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Methodological Investigation of the Distance Calculation Effect on 2SFCA Analysis Across Multiple Models

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Abstract

Geographical distance between locations plays a crucial role in establishing healthcare accessibility in Two-Step Floating Catchment Area (2SFCA) models. In this article, we analyze three sets of distances: a straight-line distance and two network-based distances to determine how the distance calculation affects the models. We empirically examine the distances across several 2SFCA models and several input parameters. We find that the accessibilities derived from network-based distances correlate with each other, whereas the accessibility derived from straight-line distance does not correlate with them. The study is based on the data from the South Moravian region.

KEY WORDS: *2SFCA, accessibility, distance calculation, South Moravia, Pearson correlation, ArcGIS Pro, Catchment area, Health*

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1. Introduction

Healthcare is a key component of the state's infrastructure. It provides healthcare services to the population, thereby increasing their comfort and, above all, their safety. During the pandemic crisis, healthcare workers were on the front line of the fight against the coronavirus infection, saving lives. They prevented the further spread of the disease and limited its impact on uninfected residents. This is clear evidence of the protection that the healthcare system provides to the state's population.

This role is all the more critical in today's era, when a new virus can be systematically developed and deployed against the civilian population. At the same time, the pathogen can be deployed against the enemy during a war conflict, as well as a tool of hybrid warfare. A practical and robust healthcare system is essential for protecting the population and mitigating the potential impact of these threats. At the same time, the history of colonial expansion in North and South America demonstrates that pathogens can play a more significant role in war conflicts than the weapons themselves.

To ensure an effective and robust healthcare system, medical care needs to be accessible to the population. Even the best healthcare with top-notch doctors cannot protect the population if medical facilities are inaccessible. Multiple factors can cause inaccessibility. For example, high individual costs for patients make healthcare inaccessible to people from lower and middle social classes. At the same time, lost income and time spent traveling for medical care also have a significant impact on the accessibility of medical care. If medical care is too far away from people, then working individuals, those caring for children or relatives, have to choose between medical care and other obligations.

In this study, we investigate the impact of geographical distance on the accessibility of medical care. We use the already established 2SFCA models, which combine information on the demand and supply of medical care with the geographical distance between populations seeking medical care and hospitals providing medical care. These models were developed around the turn of the millennium [1,2] and have since undergone rapid development [3,4]. Today, there are several generalizations of these models [4,5]. They are currently the most widely used models of geographical accessibility [5] and continue to be utilized, as seen in [6–8] and many others.

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In our research, we are primarily interested in how the method of calculating geographic distance affects the resulting analysis of 2SFCA models. We are therefore looking for answers to the following questions:

- How significant is the impact of the distance calculation method on the model results? Will the results be different if we use a different calculation method?
- Can distances calculated using the road network be approximated in the models by a more straightforward calculation of the straight-line distance?
- Does the choice of the 2SFCA model affect how distance affects the calculation results?

In this work, we examine three sets of distances. The first set of distances, as the crow flies, was obtained through a simple calculation in MATLAB based on the WGS84 coordinates of the locations. The second set was obtained using the road network implemented in ArcGIS Pro 3.5.2 software [42,43,45]. The third set was calculated using the Mapy.com web application, which allows you to search for the shortest or fastest route between two points on the map.

These three sets of distances are used to calculate accessibility in several 2SFCA models. In this work, we empirically analyze the availability of medical care in the South Moravian Region. The resulting accessibility for each set of distances is then compared with that of the others, and it is found that the accessibilities based on network-based distances strongly correlate. In contrast, accessibility based on straight-line distance does not correlate with them. This conclusion remains valid independently of the chosen 2SFCA model and of the selected parameters. However, our findings contradict the findings of [9]. We hypothesize that the difference stems from the fact that [9] investigates a metropolitan area, whereas we study the South Moravia region, which combines both urban and rural locations.

2. Methodology

Various models are used to mathematically represent geographical accessibility. In this article, we analyze models that belong to the family of Two-Step Floating Catchment Area (2SFCA) models, which are themselves part of the gravity model family. These models aim to measure people's access to medical attention in a geographical area. The models compare the demand and supply for medical attention locally within a small floating catchment (a small geographical unit around a location).

The number of people in the floating catchment estimates the demand. For that, we need point features i representing populations where people gather (for example, municipalities) and the number of people P_i that gather at location i. This can be the number of people who live in a municipality. Consequently, it is then easy to estimate demand by counting all the populations within the catchment.

The supply is typically estimated by counting the total number of hospital beds in each catchment (other options appear in the literature as well). For that, we need point features j representing hospitals and their number of hospital beds, S_j.

In the first step, the supply-to-demand ratio R_j is calculated to estimate each hospital's ability to treat patients. It is given as

$$R_j = \frac{S_j}{\sum_i P_i f(d_{i,j})},$$

where $d_{i,j}$ is the distance between features i and j, f is the distance decay function. Distance decay represents the fact that people are less willing to travel to a hospital that is further away, hence it is usually non-increasing and non-negative. Distance decay f usually contains cut-off distance d_0 such that $f(d_{i,j}) = 0$ if $d_{i,j} \geq d_0$. The cut-off distance represents the point at which people are no longer willing to travel to a location that is too far away.

When R_j is too low, this means that the hospital j is potentially overused, and it might suffer from overcrowding. On the other hand, when R_j is too high, this means that the hospital j is potentially underutilized.

In the second step, the access to medical attention A_i is calculated for each population i as

$$A_i = \sum_j f(d_{i,j}) R_j.$$

A higher A_i means that population i has better potential access to medical attention and hence bigger A_i is usually better. However, in the Czech Republic, the state provides the medical attention, and everyone should have equal access to it. Therefore, even if a bigger A_i is better for population i we should strive to ensure a society where A_i increases for everyone.

This paper examines the methodological impact of how the distance $d_{i,j}$ is calculated. To broaden the horizon of the comparison, multiple models are considered. Selected models primarily differ with the choice of distance decay function. Linear decay is one of the most basic possible decays (see, for example, [10–13]**)** and it is given as

$$f_{LIN}(d_{i,j}) = \max\left\{1 - \frac{d_{i,j}}{d_0}, 0\right\}.$$

The Gaussian model is based on a bell curve, and it is apparently one of the most commonly used distance decays, see, for example, articles [14–20] and many others. The decay function is given as

$$f_G(d_{i,j}) = \begin{cases} \dfrac{e^{-\frac{1}{2}\left(\frac{d_{i,j}}{d_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & d_{i,j} < d_0, \\ 0, & d_{i,j} \geq d_0. \end{cases}$$

We emphasize that in the literature 2SFCA models with Gaussian decay are sometimes called Ga2SFCA models. Butterworth decay was applied in articles [11,12], which is based on a Butterworth filter used in signal processing [21]. It is unclear which version of the Butterworth filter has been applied in [11,12] as the function is not given precisely. Nevertheless, the following function is a probable candidate as it approximates the graph in [11].

$$f_B(d_{i,j}) = \frac{3d_{i,j}}{2d_0\sqrt{1 + d_{i,j}^6}}.$$

And finally, Fully Proportional 2SFCA model that was defined in [22] and is roughly given as

$$A_i^{FP} = \sum_j \frac{f_{FP}\left(\tilde{d}_{i,\sigma_i(j)}\right)s_j}{\sum_k P_k\, f_{FP}\left(\tilde{d}_{k,\sigma_k(j)}\right)},$$

where $\tilde{d}_{i,j}$ is the ordered distance from the shortest ($j = 1$) to the longest, $\sigma_i(j)$ is a rank function such that $d_{i,j} = \tilde{d}_{i,\sigma_i(j)}$, and

$$f_{FP}(\tilde{d}_{i,j}) = \begin{cases} 2 - \dfrac{\tilde{d}_{i,j}}{\tilde{d}_{i,1}}, & \dfrac{\tilde{d}_{i,1}}{\tilde{d}_{i,j}} > 1 - \dfrac{1}{j}, \\ 0, & \text{otherwise.} \end{cases}$$

3. Data

The accessibilities are empirically compared, and to do so, the South Moravia region, located in the Czech Republic, was selected. The region comprises 906 municipal parts, where each municipal part consists of either a small village or town or forms part of a larger city. The division corresponds to the region’s official administrative division. The region is dominated by a significant administrative center, the city of Brno, where roughly one-third of the region's population lives, and where we can find the region’s largest hospitals. Overall, 15 hospitals are situated in the South Moravia region, where 6 of them are located in Brno. The distribution of hospitals and municipal parts is depicted in Figure 1.

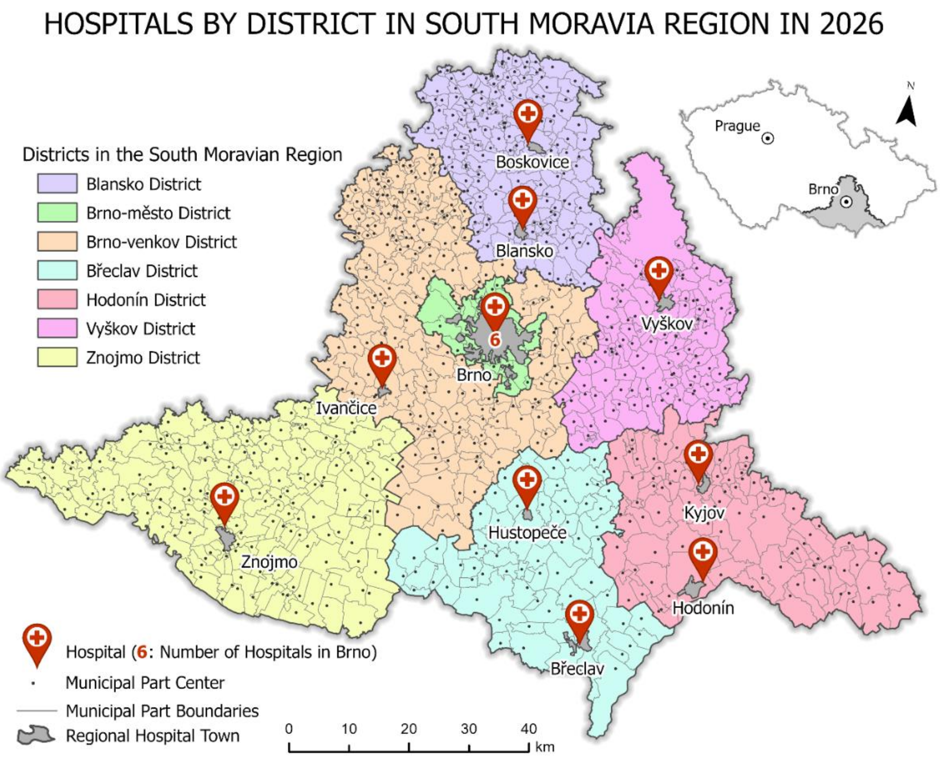

Fig. 1. Map of municipal parts and hospital locations in South Moravia.

Three sets of distances $d_{i,j}$ were calculated. First of all, distances $d_{i,j}^{GIS}$ were calculated in ArcGIS Pro which were compiled based on created transportation network [42–45]. For creating the network dataset were used layers from a digital vector geographic model of the territory of the Czech Republic [23]. The route service was used for calculating the distances $d_{i,j}^{GIS}$ defining the closest route from the municipality to the hospitals. Second of all, a routing software was used to calculate the shortest distance $d_{i,j}^{RS}$ between locations i and j. The routing software is provided by mapy.com, a Czech company-developed product that is widely used in the Czech Republic. These distances serve as benchmarks, as the routing software is developed by a group of experts specializing in this field, and its quality is widely recognized by customers.

Finally, the distances $d_{i,j}^{CROW}$ as the crow flies (straight line distance, Euler distance) that were calculated between locations i and j from their WGS84 coordinates with the help of MATLAB package [24]. The network-based distances $d_{i,j}^{GIS}$ and $d_{i,j}^{RS}$ are used to represent the proper way to calculate the distances. On the other hand, $d_{i,j}^{CROW}$ represents a simplified distance estimate which calculation is much easier.

To further broaden the analysis, three choices for d_0 were considered, that is 25 km, 50 km, and 75 km. Let us denote the accessibilities calculated with f_{STEP} as A^{STEP}, with f_{LIN} as A^{LIN}, f_G as A^G, and recall that A^{FP} denotes the accessibility from Fully Proportional 2SFCA model. Furthermore, the notation $A^G(50)$ represents Gaussian accessibility based on f_G with $d_0 = 50$ km. Similarly, $A^G(25)$ represents $d_0 = 25$ km and $A^G(75)$ represents $d_0 = 75$ km. Similarly, $A_{GIS}^G(25)$ represents accessibility derived from $d_{i,j}^{GIS}$, $A_{RS}^G(25)$ from $d_{i,j}^{RS}$ and $A_{CROW}^G(25)$ from $d_{i,j}^{CROW}$.

4. Results

Pearson correlation coefficients were used to measure the level of alignment between different distance calculation methods.

Table 1 summarizes Pearson correlation coefficients for accessibilities derived from linear f_{LIN} decay. The important values in Table 1 are highlighted in grey. We observe a strong correlation between A_{GIS}^{LIN} and A_{RS}^{LIN}. See for example the correlation between $A_{RS}^{LIN}(25)$ and $A_{GIS}^{LIN}(25)$ which is 0.977. On the other hand, A_{CROW}^{LIN} shows no correlation with both A_{GIS}^{LIN} and A_{RS}^{LIN}. This conclusion is also independent of the d_0 because for example the correlation between $A_{RS}^{LIN}(25)$ and $A_{CROW}^{LIN}(25)$ is -0.013 and the correlation between $A_{RS}^{LIN}(75)$ and $A_{CROW}^{LIN}(75)$ is 0.016.

However, a weak to moderate correlation was discovered even between A_{GIS}^{LIN} and A_{RS}^{LIN} with different cut-off distance d_0. For example, correlation between $A_{RS}^{LIN}(25)$ and $A_{RS}^{LIN}(50)$ is still 0.680. Accessibility A_{CROW}^{LIN} correlates only with itself for different choices of cut-off distance d_0. See, for example, $A_{CROW}^{LIN}(25)$ and $A_{CROW}^{LIN}(50)$ which is 0.537.

Table 1.
Pearson correlation matrix between accessibilities derived from f_{LIN} decay.

	$A_{GIS}^{LIN}(25)$	$A_{CROW}^{LIN}(25)$	$A_{RS}^{LIN}(50)$	$A_{GIS}^{LIN}(50)$	$A_{CROW}^{LIN}(50)$	$A_{RS}^{LIN}(75)$	$A_{GIS}^{LIN}(75)$	$A_{CROW}^{LIN}(75)$
$A_{RS}^{LIN}(25)$	0.977	-0.013	0.689	0.621	0.023	0.502	0.467	0.030
$A_{GIS}^{LIN}(25)$		-0.005	0.705	0.652	0.018	0.518	0.494	0.022
$A_{CROW}^{LIN}(25)$			0.002	-0.003	0.537	-0.013	-0.019	0.436
$A_{RS}^{LIN}(50)$				0.977	0.045	0.895	0.877	0.035
$A_{GIS}^{LIN}(50)$					0.036	0.921	0.924	0.025
$A_{CROW}^{LIN}(50)$						0.024	0.011	0.929
$A_{RS}^{LIN}(75)$							0.986	0.016
$A_{GIS}^{LIN}(75)$								0.004

The results in Table 2 show Pearson correlation coefficients between accessibilities derived from Gaussian decay f_G decay. The results in Table 2 lead to the same conclusion as with the Table 1. To summarize Table 2, accessibilities A_{GIS}^G, A_{RS}^G strongly correlate together but they do not correlate with A_{CROW}^G.

Table 2.
Pearson correlation matrix between accessibilities derived from f_G decay.

	$A_{GIS}^G(25)$	$A_{CROW}^G(25)$	$A_{RS}^G(50)$	$A_{GIS}^G(50)$	$A_{CROW}^G(50)$	$A_{RS}^G(75)$	$A_{GIS}^G(75)$	$A_{CROW}^G(75)$
$A_{RS}^G(25)$	0.972	-0.008	0.605	0.517	0.024	0.401	0.378	0.025
$A_{GIS}^G(25)$		-0.002	0.630	0.554	0.015	0.422	0.409	0.015
$A_{CROW}^G(25)$			0.004	-0.005	0.404	-0.022	-0.032	0.357
$A_{RS}^G(50)$				0.971	0.049	0.854	0.839	0.032
$A_{GIS}^G(50)$					0.040	0.892	0.897	0.021
$A_{CROW}^G(50)$						0.024	0.010	0.918
$A_{RS}^G(75)$							0.984	0.012
$A_{GIS}^G(75)$								0.001

The results in Table 3 show Pearson correlation coefficients between accessibilities derived from Butterworth decay f_B decay. Here again the results showed the same picture as with accessibilities derived from linear decay f_{LIN} and Gaussian decay f_G. To summarize Table 3, accessibilities A_{GIS}^B, A_{RS}^B strongly correlate together but they do not correlate with A_{CROW}^B.

Table 3.
Pearson correlation matrix between accessibilities derived from f_B decay.

	$A_{GIS}^B(25)$	$A_{CROW}^B(25)$	$A_{RS}^B(50)$	$A_{GIS}^B(50)$	$A_{CROW}^B(50)$	$A_{RS}^B(75)$	$A_{GIS}^B(75)$	$A_{CROW}^B(75)$
$A_{RS}^B(25)$	0.981	0.010	0.717	0.641	0.032	0.514	0.487	0.025
$A_{GIS}^B(25)$		0.009	0.767	0.706	0.025	0.560	0.541	0.019
$A_{CROW}^B(25)$			0.004	-0.005	0.636	-0.020	-0.029	0.545
$A_{RS}^B(50)$				0.981	0.033	0.910	0.889	0.021
$A_{GIS}^B(50)$					0.026	0.928	0.930	0.015
$A_{CROW}^B(50)$						0.016	0.009	0.943
$A_{RS}^B(75)$							0.986	0.009
$A_{GIS}^B(75)$								0.005

Finally, the Pearson correlation coefficients for Fully Proportional 2SFCA model are: 1) between A_{RS}^{FP} and A_{GIS}^{FP} it is 0.859, 2) between A_{RS}^{FP} and A_{CROW}^{FP} it is 0.012, 3) between A_{GIS}^{FP} and A_{CROW}^{FP} it is 0.017. Here again we arrive to the same conclusion that even with a complex model the accessibilities A_{RS}^{FP} and A_{GIS}^{FP} derived from the network-based distances correlate and that they do not correlate with accessibility A_{CROW}^{FP} derived from the straight line distance. The Fully Proportional 2SFCA model does not incorporate the cut-off distance d_0 and thus only three correlations are sufficient to completely compare the models.

Beforementioned tables and Pearson correlations compared the same accessibility model across various distance calculation methodologies and across different input parameters. Table 4 on the other hand compares different accessibility models via Pearson correlation coefficients. Correlations for 2SFCA models which differ only with the choice of distance decay function are highlighted in grey and correlations with Fully Proportional 2SFCA model (a complex generalization of the basic 2SFCA model) are highlighted in blue.

Table 4.
Pearson correlation matrix between accessibilities derived from different models.

	$A_{RS}^G(25)$	$A_{RS}^B(25)$	A_{RS}^{FP}		$A_{RS}^G(50)$	$A_{RS}^B(50)$	A_{RS}^{FP}		$A_{RS}^G(75)$	$A_{RS}^B(75)$	A_{RS}^{FP}
$A_{RS}^L(25)$	0.994	0.878	0.451	$A_{RS}^L(50)$	0.987	0.927	0.376	$A_{RS}^L(75)$	0.986	0.947	0.307
$A_{RS}^G(25)$		0.903	0.472	$A_{RS}^G(50)$		0.963	0.353	$A_{RS}^G(75)$		0.982	0.271
$A_{RS}^B(25)$			0.427	$A_{RS}^B(50)$			0.305	$A_{RS}^B(75)$			0.229

Table 4 shows that there is a very strong correlation between 2SFCA models derived from linear A_{RS}^L and Gaussian A_{RS}^G decay where correlations are always close to 1. The 2SFCA model derived from Butterworth decay A_{RS}^B also strongly correlates with A_{RS}^L and A_{RS}^G however the correlation slightly decreases when d_0 is low. Apparently, the accessibility A_{RS}^B correlates the strongest with A_{RS}^G. On the other hand, Fully Proportional 2SFCA model A_{RS}^{FP} correlates only moderately to weakly with the basic 2SFCA models and this is independent of the chosen distance decay. The correlation is moderate when d_0 is 25 km and decreases to a weak correlation when d_0 increases to 75 km. However, A_{RS}^{FP} correlates the worst with A_{RS}^B.

5. Discussion

The main objective of this article was to find if a complex distance calculation via a road network can be replaced with a simplified distance estimate as the crow flies. However, the empirical analysis showed that this is not possible. The accessibilities derived from network-based distances were strongly correlated for all models and for all selected cut-off distances d_0. This indicates that the accessibility coefficients remain consistent even when the distance calculation method is changed. On the other hand, the accessibility derived from straight-line distance showed poor correlation with both of them, consistently and independently of the selected model and the choice of cut-off distance d_0.

This outcome was initially anticipated before a more thorough analysis was conducted. The network-based distance between two locations is expected to be longer than the straight-line distance because the road has to circumvent obstacles such as mountains, lakes, buildings, military areas, and other similar features. However, upon closer examination, several mitigating factors emerge that complicate the picture. The South Moravia region has primarily flat terrain with a complex road network. For more details about South Moravia, see [25] and the references cited therein.

Furthermore, even without an objective metric to base these conclusions on, it is the authors' subjective opinion that the municipalities in the South Moravia region are connected mainly with straight roads running from one place to another. Consequently, it was expected that the accessibilities A_{GIS}, A_{RS}, and A_{CROW} might moderately correlate at least for some models and some cut-off distances d_0. Nevertheless, the analysis revealed that this was never the case.

A similar study, which analyzed an urban area and compared six types of distance, including straight-line distance and network-based distance in ArcGIS Pro, appears in [9]. This study also utilized the Pearson correlation coefficients to compare the different distance calculation methods. However, in [9], a strong correlation was found between straight-line distance accessibility and network-based accessibility. Hence, the article arrived at a different conclusion than our investigation. We hypothesize that this is because the article [9] focuses on an urban area and a small region. There is, however, a difference between accessibility in urban and rural areas [26], where the South Moravia region is a mixed area with both urban and rural locations. A more thorough analysis might therefore be required to investigate this phenomenon further.

The secondary findings showed that the accessibility models correlated even with a different choice of cut-off distance d_0. This indicates that the accessibility analysis is partially immune to the incorrect choice of d_0 and the results might be trusted even then. Models with cut-off distances of 50 and 75 kilometers showed strong correlation. See, for example, correlation between $A_{RS}^{B}(50)$ and $A_{RS}^{B}(75)$ which was 0.910. Moreover, the lower cut-off distance of 25 kilometers still moderately correlated with other cut-off distances. See, for example, correlation between $A_{RS}^{B}(25)$ and $A_{RS}^{B}(75)$ which was 0.514. We estimate that 50 kilometers is an appropriate choice of cut-off distance for South Moravia region, hence our analysis shows that a potential overestimation of d_0 is better than the underestimation.

However, the conclusion changes if our initial expectation changes. If we expect that the cut-off distance of 25 kilometers is better suited for the South Moravia region, then we conclude that a twofold cut-off overestimation can still be acceptable. See, for example, correlation 0.605 between $A_{RS}^{G}(25)$ and $A_{RS}^{G}(50)$ which is still usually acceptable level of correlation in social sciences. Nevertheless, the establishment of the catchments and thus of d_0 is still an essential part of the accessibility analysis and should not be overlooked [27,28].

The effect of cut-off distance selection was also explored recently in [29], where it was discovered that an increase in d_0 leads to the homogenization of accessibility because when d_0 is large, everyone can access every hospital. Hence, a smaller d_0 might be more realistic, but this can lead to a situation where particular populations cannot reach any hospital. Hence, a model with variable d_0, such as in [30], or the Fully Proportional 2SFCA model [22], might be preferable.

Recently, another study that investigated the methodology of 2SFCA models was published in [31]. It analyzed the effect of the population selection, and in the process, the study also revealed a strong correlation between different input parameters. This also underlines the fact that the accessibility analysis might be resistant to input errors.

Two sets of network-based distances were used to juxtapose different distance calculation methods. This shows that we can expect a strong correlation even when the distance calculation is not optimal. In fact, we expect that the distances $d_{i,j}^{RS}$ are the most precise because they are obtained from specialized routing software that is developed by experts. The residents of the area also validate the routing software because they widely use it. However, such routing software might not be available for all regions, or its calculations might be unavailable. For example, in military contexts where unpaved roads might be used [32–35,42,46] or where rivers might be crossed [36,41]. In that case, our results indicate that the ArcGIS Pro calculations are sufficiently accurate to be used as an alternative [42,43,45].

The comparison between models showed that the basic 2SFCA models are not impacted much by the choice of distance decay function. The lowest Pearson correlation among all the selected basic 2SFCA models and all the selected cut-off distances was 0.878 and that was between $A_{RS}^{B}(25)$ and $A_{RS}^{LIN}(25)$. On the other hand, the correlation decreased significantly when a more complex model, the Fully Proportional 2SFCA model, was compared against the basic models. This indicates that the generalization of the Fully Proportional model is nontrivial and that it measures accessibility in a distinct manner. However, the last two decades have led to the development of many generalized 2SFCA models [5,10,18,20,22,37]. A more thorough study should focus on these models to determine which ones offer only minor changes and which generalizations yield substantial improvements.

Recently, the data-driven distance decay has been explored [38,39], an approach that promises to eliminate doubts about the choice of cut-off distance and the correct distance decay function. However, such approaches are data-dependent and influenced by the availability of data. Hence, this approach might not be available in many contexts.

6. Conclusions

The findings of this article show that in 2SFCA analysis, road network distances must be used and cannot be approximated by straight-line distance. The conclusion is independent of the selected model and selected input parameters. The findings are consistent and thus valid in the South Moravia region and potentially in other similar areas. However, further investigation is likely still required to make a final judgment, as our conclusions differ from those in [9].

The findings of this article may be of use to anyone working with 2SFCA models. The results contribute to the current understanding of 2SFCA methodology. The results thus have the potential to impact accessibility analysis across various applications. Throughout the article, we have focused on the healthcare sector; however, the conclusions are also applicable to other applications, such as firefighter response time, where a 2SFCA analysis was performed in [11]. We hope that our findings will contribute to the quality of the subsequent accessibility analysis. When it comes to healthcare accessibility, every small improvement might lead to saved lives and improved quality of life. That is the reason why methodological studies of 2SFCa models remain relevant to this day, see also [40].

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