Physical metrics of pedestrian movement in the urban context: development of a test model

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Abstract

It was intended to develop a model that allows the parameterization and comparison of the pedestrian travel conditions in an urban center, relating the time and energy expenditure with the circulation characteristics of the built environment.

The created model was able to show the influence of the different layers of characterization and parameterization on the results of pedestrian movement. The footpaths' slopes, the presence of stairs and pedestrian crossings influenced the travel times simulated in this model, with results similar to those obtained with already existing tools. The added preferences and prohibitions using the modeled characteristics allowed to bring a new dimension to the pedestrian movement prediction.

The calculation and display of oxygen consumption and energy expenditure were metrics that helped inform and contextualize the pedestrian movements in the researched and related areas.

Keywords: Pedestrian Travel, Active Design, Healthy City, Pedestrian Routes, Pedestrian Service Areas, Shading Footpaths

1. Introduction

This work relates to the concept of Active Design (AD), the search for intervention principles in built environment at the city-level scale through non-intrusive and intuitive solutions to the user, to ensure opportunities to practice moderate and integrated Physical Activity (PA) into daily routines without need to resort to auxiliary devices and specialized or costly solutions. It’s part of an emerging line of research anchored in creating proactive conditions in the built environment.

Health and transportation research began to study PA from different perspectives: public health studies focus on the leisure or recreation PA, in which walking is one of its most common forms; while research in urban planning and transportation is interested almost exclusively in walking or cycling with utilitarian purposes, defining them as non-motorized transport [16].

It is also in this context that the concept of Healthy Cities arises. This points to the existence of a relationship between the process of urbanization and health, which requires knowing the conditions in which the urban physical environment interacts with people, facilitating or inhibiting behaviors related to healthy lifestyles, in particular the various components of the urban form and the conditions (modes and systems) of daily mobility.

The architecture as a broad area of knowledge that aggregates several disciplines related to the built environment, and the architect as the main actor has a tremendous social responsibility. This responsibility can be both rewarding and overwhelming but can never be ignored and should be the catalyst for a continuous search of knowledge that enriches the influence of the architect’s work. The way the built environment is thought, designed and built influences its users.

There are several route planners that offer directions for walkers who want to take a trip from one specific location to another [11] [20] [4]. However they ignore many footpaths that can be hiked like parks and gardens, even if they begin to show improvements in this aspect. From the OpenStreetMap [15] project that provides free geographic data, there is a wide variety of applications. OpenRouteService [14] is similar to the aforementioned applications but in some tested situations features more complete footpaths, however still ignoring some. WheelchairRouting [19] is an application that aims to provide accessible paths for wheelchair users by identifying obstacles and showing the slopes. Some of the limitations of these applications result from the geographical data based not on the pedestrian but in motorized
travel. It has been detected that this translates into very different results in various kinds of analysis [5].

KESUE Project [6] developed a different network going from one model using the roads’ center lines to a model based sidewalks, crosswalks and all existing footpaths in the case study. In another project [10] rules were created for digitizing all footpaths, informal pedestrian crossing included, thus helping to streamline and standardize the creation of a model identical to that mentioned above. Using the slopes and from a quantitative and qualitative assessment of the conditions of the footpaths it was also developed an evaluation of walkability – the measure or ability to perform pedestrian travel.

Walkability is often positively linked with AD and the promotion of PA [13]. Badland and Schofield [3] analyze and summarize how several factors of the built environment result in certain physical behaviors and are associated with many health risks. Finally suggest the use of measuring tools, the evaluation of how users travel, their health and a greater collaboration between urban planners and those who study the these two areas. Frank et al. [8] used pedometers to measure pedestrian PA and positively related the results to several urban measures that were translated into a walkability index. Gomez et al. [9] analyze various districts and their socio-economic status, slopes, proximity to the transport system and the percentage of area dedicated to public parks. Among other findings a negative relationship between slopes higher than 4% and regular PA was found.

2. Model development

Being developed at IST a work on walkability based on a pedestrian network with principles equal to those defined for this work [10], this network was used as the starting point for the model. The pedestrian network had its footpaths digitized and for the purpose of this model we needed to further characterize the pedestrian crossings.

Faria et al. compare short urban travels in several means of transport, pedestrian included, and measured several waiting times for signalized pedestrian crossings, zebra pedestrian crossings and informal crossings. In the former two types of pedestrian crossings it was assumed that the waiting time was zero [7]. For the Transportation Research Board a starting time of three seconds is considered reasonable to calculate pedestrian crossing pedestrians [18]. For these reasons it was considered that, in informal and zebra crossings, the pedestrian stops at the beginning of each one resuming the march immediately with no waiting time. This translates into the considered starting time of three seconds for each one.

Almost all the signalized intersections in Lisbon have some degree of dynamic adaptation of the green time, and therefore both the average green time for every crosswalk and the temporal relationship between them are unknown. Several crossings are divided in segments and as a result it is not possible to know which pedestrian walking speeds allow the crossing of a given number of segments in one go. Therefore we are unable to identify the situations where there may exist several stops on a crossing. Without a correct way to characterize the signalized crosswalks, these were treated as the remaining crossings – three-second penalty, the pedestrian start time.

To identify the elevation of each segment of the network, data required to calculate the slope and walking speed, a Digital Terrain Model (DTM) was necessary. If it had insufficient spatial resolution it could result in too many small segments with no slope. Additionally, segments too close to the DTM’s cell limits could end up with an incorrect slope. For these reasons it was created with a new DTM with one meter resolution, 100 times bigger than the available DTM.

The walking speed was calculated in order of the slope of each segment as it was considered this was the physical measurement with greater impact. For this purpose the following equation by Tobler [17] was used, where is S the slope in degrees and W the speed:

\[
W = 6 e^{−3.5 \cdot |S + 0.05|} \quad (1)
\]

This equation was chosen over others since it considers any slope, negative or positive.

In terms of speed, slope, or both it is possible to estimate the oxygen consumption, which allows the calculation of calorie expenditure [2]. Several equations and the corresponding graphs were evaluated before the choice of the equation to be used in the developed model. This equation was estimated using the findings of Yamazaki et al. [21]

Another option included in the model is the choice of routes depending on the shade of footpaths. To be able to identify footpaths exposed to the sun or the shade it was first necessary to create the volumes that represent the shading of the buildings. These buildings were modeled using the map data used in the DTM creation. Due to the nature of this data, the model ignores walls and simplifies the buildings, not including archways and
cantilevered elements. Because of their inherent complexity the plants and street furniture elements were ignored.

To represent summer and winter, the hottest day and the coldest day recorded for the city of Lisbon were chosen. The winter shading volumes were created for five moments of the day: 9h00, 11h00, 13h00, 15h00 and 17h00. For summer six volumes were created, being represented in addition the 19h00 moment. Being created the various representative volumes of shading, the footpaths were identified as fully shaded, partially shaded or not shaded.

After being fully characterized, the pedestrian network had a footpath average length of 7.79 meters with a standard deviation of 2.52 meters, in a total of 21393 segments which together measure 166693 meters. For each calculated field were stores two values, one in each direction of the footpath. Thus it is possible to calculate all results in both directions, essential to identify the effect of the slopes in the pedestrian walking.

Before generating the Service Areas (SA) and pedestrian routes (PR) it was necessary to create the network database. The various footpaths were added and from its stored values the model impedance costs were selected. The SA and PR may be generated according the distance, oxygen consumption, time ignoring slopes, time considering the slopes and stairs. Any value that is not used as the main impedance cost can be calculated and stored. This allows knowing the oxygen consumption in a PR generated according the time, for example. Other fields were also added to the model as restrictions and descriptors. These can identify the footpaths as stairs, their slope and their shade state for every modeled moment. Finally, with the footpaths identified as pedestrian crossings, midpoints for each were created and added to the model as added cost points.

### 3. Case studies and results

One of the first applications of the model is the analysis using the footpaths’ slope. The network of footpaths of the study area has an average slope of its segments of 4.60%. Given that the various segments that compose this network have different lengths, performing a weighted average gave the average slope of the network: 4.53%. In figure 1 the footpaths spread over different slope ranges are visible and in table 1 the number of segments, the total length of footpaths and the percentages for each slope range. An interesting fact to take from this table is that 83.4% of the study area has slopes under 8%, a figure relevant to the study of some user groups with reduced mobility.

![Figure 1: Footpaths slope [%].](image-url)

<table>
<thead>
<tr>
<th>Slope [%]</th>
<th>Segment total</th>
<th>Total length [m]</th>
<th>%</th>
<th>Accumulated %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 2</td>
<td>7627</td>
<td>59580</td>
<td>35.7%</td>
<td>35.7%</td>
</tr>
<tr>
<td>2 - 4</td>
<td>4821</td>
<td>37861</td>
<td>22.7%</td>
<td>58.5%</td>
</tr>
<tr>
<td>4 - 6</td>
<td>3157</td>
<td>24720</td>
<td>14.8%</td>
<td>73.3%</td>
</tr>
<tr>
<td>6 - 8</td>
<td>2105</td>
<td>16833</td>
<td>10.1%</td>
<td>83.4%</td>
</tr>
<tr>
<td>8 - 10</td>
<td>1311</td>
<td>10252</td>
<td>6.2%</td>
<td>89.5%</td>
</tr>
<tr>
<td>10 - 12</td>
<td>852</td>
<td>6499</td>
<td>3.9%</td>
<td>93.4%</td>
</tr>
<tr>
<td>12 - 15</td>
<td>652</td>
<td>4846</td>
<td>2.9%</td>
<td>96.3%</td>
</tr>
<tr>
<td>15 - 20</td>
<td>422</td>
<td>3073</td>
<td>1.8%</td>
<td>98.2%</td>
</tr>
<tr>
<td>20 - 30</td>
<td>186</td>
<td>1219</td>
<td>0.7%</td>
<td>98.9%</td>
</tr>
<tr>
<td>&gt;30</td>
<td>34</td>
<td>218</td>
<td>0.1%</td>
<td>99.0%</td>
</tr>
<tr>
<td>Stairs</td>
<td>226</td>
<td>1590</td>
<td>1.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 1: Footpaths slope.

Knowing if the footpaths are shaded it is possible to create another analysis of the network. As mentioned above, the partially and fully shaded footpaths were identified. Partially shaded footpaths were all treated the same, not being detailed the percentage of shade and sun. The study area with modeled shading is limited to the north by Avenida Elias Garcia and Avenida António José de Almeida, to the west by Rua Marquês Sá da Bandeira, to the south by Rua Tomás Ribeiro, Rua Almirante Barroso and Rua Pascoal de Melo, and the east by the Avenida Almirante Reis. It has 6120 segments which together measure 49017 meters. The segments have an average slope of 3.09% and the network 3.14%. In table 2 the length and percentage of fully shaded, partially shaded or not shaded footpaths for the several modeled moments are shown. In the following figures some examples. The fully shaded footpaths are shown in black, partially shaded in grey and not shaded in yellow.
Table 3: Pedestrian routes.

Whenever features were heavily penalized, longer routes were proposed. For several moments of shading different routes were often suggested. The southern sidewalk of Avenida Rovisco Pais was never part of any designated route, despite being one of the few shaded footpaths in the summer. This was possibly because of the omission of the pedestrian crossing on this avenue, opposite to the entrance of IST.
In figure 4 the pedestrian route created using time ignoring slopes and using time considering slopes. Figure 5 depicts several routes created: winter 09h, winter 17h, summer 13h, oxygen consumption, time considering slopes slopes and stairs and time considering slopes, stairs and crossings. When using medium penalties for stairs and slopes higher than 8% the same route was created.

In figure 6 the route created when using high penalties for stairs and slopes higher than 8%. Figure 7 depicts the pedestrian route suggested for winter 11h. In figures 8 and 9 the pedestrian routes suggested for winter 15h, with medium and high penalties for the shaded footpaths, respectively. In figures 10, 11 and 12 the pedestrian routes for summer 11h, 13h and 15h.
The Google Maps’ results shown in figures 13 are very similar to the obtained results. The suggested route with 700m and 10min towards IST (and 8min towards Alameda, not shown here), are equal to the route visible in the figure 5, which has the same length and the same calculated times. The fastest route suggested by Google Maps was never represented in the created model since it uses an informal pedestrian crossing that was not considered in the digitized network. A set of rules was created and it does not consider informal pedestrian crossings this close to signalized or zebra crossings [10].

3.2. Pedestrian service areas
These areas translate where a pedestrian can go considering a certain number of locations. The shown case study uses Saldanha subway station. The average distance a pedestrian can easily walk is 400 meters [1], which corresponds to a five minute walk [12]. These values, and its double, will be the metric used when creating the SA.

In the first SA the footpaths were drawn within a radius of 400m and 800m from the various entrances to the subway station, as visible in figure 14. These have the advantage of being easily represented because it was not necessary to create a network database. However, it does not truthfully represent the 400m and 800m footpath distances.

Using the created network database more accurate representations were drawn. As depicted in figure 15, the SA is using the distance as impedance cost. When using the time while ignoring slopes as
impedance cost, the SA increases slightly (figure 16). Using 5 and 10 minutes values in the Tobler equation, we obtain 420m and 840m pedestrian walks, respectively.

When using the time while considering slopes there’s differences between the SA towards and away the subway station. If in one direction the footpath has certain slopes, in the opposite direction these slopes have symmetrical values. As a result, the walking speed is different in both directions. In figures 17 and 18 are shown the SA towards and away the subway station – the SA using time without slopes is represented in red. Towards Saldanha subway station the SA is smaller, justified by the fact that Saldanha is on top of a plateau, which reduces the walking speed mostly in that direction. With the intersection of these two SA, the combined SA is shown in figure 19, which always considers the worst case possible.

Using the time while considering slopes and stairs, the differences are almost null, and so the corresponding figure was not included. After adding the pedestrian crossings time penalty and repeating the logic used in the route design, the SA reduces its size, shown in figure 20 the intersection of the results in both directions.
Inside the subway station the pedestrian still needs to go through the station itself. The corresponding time was accounted for in the design of the next SA and costs were added to each point that represents an entrance to the station. Away from the station the delay was considered to be 100s while towards the station this delay took the value of 85s [7]. As shown in figure 21, the intersection of the results.

Table 4 measures the SA and presents the percentage of each of these values compared to the first. It is evident how much the SA reduces in size as more detail is used. Adding the time cost to the subway station had a considerable impact. With the restriction of reduced mobility there was a great reduction mainly caused by having only one access station.

4. Conclusions

The created model was able to show that the different characterization and parameterization of the footpaths’ layers influence the results of pedestrian movement. The footpaths’ slopes, the presence of stairs and pedestrian crossings influenced the travel times simulated in this model, with results similar to those of available tools. The added preferences and prohibitions using the modeled characteristics allowed to bring a new dimension to the route planning.

The presence of shaded and non-shaded footpaths and its use brought relevant results and encourage the continuation of its development. The modeling of shading can be improved in several ways. In this work, shading was assessed at the level of the footpath but precision could be gained if it was assessed at a certain height from the ground, to verify if the pedestrian is in the shade instead of the footpath. In order to do so, the definition of that height and how the pedestrian network would have to be changed. Unlike other features, the shading may have relevant differences across the width of the footpath and the pedestrian can choose in which area he or she walks – a wide enough footpath may be in the sun and shade at the same time.

The modeling and characterization of the remaining elements of the built environment would also
be an important addition – archways, cantilevered elements on the facades and trees are just a few examples. Trying software that is able to project the shadows in a different way would allow extra precision and could facilitate the communication and creation of routes.

The calculation and display of oxygen consumption and energy expenditure are metrics that helped inform and contextualize the pedestrian movements in the researched and related areas. It would be interesting to carry out experimental verification of these results, not only to validate the estimated oxygen consumption equations, but also to validate the equation used to calculate the walking speed – which influences the calculated walking time, oxygen consumption and consequently the energy expenditure.

Modeling the signalized pedestrian crossings with the average green time and the temporal relationship between them would allow a more complete and accurate analysis of their influence on pedestrian travel. Oxygen consumption could also be calculated for the stopping, starting and waiting times, which would result from this analysis. For the case studies using the subway stations, their digitization would improve the quality of the created data. This modeling would further allow the development of multimodal information systems with higher quality and precision.

References