# Urban Simulation Final Assessment

Student ID: 23130397 **|** Word Count: xxxx **|** Source Code

## 1 London’s underground resilience

### 1.1 Topological Network

#### 1.1.1 Centrality Measures340

Among all centrality measures comparatively illustrated on **Table 1**, the ‘closeness centrality’, ‘betweenness centrality’ and ‘information centrality’ have been selected as the measures for the following study.

**Table 1 Definition and Equation of different Centrality Measures(Oldham et al., 2019)**

|  |  |  |
| --- | --- | --- |
| **Centrality Measure** | **Characteristics of a central node** | **Equation** |
| Degree Centrality | Connected to many other nodes |  |
| **Closeness Centrality** | **Minimal total cost to access to all other nodes** |  |
| **Betweenness Centrality** | **Most frequent stop-by in all potential routes** |  |
| Eigenvector Centrality | Connected to many other high-degree nodes |  |
| Katz Centrality | Connected to many other nodes from global network accessibility |  |
| **Information Centrality** | **Can be easily reached by paths from other nodes** | or |
| Laplacian Centrality | Removal of this node would greatly impair the network |  |
| adjacent matrix; degree of node i; number of nodes in a network; length of the mean geodesic between nodes and j; leading eigenvalue of ; leading eigenvector of ; the number of shortest-paths between any nodes pair and ; the number of shortest-paths between any nodes pair and which pass through ; penalty on distant connections to a node’s centrality score; preassigned centrality constant; where is the Laplacian of and is a with all elements equal to 1; is the network’s global efficiency and is the network’s global efficiency after removing node . | | |

The reasons for selecting these measures are:

* As the London tube network is undirected, some measures like ‘PageRank Centrality’, specifically for directed one is not appropriate for this question, same for some local centrality measures(Wan *et al.*, 2021) like degree or H-index.
* In terms of the robustness and resilience of network, betweenness centrality and harmonic closeness centrality will be more indicative(Wan *et al.*, 2021) on each node’s functional support for the whole system, while degree centrality and Katz centrality only consider the neighbors rather than global factors.
* Honestly, Laplacian centrality(Qi *et al.*, 2012) might be the best choice for measuring nodes’ significance of maintaining network’s functional structure, which perfectly aligns with our research question on resilience. Yet, the networkX does not have corresponding functions for convenient calculation.
* As the commuting flow could be generalized as information flow, the information centrality could be also useful for measuring the efficiency of whole system transferring information or people.

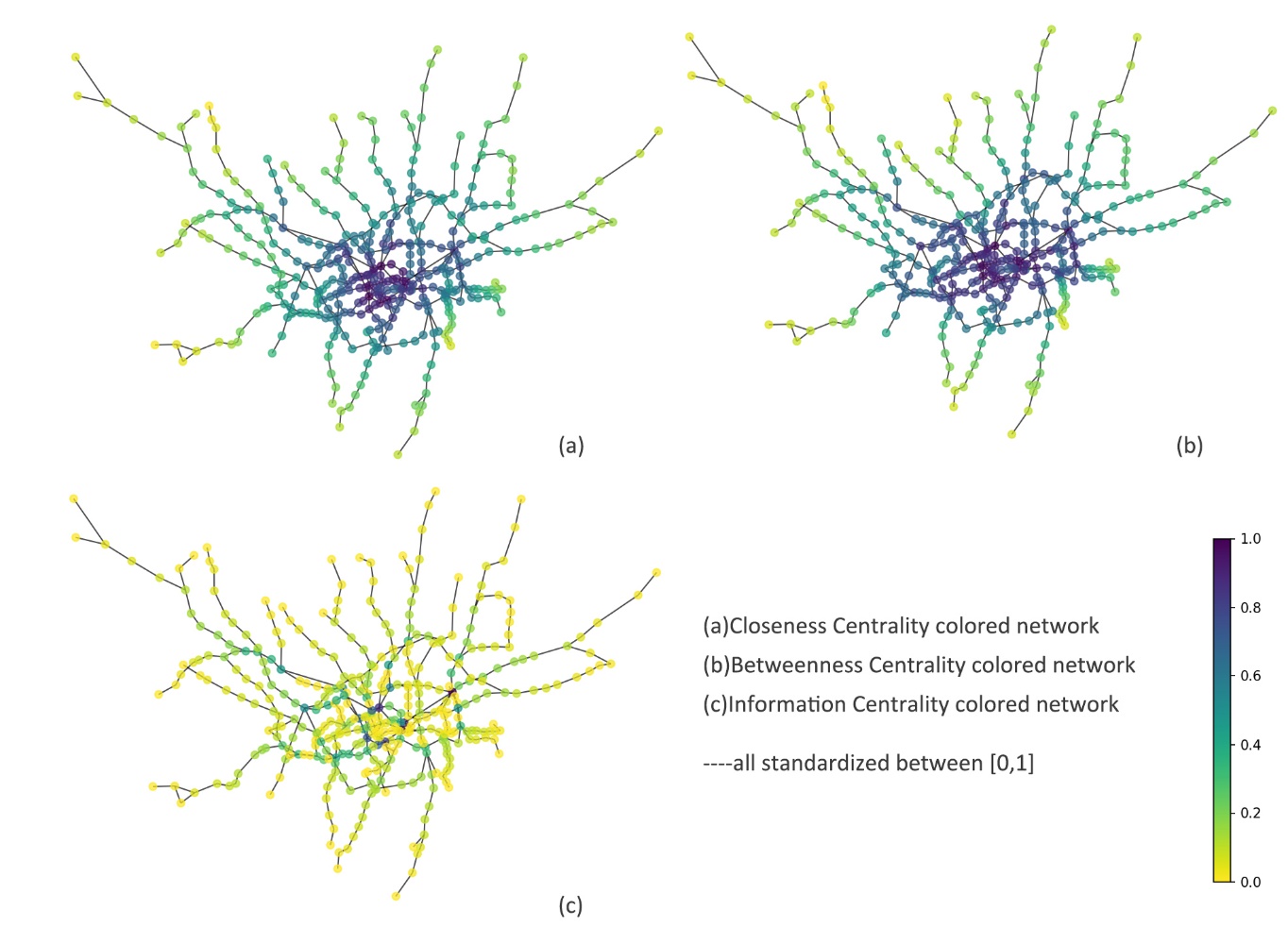
In general, closeness centrality could quantify the accessibility of a station, indicating its efficiency in serving as a departure point for reaching all other stations in the network with minimal travel distance. It underscores the station's role in facilitating relatively short and convenient trips across the network. Betweenness centrality identifies the key transit hubs, highlighting the stations serving as critical junctions or bridges in the system. And information centrality represents station’s importance as boosting network’s operating efficiency on transferring passengers.

The calculation results are shown as **Table 2** and **Figure 1**.

**Table 2 Top 10 Stations for 3 Centrality Measures**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **RANK** | **Closeness Centrality** | | **Betweenness Centrality** | | **Information Centrality** | |
| Station Name | Score | Station Name | Score | Station Name | Score |
| 1 | Green Park | 0.1148 | Stratford | 0.298 | Bank and Monument | 0.000598 |
| 2 | Bank and Monument | 0.1136 | Bank and Monument | 0.290 | King’s Cross St. Pancras | 0.000591 |
| 3 | King's Cross St. Pancras | 0.1134 | Liverpool Street | 0.271 | Liverpool Street | 0.000587 |
| 4 | Westminster | 0.1125 | King's Cross St. Pancras | 0.255 | Oxford Circus | 0.000586 |
| 5 | Waterloo | 0.1123 | Waterloo | 0.244 | Green Park | 0.000585 |
| 6 | Oxford Circus | 0.1112 | Green Park | 0.216 | Waterloo | 0.000579 |
| 7 | Bond Street | 0.1110 | Euston | 0.208 | Baker Street | 0.000578 |
| 8 | Farringdon | 0.1107 | Westminster | 0.203 | Bond Street | 0.000573 |
| 9 | Angel | 0.1107 | Baker Street | 0.192 | Stratford | 0.000572 |
| 10 | Moorgate | 0.1103 | Finchley Road | 0.165 | Moorgate | 0.000570 |

While the first two metrics align with our expectations, indicating that stations in the city center exhibit higher centrality, but the information centrality appears a little weird. This is possibly due to unweighted network, where the distances between stations are not considered. Consequently, stations on suburban lines, characterized by longer distances between fewer stations (steps), tend to stand out more easily. For example, Caledonian Road would be recognized as same closer to King’s Cross as Russell Square because they are both one step to King’s Cross.



**Figure 1 Three Centrality Measures for London Tube Network**

#### 1.1.2 Impact Measures180

In order to assess the resilience of London's underground network, especially in scenarios of node removal, two global measures to evaluate are "Global Efficiency" and "Modularity".

**Equation 1 Equation of Global Efficiency**

Global Efficiency (**Equation 1**) is an indicator of the overall communication efficiency within a network. For the London Underground, a decline in global efficiency would translate to longer travel times between stations, directly impacting commuter convenience and system service levels. A minimal change in global efficiency after node removal would suggest that the network maintains the efficiency of information flow, or in this case, passenger flow.

**Equation 2 Equation of Modularity**

Modularity (**Equation 2**) refers to the extent to which the network can be divided into modules or communities with dense interconnections within modules. A significant increase in modularity upon node removal might indicate the loss of critical bridges which connected different communities and bond different regions together.

To summarize, Global Efficiency stands from the perspective of flowing efficiency, while modularity is seeking insights in terms of structural stability, both helping to identify vulnerabilities and inform strategies to enhance the network's robustness. The computing results of impact measures is shown in **Table 3**.

**Table 3 Global Measures of London Tube Network**

|  |  |
| --- | --- |
| **Global Efficiency** | **Modularity** |
| 0.10125619359721513 | 0.8302138117924331 |

#### 1.1.3 Node Removal486

##### 1.1.3.1 Non-sequential Removal

As required in assignment, the codes of removal process could be accessed [here](http://www.baidu.com). The results are shown in **Figure 2** and **Figure 3** (‘*GE*’: Global Efficiency; ‘*Mod*’: Modularity; And the difference is compared to the previous removal step instead of the initial measure value). The more detailed numeric table, including every node’s name and centrality measure, is in tables in ***Appendix***.

图表

描述已自动生成

**Figure 2 Impact Measures Trend of Removing 70% of all nodes**

As we expected in 1.1.2 Impact Measures, removing high-centrality nodes would generally increase the modularity and decrease the Global Efficiency as shown on **Figure 2**, indicating that network system is more likely divorced into several separated communities and weakened on its flow efficiency.

**Figure 3 Impact Measure difference after each Non-sequential Removal.**

However, following certain node removals, the corresponding measurements did not continue to rise or fall as expected, but rather oscillated in the opposite direction (**Figure 3**). Surprisingly, some of the values even crossed the zero threshold, indicating a complex and possibly non-linear response in the system dynamics.

##### 1.1.3.2 Sequential Removal

In the Sequential Removal process, the weird oscillation did not show again. All the Global Efficient measures consistently decrease as nodes are being removed no matter which centrality measures are used as guidance. Same situation for Modularity.

**Figure 4 Impact Measure difference after each Sequential removal**

图表, 折线图

描述已自动生成

**Figure 5 Impact Measure difference after each Sequential Removal**

Following the sequential removal principles, the entire curve could be smoother, the reason for only removing 50 percent of all nodes is that there will be no more meaningful or valuable edges anymore, which makes the global efficiency less indicative. For example, we could see that once beyond 40%, modularity will decrease sharply (**Figure 5**), indicating that the whole network has been broken into several parts and lost its functional structure as public transport system.

##### 1.1.3.3 Comparative Analysis

图表, 折线图

描述已自动生成

**Figure 6 Comparison between Two Removal Strategies Guided by Three Centrality Measures**

By comparing two different removal strategies (**Figure 6**), we can conclude that sequential removal always has better performance than non-sequential removal in following aspects:

1. Convergence rate: sequential removal will reach stability in relatively less steps, indicating that this strategy will negatively impact on the system more prominently.
2. Monotonic Behavior: sequential one exhibits a consistent monotonic increasing or decreasing trend without significant fluctuations, while non-sequential removal, without a real-time updated indicator’s guidance, is more unpredictable.
3. Robustness towards measures: sequential strategy does not differ significantly towards different centrality measures. And for non-sequential removal, betweenness centrality has prominent advantages over the other two indicators, with closeness centrality be the worst one.

In conclusion, betweenness centrality reflects more indicative importance of a station for functioning of the underground. And sequential strategy is more effective in terms of studying resilience. Additionally, global efficiency is the better one when aiming to assess the damage after node removal because modularity will illustrate weird bounce-back after 40 percent removal.

### 1.2 Flows: weighted network

The weighted network added distance attributes to every edge in the network, also with the flow population between any neighbor stations. We could re-compute all centrality measures and global impact measures by taking distance or flow population into consideration.

#### 1.2.1 Centrality Measures

In centrality measures computation, the weight of edges could be interpreted as various representations according to research question context. For example, the distance can represent ‘commuting cost time’ or ‘possibility of maintenance’, and the flow could refer to ‘connection intensity’ or ‘construction cost for larger space’.

When calculating these centrality measures (closeness centrality, betweenness centrality, and information centrality) in weighted networks, they are generally based on the concept of shortest paths, where "cost" can be understood as the total weight of the path. Therefore, we set the argument “weight=’distance’” to re-calculate all above. The results are shown in .

#### 1.2.2 xxxxx

#### 1.2.3 xxxxx

## 2 Spatial Interaction Models

### 2.1 Models and Calibration

### 2.2 Scenarios

#### 2.2.1 Scenarios A

#### 2.2.2 Scenarios B

#### 2.2.3 Scenarios C

## Reference

Oldham, S., Fulcher, B., Parkes, L., Arnatkevic̆iūtė, A., Suo, C. and Fornito, A. (2019). ‘Consistency and differences between centrality measures across distinct classes of networks’. *PLOS ONE*. Public Library of Science, 14 (7), p. e0220061. doi: 10.1371/journal.pone.0220061.

Qi, X., Fuller, E., Wu, Q., Wu, Y. and Zhang, C.-Q. (2012). ‘Laplacian centrality: A new centrality measure for weighted networks’. *Information Sciences*. (Intelligent Knowledge-Based Models and Methodologies for Complex Information Systems), 194, pp. 240–253. doi: 10.1016/j.ins.2011.12.027.

Wan, Z., Mahajan, Y., Kang, B. W., Moore, T. J. and Cho, J.-H. (2021). ‘A Survey on Centrality Metrics and Their Network Resilience Analysis’. *IEEE Access*, 9, pp. 104773–104819. doi: 10.1109/ACCESS.2021.3094196.

## Appendix

**Table 4 Non-sequential Removal Top-10 nodes by Closeness Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Green Park | 0.1148 | 0.09919 | -0.00207 | 0.83402 | +0.00381 |
| 2 | Bank&Monument | 0.1136 | 0.09487 | -0.00432 | 0.84388 | +0.00986 |
| 3 | King's Cross St. Pancras | 0.1134 | 0.08793 | -0.00694 | 0.85017 | +0.00629 |
| 4 | Westminster | 0.1125 | 0.08737 | -0.00056 | 0.84858 | -0.00159 |
| 5 | Waterloo | 0.1123 | 0.08486 | -0.00251 | 0.8502 | +0.00162 |
| 6 | Oxford Circus | 0.1112 | 0.08278 | -0.00208 | 0.85484 | +0.00464 |
| 7 | Bond Street | 0.111 | 0.08258 | -0.0002 | 0.85983 | +0.00499 |
| 8 | Farringdon | 0.1107 | 0.08261 | +0.00003 | 0.86079 | +0.00096 |
| 9 | Angel | 0.1107 | 0.08262 | +0.00001 | 0.86025 | -0.00054 |
| 10 | Moorgate | 0.1103 | 0.08167 | -0.00095 | 0.8583 | -0.00195 |

**Table 5 Non-sequential Removal Top-10 nodes by Betweenness Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Stratford | 0.298 | 0.08892 | -0.01234 | 0.83571 | +0.0055 |
| 2 | Bank and Monument | 0.290 | 0.08586 | -0.00306 | 0.84676 | +0.01105 |
| 3 | Liverpool Street | 0.271 | 0.08496 | -0.0009 | 0.85214 | +0.00538 |
| 4 | King's Cross St. Pancras | 0.255 | 0.07849 | -0.00647 | 0.85317 | +0.00103 |
| 5 | Waterloo | 0.244 | 0.07594 | -0.00255 | 0.85951 | +0.00634 |
| 6 | Green Park | 0.216 | 0.07415 | -0.00179 | 0.85988 | +0.00037 |
| 7 | Euston | 0.208 | 0.06821 | -0.00594 | 0.86629 | +0.00641 |
| 8 | Westminster | 0.203 | 0.06766 | -0.00055 | 0.86589 | -0.0004 |
| 9 | Baker Street | 0.192 | 0.06470 | -0.00296 | 0.87323 | +0.00734 |
| 10 | Finchley Road | 0.165 | 0.06314 | -0.00156 | 0.87671 | +0.00348 |

**Table 6 Non-sequential Removal Top-10 nodes by Information Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Bank&Monument | 0.0005983 | 0.09673 | -0.00453 | 0.83798 | +0.00777 |
| 2 | King's Cross | 0.0005906 | 0.08988 | -0.00685 | 0.84551 | +0.00753 |
| 3 | Liverpool Street | 0.0005865 | 0.08744 | -0.00244 | 0.84885 | +0.00334 |
| 4 | Oxford Circus | 0.0005862 | 0.08598 | -0.00146 | 0.85769 | +0.00884 |
| 5 | Greed Park | 0.0005847 | 0.0831 | -0.00288 | 0.85497 | -0.00272 |
| 6 | Waterloo | 0.0005788 | 0.08113 | -0.00197 | 0.85848 | +0.00351 |
| 7 | Baker Street | 0.0005786 | 0.0788 | -0.00233 | 0.86338 | +0.0049 |
| 8 | Bond Street | 0.0005726 | 0.07884 | +0.00004 | 0.86471 | +0.00133 |
| 9 | Stratford | 0.0005722 | 0.06999 | -0.00885 | 0.86762 | +0.00291 |
| 10 | Moorgate | 0.0005705 | 0.0703 | 0.00031 | 0.86909 | +0.00147 |

**Table 7 Sequential Removal Top-10 nodes by Closeness Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Green Park | 0.11478 | 0.09919 | -0.00207 | 0.83403 | 0.00382 |
| 2 | King's Cross St. Pancras | 0.11236 | 0.09443 | -0.00476 | 0.84241 | 0.00838 |
| 3 | Waterloo | 0.10465 | 0.09182 | -0.00261 | 0.84603 | 0.00362 |
| 4 | Bank & Monument | 0.09742 | 0.08543 | -0.00639 | 0.85148 | 0.00545 |
| 5 | West Hampstead | 0.08173 | 0.08054 | -0.00489 | 0.85461 | 0.00313 |
| 6 | Canada Water | 0.07598 | 0.0581 | -0.02244 | 0.85891 | 0.0043 |
| 7 | Stratford | 0.06373 | 0.05188 | -0.00622 | 0.86943 | 0.01052 |
| 8 | Earl's Court | 0.06364 | 0.05035 | -0.00153 | 0.87051 | 0.00108 |
| 9 | Sheperd's Bush | 0.06043 | 0.04439 | -0.00596 | 0.87785 | 0.00734 |
| 10 | Oxford Circus | 0.0505 | 0.04296 | -0.00143 | 0.88236 | 0.00451 |

**Table 8 Sequential Removal Top-10 nodes by Betweenness Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Stratford | 0.29785 | 0.08892 | -0.01234 | 0.83571 | 0.0055 |
| 2 | King's Cross St. Pancras | 0.24726 | 0.0846 | -0.00432 | 0.84501 | 0.0093 |
| 3 | Waterloo | 0.25418 | 0.08183 | -0.00277 | 0.85645 | 0.01144 |
| 4 | Bank and Monument | 0.21465 | 0.07768 | -0.00415 | 0.86075 | 0.0043 |
| 5 | Canada Water | 0.2449 | 0.07283 | -0.00485 | 0.86425 | 0.0035 |
| 6 | West Hampstead | 0.45683 | 0.05321 | -0.01962 | 0.86982 | 0.00557 |
| 7 | Earl's Court | 0.09618 | 0.5166 | 0.46339 | 0.87119 | 0.00137 |
| 8 | Sheperd's Bush | 0.12885 | 0.04584 | -0.47076 | 0.88107 | 0.00988 |
| 9 | Euston | 0.08708 | 0.04163 | -0.00421 | 0.88125 | 0.00018 |
| 10 | Baker Street | 0.09844 | 0.03816 | -0.00347 | 0.88793 | 0.00668 |

**Table 9 Sequential Removal Top-10 nodes by Information Centrality**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Removal Node | Node’s Centrality | Global Efficiency | Change on Global Efficiency | Modularity | Change on Modularity |
| **0** |  | | **0.10126** | **NA** | **0.83021** | **NA** |
| 1 | Bank and Monument | 0.0005983 | 0.09673 | -0.00453 | 0.83798 | 0.00777 |
| 2 | King's Cross St. Pancras | 0.0005693 | 0.08988 | -0.00685 | 0.84551 | 0.00753 |
| 3 | Green Park | 0.0004761 | 0.08793 | -0.00195 | 0.85017 | 0.00466 |
| 4 | Baker Street | 0.000456 | 0.08436 | -0.00357 | 0.85577 | 0.0056 |
| 5 | Canada Water | 0.0004407 | 0.07711 | -0.00725 | 0.8633 | 0.00753 |
| 6 | West Hampstead | 0.0002965 | 0.05575 | -0.02136 | 0.86665 | 0.00335 |
| 7 | Earl's Court | 0.0006428 | 0.05413 | -0.00162 | 0.86842 | 0.00177 |
| 8 | Shepherd's Bush | 0.0005907 | 0.04849 | -0.00564 | 0.87313 | 0.00471 |
| 9 | Turnham Green | 0.0005748 | 0.04256 | -0.00593 | 0.87672 | 0.00359 |
| 10 | Stratford | 0.0014937 | 0.03616 | -0.0064 | 0.88803 | 0.01131 |