Comparing the costs of pedestrian wayfinding heuristics across different urban network morphologies

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Abstract

During wayfinding, pedestrians do not always choose the shortest available route. Instead, route choices are guided by several well-known wayfinding strategies or heuristics. These heuristics minimize cognitive effort and usually lead to satisfactory route choices. The length of the route obtained from applying a wayfinding heuristic is dependent on the spatial arrangement or morphology of the urban pedestrian network. This study evaluates the cost of four popular wayfinding heuristics across nine different urban network morphologies. It observes that the cost of these wayfinding heuristics vary significantly and individually differently with morphology, supporting the assumption that people choose heuristics by environment.

Keywords: pedestrian wayfinding, route choice, heuristics, urban network morphologies

1 Introduction

Human wayfinding in outdoor spaces involves selecting path segments from an existing real-world network to determine a route between any two given points in the network (Golledge, 1995). Pedestrians, during wayfinding, do not always choose the shortest available route (Christenfeld, 1995), but apply certain wayfinding strategies or heuristics that minimize their cognitive effort (Bailenson et al., 2000). These wayfinding heuristics are not only applied by a navigator in an unfamiliar environment, but also by people having complete spatial knowledge relevant for making wayfinding decisions.

Golledge (1995) observed that path selection criteria of pedestrians change with a change in the environment. A possible reason for this being, that the route lengths of different heuristics change with a change in the spatial arrangement of the pedestrian network, also known as network morphology. Hence, pedestrians possibly prefer one heuristic in a certain morphology, and a different one when the morphology changes, in an attempt to minimize not only their cognitive load, but also the difference in length with the shortest route. In this study we are estimating the cost of a wayfinding heuristic in different network morphologies, for which we consider the difference in route lengths between a heuristic route and the shortest one.

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A review of existing human wayfinding literature reveals that a substantial amount of research has been conducted on theorising pedestrian wayfinding heuristics based on observations of actual and probable pedestrian behaviour in relatively small environments (Golledge, 1995; Christenfeld, 1995; Hochmair, 2000; Bailenson et al., 2000; Dalton, 2003; Duckham and Kulik, 2003). Hochmair and Karlsson (2005) inferred the conditions of preference between two well-known heuristics, by observing probable pedestrian behaviour at one road intersection. But no study has either evaluated the costs of several well-known wayfinding heuristics on a large, city-wide scale, or compared the variations among the cost of these heuristics across different types of network morphologies. In contrast, this study investigates the cost of multiple pedestrian wayfinding heuristics in nine cities with different network structures to understand the influence of network morphology on possible pedestrian route choice. The objectives of this research are

1. to evaluate the cost of multiple well-known pedestrian wayfinding heuristics, and
2. compare the variations among the cost of these heuristics across different urban morphologies.

To attain the stated research objectives, this study undertakes a simulation approach and uses OpenStreetMap to obtain network information. Four well-known pedestrian wayfinding heuristics, which are solely dependent on the structural characteristics of the pedestrian network rather than functional ones, were simulated by developing algorithms based on their definitions found in the literature.

2 Methodology

2.1 Selecting the cities for this study

Thompson et al. (2018) identified that the design of cities is associated with the burden of road transport injury and targeted urban design as an approach to mitigating the challenges associated with rapid motorization. They applied a combined convolutional neural network and graph-based approach on a set of map images of 1632 cities across the globe and distinguished nine distinct urban morphologies. They found *informal*, *irregular*, *large block*, *cul-de-sac*, *high transit*, *motor city*, *chequerboard*, *intense* and *sparse* morphologies. For our study, one representative city from each of these nine categories was selected. To extract information about the pedestrian network of each city, data from OpenStreetMap, a collaborative mapping project with data contributed by volunteers, was used. Since this study concerns wayfinding of pedestrians, it was made sure that the representative cities have a good pedestrian network coverage in OpenStreetMap, keeping in mind the fact that pedestrian network coverage is notoriously neglected in OpenStreetMap (Barrington-Leigh and Millard-Ball, 2017). The results should not be biased by varying degrees of data coverage.

2.2 Selecting the study area for each city

By querying the names of the selected cities in the GeoNames gazetteer the co-ordinates of center points for each city were obtained. Around these center points a square area of 5 kilometers side length was chosen for this experiment. The squares contain a peripheral buffer zone of 500 metres for accommodating routes, but all origins and destinations were chosen in the central areas of the squares. The extent of these squares was chosen based on the usual lengths of walking trips obtained from the literature and for the preservation of the unique morphological characteristics of the pedestrian network of each city. The uniform design of study areas enables to compare the nine different urban morphologies irrespective of the shape and size of the actual boundaries of the city centers.

2.3 Selecting the origins and destinations

For the experiment a large number of pedestrian routes were formed randomly by specifying their origin and destination (the OD pair). Origins and destinations are on nodes in the network. For the simulation, to represent actual pedestrian behaviour the network distance between the OD pairs should represent usual and realistic walking trip lengths. At the same time these simulated routes should not be too short, since for short distances heuristic routes will only be marginally different from shortest paths. Our choices were informed by literature: Yang and Diez-Roux (2012) observed that in the US the mean and median values for walking trips were 1.1 and 0.8 kilometres, respectively. Similarly, in Melbourne the average walking trip is 1.0 kilometre, while 23% of walking trips are over 1.6 kilometres (State of Victoria, 2010). Robertson (2005) observed that the mean walking distance across different boroughs of London was 0.75 kilometres. In India (Tiruchirapalli), Arasan et al. (1994) found an average critical trip time of 20 minutes (equivalent to 1.7 kilometres), while Rahul and Verma (2014) observed a mean walking trip distance in Bangalore of 0.75 kilometres.

In the experiment, the shortest distance between any OD pair was calculated using Dijkstra's shortest path algorithm (Dijkstra, 1959) along the pedestrian network. The OD pair was considered a valid one if the length of the shortest path fell in the range between 400 metres (equivalent to a five minute walk) to 2000 metres (equivalent to a 25 minute walk), based on the reviewed literature.

2.4 Number of simulated routes

Since the results reported are averages the threshold for the number of simulations was chosen to deliver stable values. Giacomin and Levinson (2015) conducted sensitivity analysis of the number of route simulations required to obtain stable values of average circuity, across different cities in the U.S. and revealed that the means converge at around 50,000 route simulations. Boeing (2019) had also chosen 50,000 random routes along street networks across different cities for their analysis of average circuity. Hence, in this study, we simulated 50,000 random routes in each of the urban pedestrian networks, observing that results converged in all cases safely.

2.5 Wayfinding heuristics

Other than calculating the shortest routes, four wayfinding heuristics were simulated. These simulated routes represent routes that would be chosen by pedestrians if they apply a single heuristic consistently during their wayfinding. The heuristics chosen for this study are *least angle strategy*, *longest-leg first strategy*, *shortest-leg first strategy* and *fewest turns strategy*. Although there exists a host of other wayfinding heuristics, only the chosen ones are geometric in nature. Since the objective of this study is to observe the variations in cost of wayfinding heuristics across urban morphologies, it is justified to select heuristics which are solely geometric in nature and hence, dependent only on the geometric structure of the network. In these heuristics, the location of taking a turn or the number of turns taken during wayfinding determine the route choice. Hence it was necessary to define what is meant by a 'turn'. Although there are a few definitions of a turn used in relevant literature (Zhou et al., 2014; Klippel and Montello, 2007), not all are appropriate for pedestrian routing. Li and Dong (2010) selected a threshold of 45° in their study of formation of strokes based on perceived good continuation. Accordingly, in our study a turn has been defined as follows: If two consecutive road segments in a route have a deflection angle (difference in bearing) of 45° or more, the move from one to the other is considered a turn. Although this definition can have different implications at different levels of geometric abstraction, it was selected for our study given its simplicity in implementation and satisfactory outputs (obtained from visualization of randomly sampled routes). The heuristics and the implemented algorithms are discussed briefly as follows.

Least angle strategy: Hochmair (2000) proposed a real-world wayfinding heuristic called 'least angle strategy' which can be applied in an unknown environment if the destination can be perceived directly by the navigator, at least at the beginning of the navigation process. At each decision point, the pedestrian prefers the road segment which has the least deviation from the direction of the intended destination. The original algorithm, resulted in significantly longer routes more often, which were impractical, meaning that these routes would not be chosen by a pedestrian during wayfinding. Hence a modified version of the original algorithm was developed, as shown in algorithm 1, which resulted in more realistic routes, more often.

Algorithm 1: Least angle strategy algorithm

Initial conditions: An undirected graph G = (N,E), where N is the set of nodes and E is the set of edges in the network with edge_weight ← edge_length;
origin, destination, node ∈ N;
Step 1: Define heuristic;
target_angle ← bearing(origin,destination)
node_angle ← bearing(origin,node)
deflection_angle ← absolute_value(target_angle - node_angle)
return 100000 * deflection_angle *(so that edge_length has minimum influence on chosen route)*
Step 2: Calculate shortest route using A-Star algorithm;
end

Longest leg first strategy: The longest leg first strategy involves basing decisions disproportionately on the straightness of the initial segments of the routes (Bailenson et al., 2000). The pedestrian chooses to prefer longer and straighter initial segments to reach as close as possible to their destination, without taking a 'turn' and thereby reducing the cognitive effort spent during wayfinding. This heuristic is also popularly known as the 'initial segment strategy'.

Algorithm 2: Longest leg first strategy algorithm

Initial conditions: An undirected graph G = (N,E), where N is the set of nodes and E is the set of edges in the network with edge_weight ← edge_length;
origin, destination ∈ N;
Nomenclature:
NT_nodes = nodes which can be traversed from origin without taking a turn;
Step 1: Search for all NT_nodes in the graph using Breadth-First Search;
Step 2: route_node ← node ∈ NT_nodes which satisfies min(dijsktra_path_length(destination,node));
Step 3: final_segment ← dijsktra_path(route_node,destination);
Step 4: initial_segment ← traversed_path(origin,route_node);
Step 5: route ← append(initial_segment,final_segment);
return route;
end

Shortest leg first strategy: Although Golledge (1995) and Dalton (2003) have mentioned the shortest leg first strategy as one of the least preferred wayfinding heuristic by pedestrians, there was no formal definition found in the literature. Hence, for this study, we have assumed that this strategy involves taking turns in the initial portion of the route to keep the latter portions as straight as possible. Hochmair and Karlsson (2005) stated that shorter initial legs provide pedestrians with the choice to explore further alternatives quickly at the next decision point, to reduce the cost of potentially required backtracking when compared to long initial segments. Based on our understanding, we have obtained the shortest leg first route for an OD pair by swapping the positions of origin and destination in algorithm 2.

Fewest turns strategy: Golledge (1995) observed that the fewest turns strategy is the most popular wayfinding strategy and ranked it just after shortest distance and least time criteria. Zhou et al. (2014) developed modified wayfinding algorithms based on this heuristic. Pedestrians tend to choose routes involving the fewest number of turns that result in so called simpler routes, since turns involve decision making and increased cognitive effort. Our algorithm involves reaching a set of nodes from the origin that do not require taking a turn, and then selecting from that set, the node closest to the destination, and repeating the entire process at every turn until the destination is reached.

Algorithm 3: Fewest turns strategy algorithm

Initial conditions: An undirected graph G = (N,E), where N is the set of nodes and E is the set of edges in the network with edge_weight ← edge_length;
origin, destination ∈ N;
route = null;
Nomenclature:
NT_nodes = nodes which can be traversed from temp_route_node without taking a turn;
Step 1: temp_route_node ← origin;
Step 2: while *temp_route_node* ≠ *destination* **do**
    Search for all NT_nodes in the graph using Breadth-First Search;
    Calculate shortest path from all NT_nodes to the destination using Dijkstra's shortest path algorithm;
    route_node ← node ∈ NT_nodes which satisfies min(dijsktra_path_length(destination,node));
    temp_route_segment ← traversed_path(temp_route_node,route_node);
    route ← append(route,temp_route_segment);
    temp_route_node ← route_node
end
return route;
end

3 Results and discussion

The results of the simulation (Table 1 and Table 2) show the obtained mean heuristic route lengths and reveal the variations in heuristic cost in and across pedestrian networks of cities having different morphologies, respectively. Figure 1 shows the mean route lengths obtained from simulating the shortest route and four wayfinding heuristics while Figure 2 shows the percentage increase in mean route length obtained from the four wayfinding heuristics with respect to the shortest route length, representing the cost of different heuristics.

3.1 Variations in heuristic cost

Figure 2 shows that the least angle strategy is the costliest (25% longer than the shortest routes when averaged across nine cities) among all the four wayfinding heuristics. This is in contrast to the statement presented by Hochmair (2000), which says "the least angle method leads to the target in most cases and results in the shortest path for most types of street networks". Hochmair and Frank (2000) conducted agent-based simulations for a relatively short pedestrian network in the inner city of Vienna and hence their results may not represent that of larger urban networks, like the ones chosen for our study, or that of other morphologies. The longest leg first and shortest leg first strategy exhibit very similar mean heuristic route lengths for each network morphology. Their route lengths are marginally longer (2% when averaged across nine cities) than the shortest routes, and hence these two heuristics have the lowest cost. The routes obtained from the fewest turns strategy were found to be on average 11% longer than the shortest routes across the nine cities, as shown in Table 2. Similar results were obtained by Duckham and Kulik (2003) who report

16%, although their algorithm determined the routes with minimum instruction complexity, which only bears an inherent similarity with fewest turns route since instruction complexity is directly proportional with the number of turns during wayfinding.

	Mean route length (in metres) obtained after 50000 simulations				
City name (Morphology)	**Shortest route**	**Least angle**	**Longest leg first**	**Shortest leg first**	**Fewest turns**
Bengaluru (Informal)	1356.6	1652.4	1401.7	1402.0	1534.4
Abu Dhabi (Irregular)	1344.8	1725.9	1370.9	1372.4	1462.9
Moscow (Large block)	1346.5	1810.4	1366.8	1365.2	1518.0
Jakarta (Cul-de-sac)	1374.6	1896.7	1407.6	1407.3	1536.6
London (High transit)	1352.9	1635.7	1379.9	1379.5	1521.8
Melbourne (Motor city)	1340.1	1589.5	1371.1	1370.9	1459.0
New Orleans (Chequerboard)	1313.0	1457.0	1358.0	1357.2	1398.7
Tokyo (Intense)	1343.9	1659.9	1374.5	1374.6	1527.8
Beijing (Sparse)	1360.2	1695.1	1393.1	1393.5	1472.7

Table 1: Variation in mean route lengths across different pedestrian wayfinding heuristics

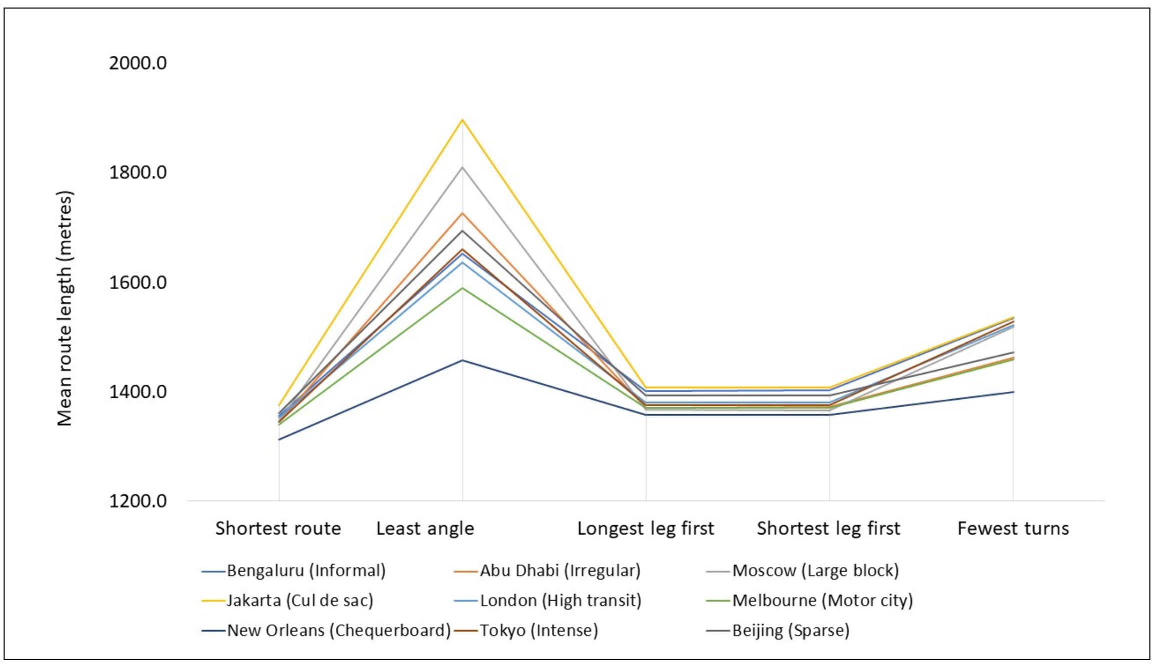

Figure 1: Mean heuristic route lengths across different urban morphologies

The boxplots of heuristic route lengths of New Orleans and Jakarta are shown in Figure 3 and Figure 4 respectively. Given the significantly wider range of route lengths obtained from simulating the least angle strategy when compared to other heuristics, even in New Orleans where it costs the least among all other cities, it can be inferred that the least angle strategy alone proves to be significantly and unnecessarily costly, especially for long-distance walks. This indicates that this heuristic is either partly employed or not employed during wayfinding by pedestrians for longer walking trips.

	Percentage increase in route length with respect to shortest route length			
City name (Morphology)	**Least angle**	**Longest leg first**	**Shortest leg first**	**Fewest turns**
Bengaluru (Informal)	22	3	3	13
Abu Dhabi (Irregular)	28	2	2	9
Moscow (Large block)	34	2	1	13
Jakarta (Cul-de-sac)	38	2	2	12
London (High transit)	21	2	2	12
Melbourne (Motor city)	19	2	2	9
New Orleans (Chequerboard)	11	3	3	7
Tokyo (Intense)	24	2	2	14
Beijing (Sparse)	25	2	2	8
Mean (%)	**25**	**2**	**2**	**11**

Table 2: Percentage increase in heuristic route length with respect to shortest route length

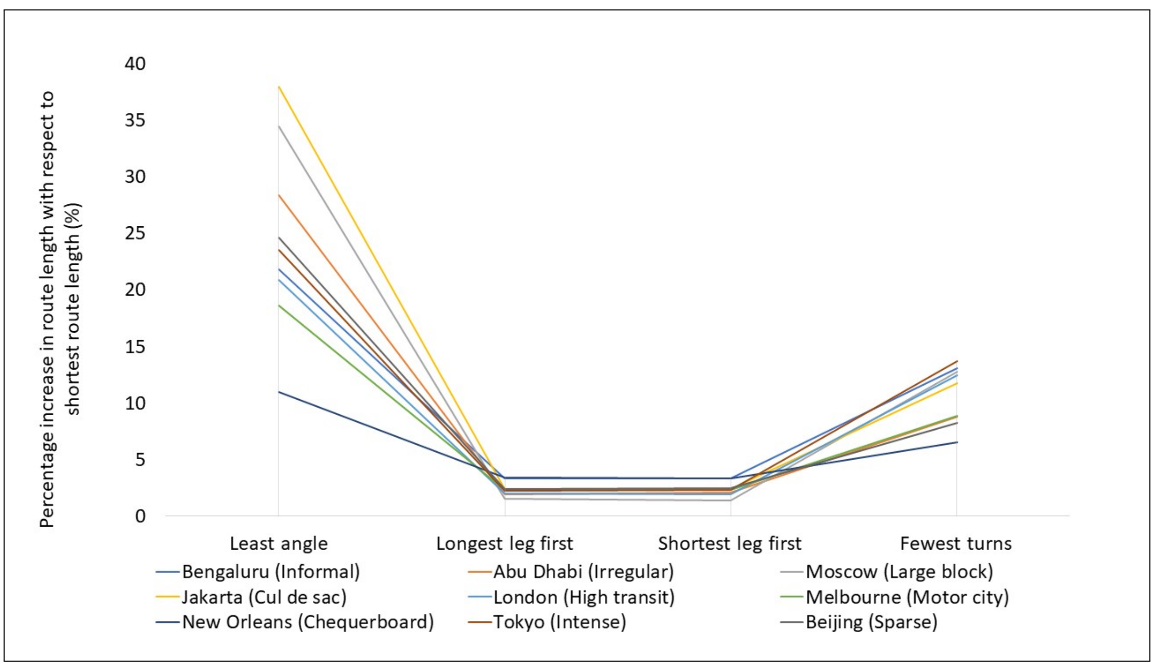

Figure 2: Percentage increase in heuristic route length with respect to shortest route length

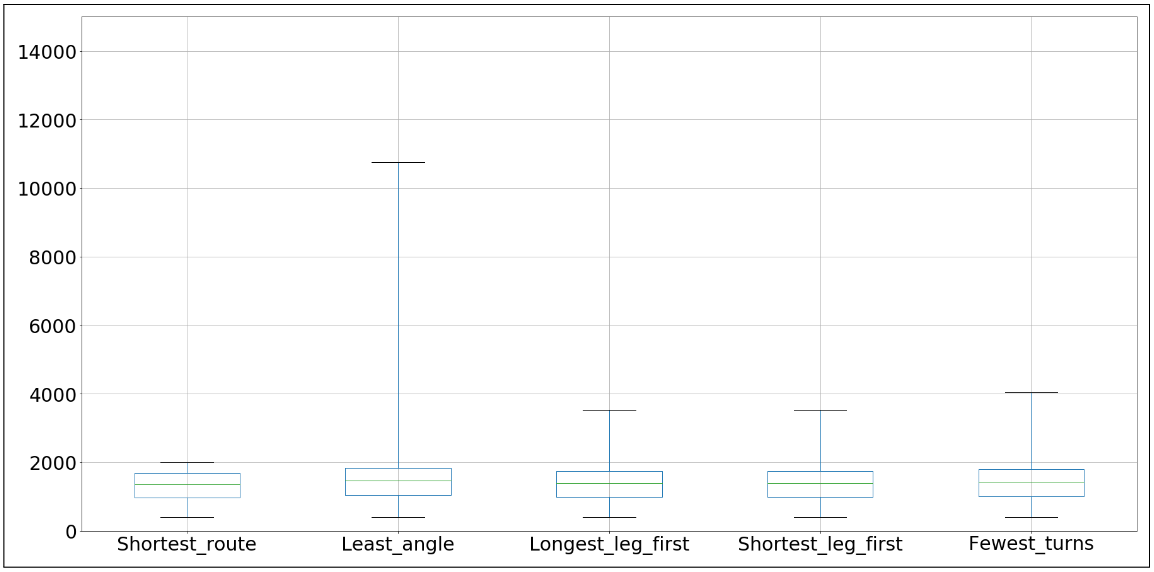

Figure 3: Boxplot of obtained route lengths (in metres) in New Orleans grouped by wayfinding heuristics

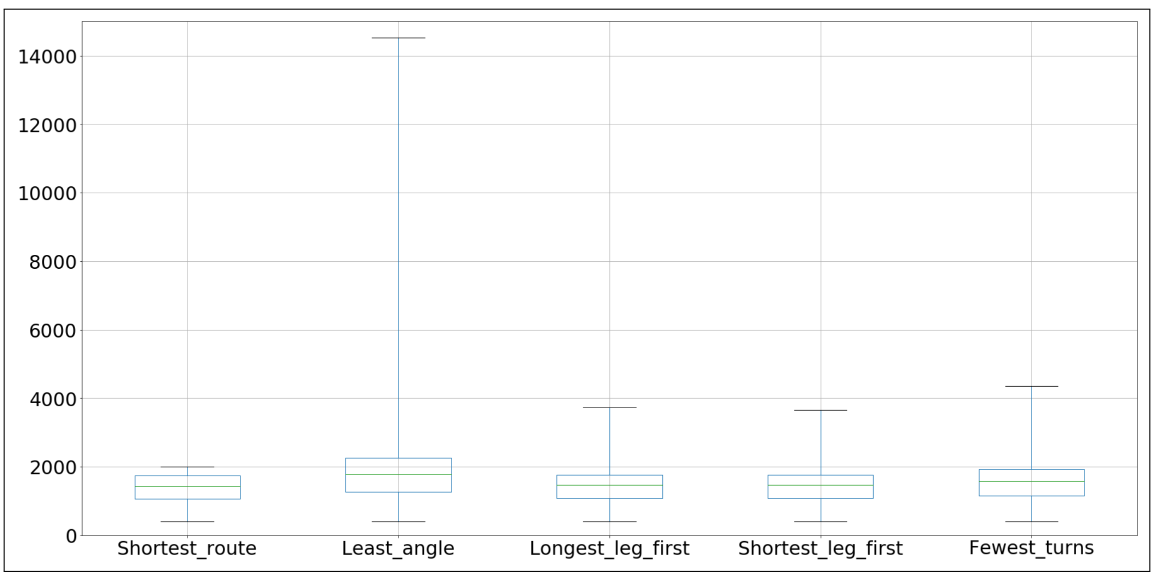

Figure 4: Boxplot of obtained route lengths (in metres) in Jakarta grouped by wayfinding heuristics

3.2 Variations in heuristic cost across different urban morphologies

It can be observed from Figure 2 that New Orleans has the least variation in cost across the four heuristics, among all the nine cities. The underlying reason can be the regular grid-like pattern of almost the entire pedestrian network around the city centre which is shown in Figure 5. Melbourne bears the closest resemblance in terms of results with New Orleans, because of the existence of a large grid-like network in its Central Business District and in some of its northern suburbs, as shown in Figure 6. Jakarta, whose pedestrian network is relatively irregular as compared to New Orleans and Melbourne, as shown in Figure 7, can be observed to have significantly larger variations among the heuristic costs when compared with other cities.

Figure 5: Pedestrian network - New Orleans

It can be inferred from these observations that regularity in network morphology is inversely related to the variations among the cost of different wayfinding heuristics. Networks that have a grid-like pattern have lesser variations in route lengths, irrespective of the chosen wayfinding heuristic. This is due to the fact that in a perfect grid network all heuristic route lengths will be equal to the length of the shortest route, resulting in zero cost. As the network becomes more irregular in terms of morphology, the heuristic routes tend to become more unique, and their cost (difference between heuristic route length and shortest route length) increases disproportionately, leading to significant variations in cost among different heuristics.

4 Conclusions and future work

This study evaluated the costs of four well-known pedestrian wayfinding heuristics by obtaining their mean route lengths via simulation using OpenStreetMap data. It investigated the variation of heuristic costs across different types of network morphologies. It was observed that the least angle strategy was the costliest wayfinding heuristic among the four, when averaged over the nine morphologies, followed by the fewest turns strategy, the longest leg first strategy and the shortest leg

Figure 6: Pedestrian network - Melbourne

Figure 7: Pedestrian network - Jakarta

first strategy. The significantly wider and unrealistic range of route lengths obtained from simulating the least angle heuristic indicates that it may not be a popular choice, especially for longer walking trips. It was also observed that the variation in the cost of these wayfinding heuristics increased with an increase in the irregularity of the network, indicating that people may opt for more diverse heuristics while walking through relatively regular networks, and may prefer specific heuristics in the relatively irregular ones.

Despite its systematic approach and robust results, this study has some limitations. First, it is a well-known fact that OpenStreetMap data varies from place to place and is still growing in its coverage, more so for pedestrian networks. Although this issue was considered by the authors while selecting the cities for this study, it had to be assumed in the simulations that the network information obtained from OpenStreetMap was complete. Second, in this study pedestrian agents follow single heuristics for the entirety of the trip. This approach allows to compare the costs of the different individual heuristics. However, it cannot be claimed that pedestrians follow only one heuristic for the entirety of the trip. Thus the simulated routes do not necessarily represent actual pedestrian behaviour, which is highly complex (Hochmair and Karlsson, 2005) and would require the development of more sophisticated simulation models.

Third, pedestrian wayfinding is often influenced by other heuristics as well, such as routes with most landmarks, maximum weather protection, maximum perceived safety, least crowded and least pollution, which have not been accounted for in this study, owing to their non-dependency with network morphology.

Since the route choice heuristics of pedestrians are dependent on the environment, and this study reveals the cost and variations in cost of different heuristics across different structures of urban pedestrian network, it would be interesting to investigate to what extent does actual pedestrian behaviour conform with the results obtained from this study. For example, since the least angle strategy is found to be significantly costlier than other heuristics in morphologies which are relatively irregular, analysing actual pedestrian trajectories in such networks may lead to interesting observations which can open up novel avenues for future research.

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