Complexity of routes in multi-modal wayfinding

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Complexity of routes in multi-modal wayfinding

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Abstract: In this paper we propose a model for assessing the complexity of routes in multi-modal public transportation. Complexity can be of different types: physical, personal, and temporal. We deal only with the physical complexity of routes in this paper. By this we mean the complexity of spatial layout and the degree of visual access of nodes and links in the public transportation system. We make a distinction between path complexity and route complexity. Each is composed of the complexity of nodes and links along the path/route. Those aspects have to be considered at two levels of detail, i.e. at the level of the network and at the level of the individual node. We show and discuss for a specific example the different measures we derive conceptually.

Keywords: human wayfinding, public transportation, criteria for route selection

1 Background

Imagine yourself in the following situation: you are new to the area, you need to find the best route to your destination, and you have decided to use the public transportation system. How can you determine the best route to your destination?

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Research on choosing routes within networks has concentrated on shortest path problems (Dijkstra, 1959) and derivatives, such as fastest or cheapest path. However, the best route can be any of the following list:

- most scenic,
- least stressful,
- least complicated to remember,
- easiest to navigate,
- best suited to a disability,
- best for the time of day (night, rush hour),
- best for current weather, etc.

Those are representatives of at least three different types of ‘best’: the first group (scenic, stressful, complicated, easiest) relies on environmental attributes that do not change, i.e. physical characteristics of the route. The second group (disability) is based on characteristics of the traveler, and the third group (time of day, weather) on attributes that change on a daily or hourly basis, i.e. temporal characteristics.

In this paper, we will derive measures of complexity to describe the physical characteristics of nodes, links, and routes. By measure of complexity, we mean a measure of how difficult a route will be for a traveler without special needs and knowing the language. We use an information processing approach to determine the complexity of nodes, links, and routes of the public transportation system, i.e. we look at the information provided in the environment, how this information is arranged, how complicated it is to find, and to use. This research contributes to the open problem of determining the information needs of wayfinding (Gluck 1991). In the future, we also plan to deal with personal and temporal characteristics of a route.
Our wayfinding problem is set within the environment of the public transportation system in Zurich. The multi-modal system encompasses feet, buses, trams, funiculars, and city-railway. Our simple example (see Fig. 1) needs trams as well as some links on foot. We make a distinction between the typical network view of a transportation system and the more detailed route view a traveler needs (Timpf 2002). More concrete, the traveler has a three-dimensional metric view of the places and links on the route, whereas the network view is one-dimensional and topological.

Fig. 1: Trip from Radiostudio to Ottikerstrasse with transfer at Schaffhauserplatz

Our aim is to assign a complexity measure to a specific route in order to compare this route to a second one while selecting the “best” route. We propose and discuss several measures for the complexity of nodes and the complexity of links. We make a distinction between the complexity of a node (link) and the complexity of this node (link) for a particular route (section 4). This distinction results in a distinction between the complexity of a path within the network and the complexity of a route.

Our model can be used as the basis for a wayfinding model that derives good wayfinding directions (Lovelace 1999, Carstensen 1991) to provide an automated assistance.
for travelers in the city of Zurich. In addition, it can be used to evaluate the public transportation network as a whole, and specific places within that network in particular to improve system legibility and ease of wayfinding.

This paper may be interesting to designers, managers, and optimizers of public transportation systems. It also considers aspects that may be inspiring to architects, environmental psychologists, cognitive scientists, and to human geographers interested in wayfinding.

2 Related Work

We build on research of Gaerling 1986, who proposed a system for classifying environments to predict the extent of wayfinding problems. Weismann 1981 recommended similar classes of environmental variables that influence wayfinding performance (meant for buildings). According to Gaerling, the following three facets of the environment are important for successful wayfinding:

- degree of (architectural) differentiation,
- degree of visual access, and
- complexity of spatial layout.

The degree of architectural differentiation is less relevant for the city environment than it is for the building literature, where Gaerling’s study originates. Within the public transportation system each node and link is well identified, either through names or numbers. We will therefore disregard differentiation in this paper.

Gaerling interprets the measure of visual access to mean the visibility of start and end nodes. The start and end nodes of a route within a city are usually not visually accessible from a single vantage point, because the space we are dealing with is at a geographic or
environmental scale (Montello 1993). However, visual access or legibility (Lynch, 1960) of features at transfer nodes improves wayfinding and spatial orientation. We will interpret degree of visual access to mean the degree to which start and end nodes are visible at transfer nodes.

Complexity of spatial layout refers to the environmental size and the number of possible destinations and routes. “A simple layout should facilitate both the formation and execution of travel plans by making it easier to choose destinations and routes, to maintain orientation, and to learn about the environment” (Evans et al., 1984, as cited in Gaerling 1986). The complexity of spatial layout and visual access are intricately linked: a complex layout can also mean a visually cluttered environment, conversely a visually legible environment does not mean a simple layout.

Raubal (1998) determines the complexity of wayfinding tasks in built environments (i.e. airports) using image schemata found in the physical structure of the environment. His approach is different from ours in that we describe the physical structure of the environment in order to derive a measure for complexity that is independent from the human person perceiving this environment. However, we take into account those physical structures that are known to have an impact on human wayfinding and orientation abilities (Gaerling, 1980) without using image schemata. It would be beneficial to compare our results with the results from a wayfinding model as proposed by Raubal (1998). This will be part of future work.

In Raubal and Worboys 1999, image schemata are augmented with action and information affordances to describe the physical environment as perceived by a human. This results in a wayfinding graph. The nodes of the wayfinding graph represent states of knowledge and current location, whereas links represent transitions between those. Gaerling’s notion of visual access might be represented with the wayfinding graph. We will investigate
the derivation of a simple measure for visual access via the wayfinding graph in the near future.
3 Representing the public transportation network

We are investigating wayfinding in urban public transportation networks, where more than one means of transportation is used. Our model includes foot, bus, tram, and funicular.

3.1 Wayfinding Example

In our wayfinding example foot and tram are used. A traveler wishes to travel from “Radiostudio” to “Ottikerstrasse”. The fastest way to do so is shown in Fig. 1, i.e. she travels from Radiostudio to Schaffhauserplatz by tram 11 and then to Ottikerstrasse by tram 7 or 15. At the transfer node “Schaffhauserplatz”, the transportation means must be changed.

![Schaffhauserplatz diagram](image)

The transfer node Schaffhauserplatz can either be simple or difficult to navigate, depending on to which tram line our traveler changes. As shown in Fig.2, if a person arrives at Schaffhauserplatz with tram 11 from direction Radiostudio, two actions can be taken:
either, she waits for tram 15 to arrive at the same tram stop or, she walks around the building to the tram stop of tram 7. The first solution is simple, the second solution is more complex. The aim of our complexity measure is to adequately represent such differences.

3.2 Hierarchical representation of transportation network

We use an graph-theoretic approach to modeling the transportation network using at least two levels (Timpf, 2002). Each bus or tram line is represented by two differently headed links (one for each direction), stops are represented by nodes. The transportation system is composed of nodes and links, where nodes are places and contain stops and links refer to rides taken in buses or trams between nodes.

This directed multi-graph represents the transportation network at the first level of detail (Fig. 3a). At the second level of detail nodes are expanded to networks, whereas links are identical to those at the first level. Node networks show stops for each transportation line within the place and links representing (foot)-paths between stops (Fig. 3b).

Fig 3: Transfer node at two levels of detail: a) less and b) more detailed
4 A model for the complexity of routes

Our aim is to derive a measure of how difficult or complex a given route will be under present circumstances. We are looking for a means to assess complexity while planning and optimizing a route. We will not consider performance of wayfinding to derive route difficulty. However, we plan to validate our model with performance measures and interviews in the near future.

Three different aspects of navigation complexity can be considered: physical, personal, and temporal complexity. Physical complexity refers to potential problems while wayfinding along the designated route. Thus, it refers to the problems inherent in the route that are due to spatial layout and visual access.

The second aspect of navigation complexity is personal difficulty, which refers to the strains that are imposed onto the person and depends very much on the fitness of the person. This measure can be used to express special needs (such as walking stick, handicapped people, blind, person with children, etc.). However, we will not take this measure into account, since we have no means to derive this information for the traveler.

The third aspect of navigation complexity is temporal difficulty, which refers to temporal aspects while navigating a specific route (such as rush hour, weather, construction work, etc.). In this paper we will only deal with physical difficulty as a measure for the complexity of routes.

The constituents of physical complexity in our two-level graph are given by the complexity of node (section 4.3.) and link (section 4.4.) at the first level. The complexity of a node at the first level is computed from the complexities of its parts (see Fig. 3), i.e., the complexity of node (section 4.1.) and link (section 4.2.) at the second level. We treat each of the measures separately starting from the second level and working our way up the hierarchy.
Finally, path and route complexity are computed from those four measures (sections 4.5 and 4.6).

### 4.1 Node complexity $C_N^2$

The complexity of the node at the second (detailed) level is computed as the number of directed links into and out of the node. This is easily determined from node in-degree and node out-degree using the hierarchical directed multi-graph. Table 1 shows node complexity at the detailed level for the places within our example route (Fig. 1). Stops are conceptualized as the locations of the sign posts indicating the name and connections at this stop.

<table>
<thead>
<tr>
<th>Node</th>
<th>stop</th>
<th>indegree</th>
<th>outdegree</th>
<th>$C_N^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottikerstrasse</td>
<td>S1</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Radiostudio</td>
<td>S1</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Schaffhauserplatz</td>
<td>S1</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>s</td>
<td>S3</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Node complexity at the detailed level

### 4.2 Link complexity $C_L^2$

Links at the second level of detail, i.e., links on foot within transfer nodes carry complexity depending on the following criteria: distance between stops, number and type of street crossings, number of non-visible stops. Non-visible stops occur if, for example, the bus stop is around the corner from the tram stop. Table 2 shows the link complexity at the second level calculated from the number of streets to cross and the number of non-visible stops. The
distance is only nominally included as our results suggest that the influence on complexity is marginal, since distances are relatively short. What is missing in this measure is the type of street crossing. Our data does not (yet) support to derive this information. The number of turns (Winter 2002, Gollende 1995) also was a candidate for inclusion within the measure. However, we found a high correlation between the number of crossings and the number of turns. The number of crossings has an impact on the link time which will be used to determine the transfer time.

<table>
<thead>
<tr>
<th>stop</th>
<th>link</th>
<th>length (m)</th>
<th>streets to cross</th>
<th>non visible stops</th>
<th>$C_{L,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottikerstrasse</td>
<td>P1-P2</td>
<td>40</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Radiostudio</td>
<td>P1-P2</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Schaffhauserplatz</td>
<td>P1-P2</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P1-P3</td>
<td>50</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>P1-P4</td>
<td>58</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>P1-P5</td>
<td>120</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>P1-P6</td>
<td>160</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>P2-P3</td>
<td>45</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>P2-P4</td>
<td>53</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>P2-P5</td>
<td>115</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>P2-P6</td>
<td>155</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>P3-P4</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>P3-P5</td>
<td>90</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>P3-P6</td>
<td>130</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>P4-P5</td>
<td>80</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>P4-P6</td>
<td>120</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>P5-P6</td>
<td>60</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Complexity of link at detailed level

4.3 Node complexity $C_N^1$

The complexity of a network node at the first level is computed from four measures taken from the physical environment: number of stops (subnodes), number of lines, the sum
of the complexity of the nodes at the second level, and the sum of the complexities of the links at the second level.

<table>
<thead>
<tr>
<th>node</th>
<th>stops n</th>
<th>links m</th>
<th>$C_N^2$</th>
<th>$C_L^2$</th>
<th>$C_N^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oberwiesenstrasse</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Radiostudio</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Schweizer Rück</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Ottikerstrasse</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Triemli</td>
<td>4</td>
<td>12</td>
<td>10</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>ETH/Universitätsspitäl</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>Milchbuck</td>
<td>6</td>
<td>12</td>
<td>20</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>Bürkliplatz</td>
<td>5</td>
<td>6</td>
<td>24</td>
<td>4</td>
<td>39</td>
</tr>
<tr>
<td>Kirche Fluntern</td>
<td>4</td>
<td>9</td>
<td>12</td>
<td>14</td>
<td>39</td>
</tr>
<tr>
<td>Stauffacher</td>
<td>6</td>
<td>12</td>
<td>22</td>
<td>8</td>
<td>48</td>
</tr>
<tr>
<td>Klusplatz</td>
<td>5</td>
<td>20</td>
<td>12</td>
<td>20</td>
<td>57</td>
</tr>
<tr>
<td>Schwamendinger Platz</td>
<td>5</td>
<td>20</td>
<td>16</td>
<td>16</td>
<td>57</td>
</tr>
<tr>
<td>Paradeplatz</td>
<td>6</td>
<td>30</td>
<td>28</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td>Kunsthaus</td>
<td>6</td>
<td>30</td>
<td>20</td>
<td>50</td>
<td>106</td>
</tr>
<tr>
<td>Schaffhauserplatz</td>
<td>6</td>
<td>30</td>
<td>20</td>
<td>50</td>
<td>106</td>
</tr>
</tbody>
</table>

Table 3: node complexity

This translates into the following formula:

$$C_{N^1} = \sum_{i=1}^{n} C_{N^i}^2 + \sum_{j=1}^{m} C_{L^j}^2 + n + m$$

(node complexity 1)

From this measure (Table 3) four categories have been derived: nodes with low, medium, higher, and high complexity. Figure 4 shows prototypical examples for each of these categories.
4.4 Link complexity $C_L$¹

Link complexity at the first level within a public transportation network is low. As soon as the traveler boards the bus or tram, no more open choices exist, thus complexity is zero.
4.5 Path complexity

The physical complexity of a path is composed of the complexity of the link and the complexity of the node at the first level. Within the public transportation network, link complexity has little influence on overall complexity because once the traveler has entered a link she cannot leave it other than at the next node. Thus, the physical complexity of a path within the network is the same complexity than the sum of the complexities of the start, end, and transfer nodes along that path. The complexity of the path from Radiostudio to Ottikerstrasse with change at Schaffhauserplatz is \( C_p = 12 + 106 + 16 = 134 \). This sum is indicative of the difficulties a traveler will experience when traveling along this path.

However, as already mentioned in section 3.1., this measure does not take into account that the actual transfer could be much simpler than the overall complexity of a transfer node. This leads to the notion of route complexity.

4.6 Route complexity

The physical complexity of a route in contrast to that of a path is composed of the complexity of the nodes and links at the second level specific to the route. This measure takes into account, that for a specific route the complexity of a node can be very low if the transfer to make consists of, e.g., getting off a tram, staying at that place, and getting onto a tram. The idea is, that each transfer node only contributes the complexity of the actual transfer that needs to be made in order to follow the route. This leads to a different formula for the start, end, and transfer nodes along the route (replaces formula (1)):

\[
(C_{N^0})_R = \sum_{j=1}^{n} (C_{N^0}^j)_R + \sum_{j=1}^{m} (C_{N^2})_R + n + m
\]

(node complexity 2)

Route complexity is then calculated as the sum of the complexity of all nodes along the route, \( r \) ist the number of transfer nodes plus one start and one end node:
\[ C_R = \sum_{i=1}^{r} C_N^i \tag{3} \]

For our example route this measure yields \( C_R = 5 + 5 + 5 = 15 \) (with \( r = 3 \)) for a change from tram 11 to tram 15. The more complex solution calls for a change from tram 11 to tram 7 which yields the complexity \( C_R = 5 + 12 + 5 = 22 \). As originally intended the complexity measure shows the difference between those two solutions.

5 Results and Future Work

We have shown that a complexity measure for physical complexity in public transportation networks can be calculated based on information on the environment at nodes and on information on the network structure. We have also shown that for a meaningful complexity measure for routes, two different levels of detail need to be considered, especially within the transfer nodes of the route. We make a distinction between path complexity and route complexity to account for the fact that the complexity of a route-node can be considerably less if only a subset of nodes and links at the second level is considered. We have demonstrated the difference between those two measures using our wayfinding example.

We will conduct surveys to validate our model in the near future in cooperation with the Public Transportation Authority Zurich (VBZ). We also expect from these surveys information on the weight of certain components within a complexity measure. For example, the component non-visible points intuitively seems to carry a greater weight than the number of street crossing in the same measure. Is this really true and if so, how can we incorporate this knowledge into our complexity model?

Architects have come to the conclusion that facilitating human wayfinding in buildings includes more than just putting up a few signs because most of the time signage cannot overcome architectural failings (Arthur and Passini 1992). We assume that this is also true for
open spaces such as transfer points in public transportation networks. According to our results, the less different stops there are within a transfer node, the less orientation and wayfinding difficulties can be expected. Visibility of stops within a transfer node is another influence for easier and more successful wayfinding. We can also deduce from our results, that those stops where visibility is poor need well positioned signs.

The definition of complexity encompasses three different aspects: physical complexity, personal complexity, and temporal complexity. In this paper we dealt with physical complexity. In the future, maybe as part of the empirical work mentioned above, we expect to be able to deal with personal complexity. Temporal aspects affect both physical and personal complexity. Some temporal information, e.g., weather, can be dealt with easily. We will study temporal complexity last.

As already mentioned, it would be beneficial to compare our results with the results from a wayfinding model as proposed by Raubal (1998). In addition, we will incorporate the wayfinding graph into our mode. We expect that the wayfinding graph can deal with automatically deducing visibility among stops, and be able to incorporate existing signage. This is one of the tasks we have set ourselves for the near future.

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