and Table 3 presents arcs connected to the node in the shape of a matrix.

Table 2. Node pairs corresponding to arc

index	*Node1*	*Node2*
1	1	1332
2	1	7474
3	2	5832
4	2	1340
5	3	2606
6	4	5200
7	4	6901
8	5	6
9	5	7654
10	7	8578
11	7	8589
12	7	8585
13	8	8742
14	8	8743
15	9	10312
16	9	9642
17	10	6260
18	11	9563
19	12	3513
20	12	13

Table 3. Arcs connected to a node

N	*1*	*2*	*3*	*4*	*5*
1	1	2	215	3468	0
2	3	4	1	0	0
3	5	0	0	0	0
4	7	8	12391	17082	0
5	9	0	0	0	0
6	9	0	0	0	0
7	13	9	15	12147	0
8	16	3920	18914	0	0
9	18	21054	497	0	0
10	20	3	0	0	0
11	22	128	0	0	0
12	23	24	0	0	0
13	24	27	29	0	0
14	27	0	0	0	0
15	30	0	0	0	0
16	32	33	3459	0	0
17	34	35	36	0	0
18	37	38	39	40	0
19	40	43	0	0	0
20	44	22254	0	0	0

3. RESULTS

Results were calculated for the scenarios presented in this paper and *P* is the number of nodes removed from the network and equal to 1, 10 , 100 and 1000 nodes, respectively. Maps are presented with such removals of nodes and arcs highlighted.

The visualization follows colour coding of Red indicating removed streets, Orange indicating removed nodes, Blue indicating existing streets and Turquoise indicating existing nodes.

3.1. Scenario 1

When 1 and 10 nodes were removed there were no arcs removed since all the nodes do not connect to the endpoint of the street and as the flow of arc is maximised.

The most impact on network is shown as a dot in Figure 3, is located between 3 hospitals and on the main road. The locations of 10 nodes removed (Figure 4) are also close to hospitals.

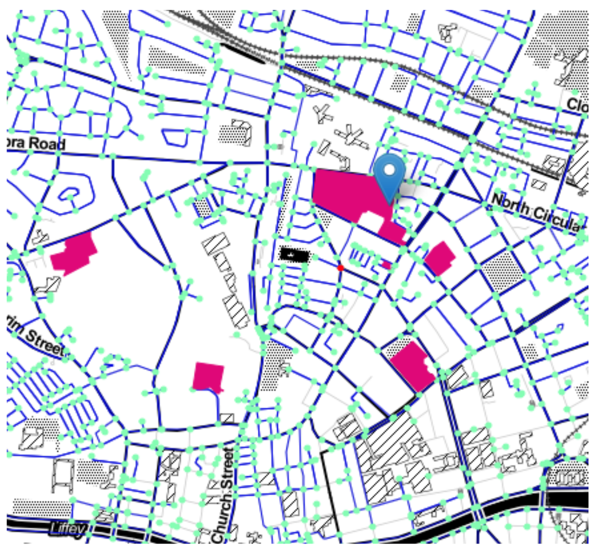

Figure 3: Scenario 1- 1 Node Removed

When 100 and 1000 nodes were removed some arcs were removed as well (Figure 5, Figure 6). The arcs which were least significant to the network with smallest attributes and in residential areas were removed.

Also, when 1000 nodes were removed, the effect on network was significant and affected several roads, although Z_2 was aimed to be maximised.

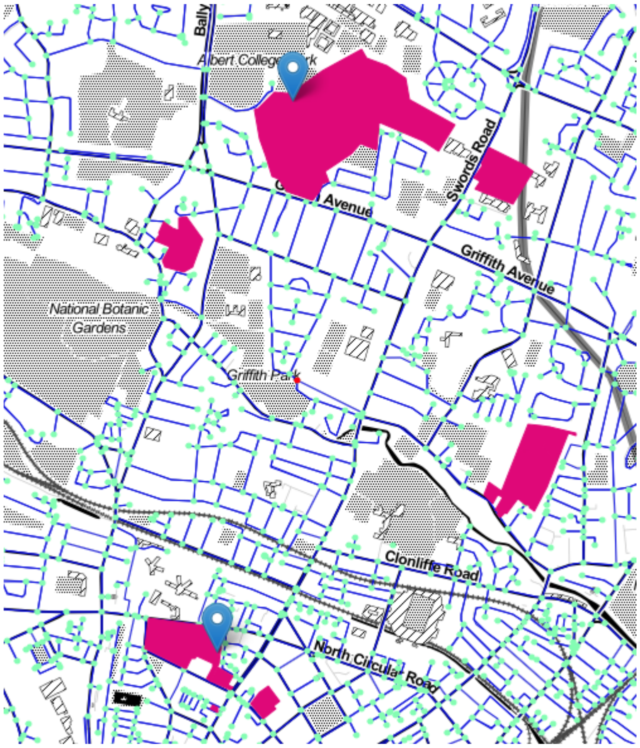

Figure 4: Scenario 1- 10 Nodes Removed

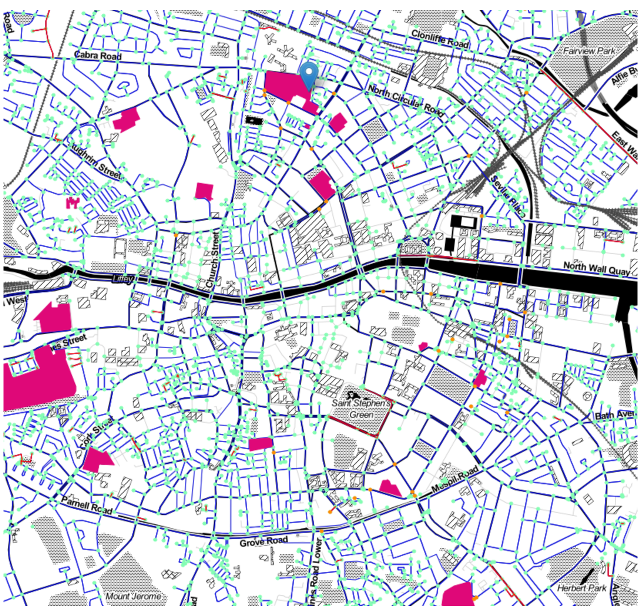

Figure 5: Scenario 1- 100 Nodes Removed

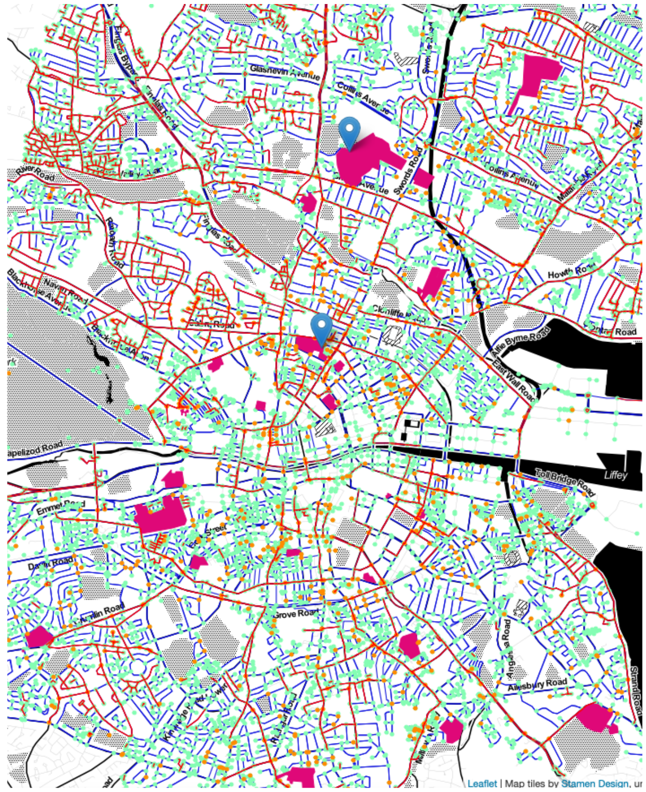

Figure 6: Scenario 1- 1000 Nodes Removed

3.2. Scenario 2

In this scenario the number of nodes removed has minimum impact and impact on flow should be bigger, indicating that flow is minimised. The least significant node was on the North side of Dublin and expectedly significantly far from hospitals (Figure 7).

Figure 7: Scenario 2- 1 Node Removed

Removal of 10 nodes (Figure 8) show a similar result, with a few arcs removed. Several main roads were removed with the removal of 100 nodes (Figure 9) and significantly more for 1000 (Figure 10, Figure 11).

Figure 8: Scenario 2- 10 Nodes Removed

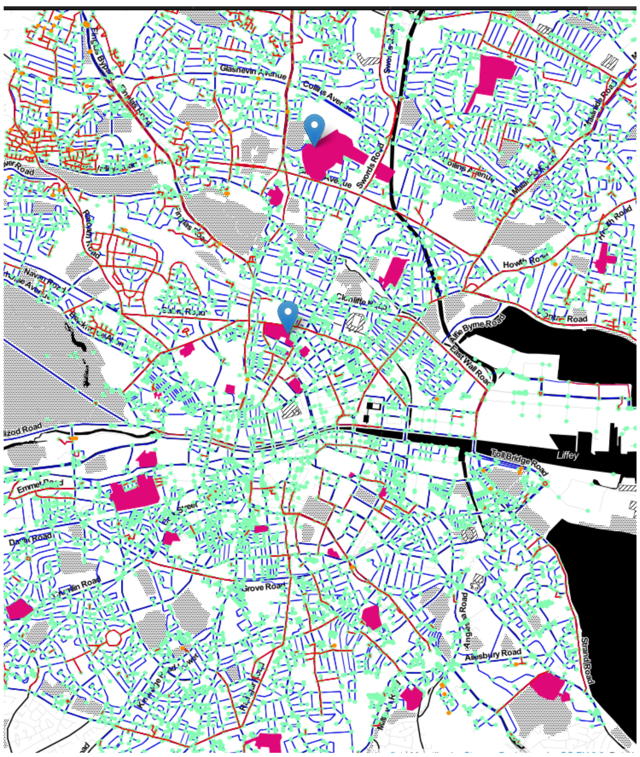

Figure 9: Scenario 2- 100 Nodes Removed

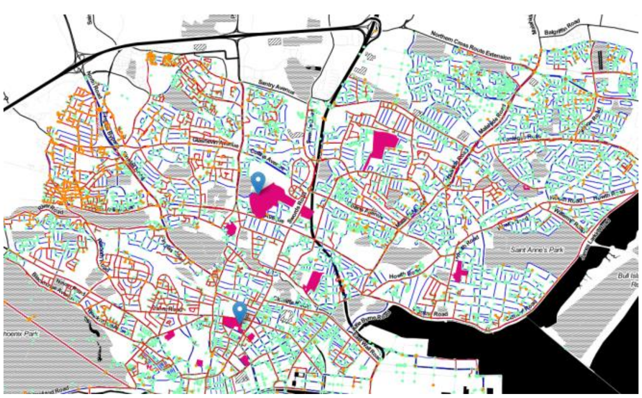

Figure 10: Scenario 2- 1000 Nodes Removed (Part Map: A)

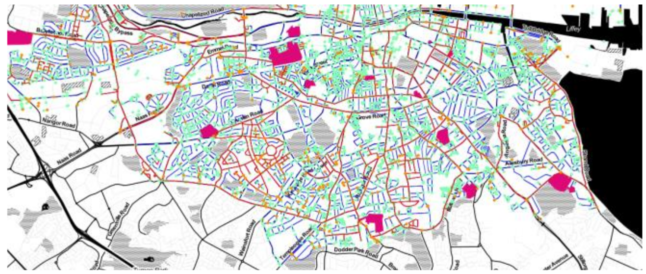

Figure 11: Scenario 2- 1000 Nodes Removed (Part Map: B)

3.3. Scenario 3

This scenario has results similar to Scenario 2 with some variations. The most relevant node for removal of 1 node selected a different node in a similar area (Figure 12).

Figure 12: Scenario 3- 1 Node Removed

For removal of 10 nodes, no arc was removed in this case (Figure 13, Figure 14).

` For the cases with 100 (Figure 15) and 1000 nodes (Figure 16), arc removal was different and types of roads affected were different.,

Figure 13: Scenario 3- 10 Nodes Removed, (Part Map: A)

Figure 14: Scenario 3- 10 Nodes Removed Part Map: B)

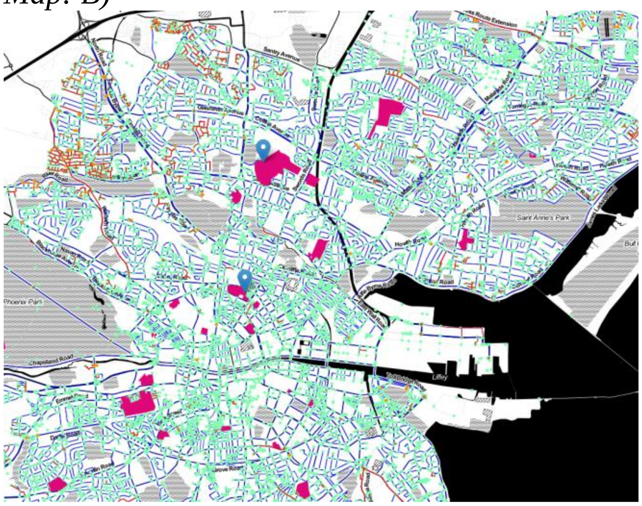

Figure 15: Scenario 3- 100 Nodes Removed

Figure 16: Scenario 3- 100 Nodes Removed

3.4. Scenario 4

This scenario has results from node removal similar to Scenario 1, with 1 node (Figure 17) and 10 node (Figure 18, Figure 19) being very similar.

Figure 17: Scenario 4- 1 Node Removed

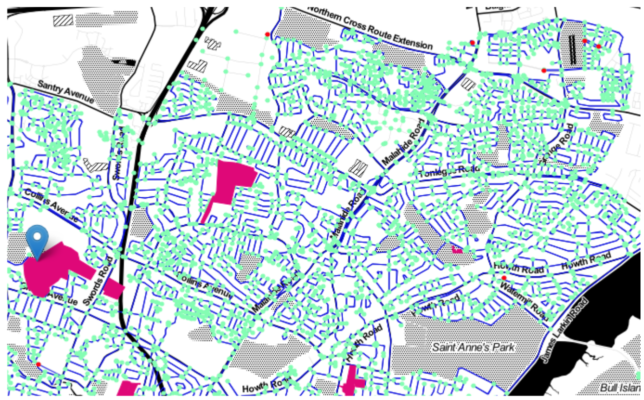

Figure 18: Scenario 4- 10 Nodes Removed: Part Map A

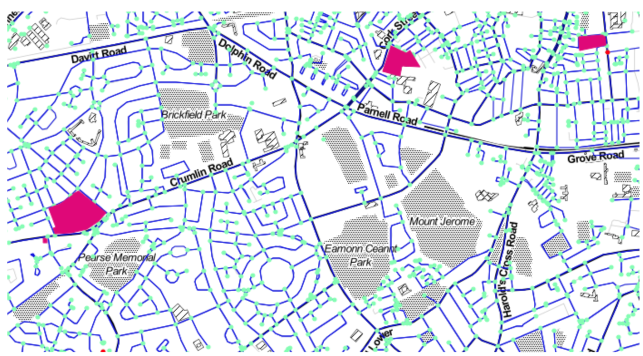

Figure 19: Scenario 4- 10 Nodes Removed: Part Map B

The location of some nodes and arcs are changed for 100 (Figure 20, Figure 21) and 1000 node (Figure 22) node removal.

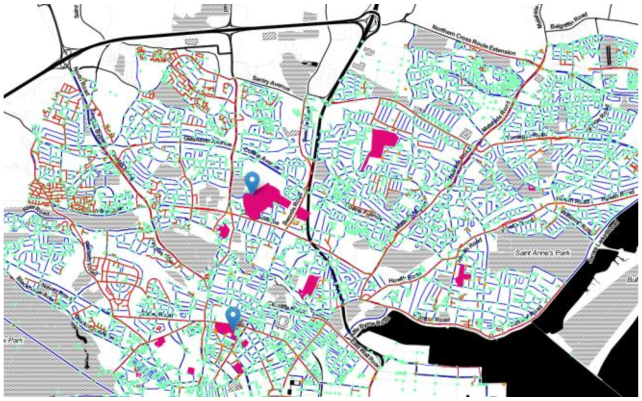

Figure 20: Scenario 4- 100 Nodes Removed: Part Map A

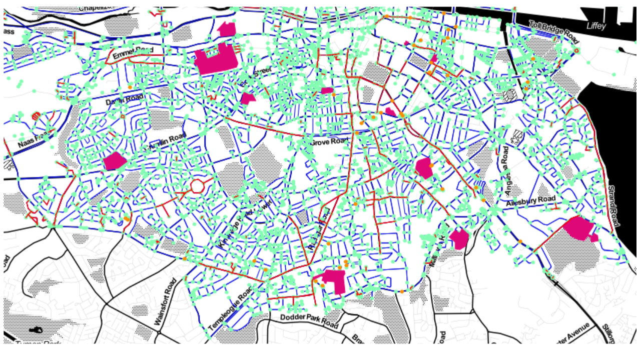

Figure 21: Scenario 4- 100 Nodes Removed: Part Map B

Figure 22: Scenario 4- 1000 Nodes Removed

4. CONCLUSIONS

The BO-NRIP method helped determine which areas of Dublin have more important nodes for infrastructure and which roads have higher importance based on their flow and demonstrated an example based on the context of positions of hospitals.

The most critical nodes were located in city center on north side around Griffith park. This area is around the hospitals and the amount of nodes around that area is lower compare to other places. Other areas in Dublin with hospitals had significantly more roads to access it and more nodes connecting them. The nodes near the entrances of the hospitals were highlighted as critical as well. Roads around Clontarf, East Wall and Griffith were highlighted to be important, with high flow but with fewer number of routes to hospital. These were highlighted when more than 100 nodes were removed, indicating their need for infrastructure as compared to the south side. Finglas was the furthest from any of the hospitals and with least amount of roads with high flow.

When 1000 nodes were removed to minimize flow, all major roads such as M50 or N11 and significant roads in city center and on the edges of Dublin were highlighted. Compared to the North side, the South has more roads and routes toward the hospitals and are more spread out. The South side was affected only when 1000 nodes were removed, but was still was accessible. North Side area of city center is most vulnerable and many hospitals started losing access when only 100 nodes were removed, and had very little access with 1000 nodes removed. Many hospitals have entrances from the main road and the North is also more prone to disruption than the South.

5. ACKNOWLEDGEMENTS

The authors acknowledge, HEA funded SPECTATOR, SFI funded NexSys 21/SPP/3756.

6. REFERENCES

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