

## Article

# Consideration of Uncertainty Information in Accessibility Analyses for an Effective Use of Urban Infrastructures

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**Abstract:** Accessibility analyses are an essential step in the evaluation and planning of urban infrastructures such as transport or pipeline networks. However, these studies generally produce sharply defined lines (called isovarones) or areas (called isovarone areas) that represent the same or similar accessibility. Uncertainties in the input data are usually not taken into account. The aim of this contribution is, therefore, to set up a structured framework that describes the integration of uncertainty information for accessibility analyses. This framework takes uncertainties in the input data, in the processing step, in the target variables, and in the final visualization into account. Particular attention is paid, on the one hand, to the impact of the uncertainties in the target values, as these are key factors for reasoning and decision making. On the other hand, the visualization component is emphasized by applying a dichotomous classification of uncertainty visualization methods. This framework leads to a large set of possible combinations of uncertainty categories. Five selected examples that have been generated with a new software tool and that cover important combinations are presented and discussed.

**Keywords:** urban infrastructure networks; accessibility analyses; uncertainty; uncertainty visualization; isovarones; isochrones

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## 1. Introduction

### 1.1. Relevance

Urban infrastructures define the underlying structure foundation of the built environment, and include buildings as well as transport, electricity, gas, water and sanitation connections [1]. They can often be mapped as networks in the sense of geometrical-topological systems. Examples are networks of traffic routes or pipelines for drinking or sewage as well as the energy supply. When using and planning such networks, the primary goal is to enable realizable, effective and efficient movements of people (e.g., in the context of mobility) or substances (e.g., in connection with basic services).

The effectiveness and efficiency of networks of urban infrastructures can be assessed in different ways: Firstly, ecological criteria can be used; for example, in the case of transport networks, CO<sub>2</sub> emissions, energy consumption (such as fuel or electricity), or noise pollution. Secondly, economic factors can relate to energy and other costs, as well as losses in pipelines. Finally, socio-economic criteria such as short travel times to infrastructure facilities can also play a role, which in extreme cases can even lead to social isolation [2].

Accessibility analyses are an elementary and important step in analyzing or evaluating networks. They pursue the “concept of ease of reaching destinations” [3], alternatively “the potential for reaching spatially distributed opportunities while considering the difficulty involved in traveling to them” [4].

In particular, this type of analysis examines the accessibility either from a location (e.g., from one's own place of residence) to the surrounding area or vice versa, i.e., from the surrounding area towards a destination (e.g., towards an airport). Due to the different directions, one should speak of the focus point more generally. Often it is not only about the accessibility in the geometric sense, but also about taking into account the specific meaning or (land) use of the surrounding places (e.g., concentrating on the accessibility of medical practices). The analyses can be carried out in the simplest way with concentric circles around the location. However, a more realistic picture is obtained if actual routes (e.g., a real road network) and modes of movement (e.g., with public transport) are considered [5].

Accessibility analyses are also assigned to the category of methods for determining the best locations; they also serve to increase the quality of urban infrastructures. For example, poor accessibility leads to reduced access to goods and services and thus to negative effects on the urban economy [6]. However, it is not just a matter of describing a status quo, but also of planning effective and efficient locations [7]. Examples in the context of urban infrastructures are the optimization of the locations of fire brigades, rescue and delivery services or freight terminals. Section 2 presents further application examples and illustrates the great relevance of accessibility analyses in the context of urban infrastructures.

### *1.2. Aim of This Paper*

In this contribution we want to stress the need for, and show a conceptual framework of uncertainty information in accessibility analyses. We use the term “uncertainty” as an umbrella term that includes known errors and unknown effects such as doubts or inconsistencies [8]. Our focus is obviously on spatio-temporal uncertainties that can be numerically described.

When looking at the available methods (see also Section 2) it becomes clear that accessibility analyses generally produce sharply defined lines or areas that represent the same or similar accessibility. Uncertainties in the input data (e.g., in the information on speeds or pipeline openings) and those that arise during data processing are usually not taken into account.

On the other hand, however, it is clear that spatial or temporal deviations (e.g., due to traffic jams, delays in timetables or congestions in pipelines) can have a critical influence on accessibility and thus lead to incorrect interpretations or decisions based on the network analyses. In the following, we will follow the “fitness for use” idea [9], i.e., that special attention will be paid to the resulting effects of the uncertainties on the analyses results for a given application, in our case the accessibility of locations.

The integration of spatiotemporal uncertainty information into decision-making processes is generally seen as an important step towards an informal gain and an increase in confidence [10,11]. In terms of decision making, the integration of uncertainty information and possible or probable deviations from “crisp” solutions leads to a more detailed evaluation of possible alternatives. As a consequence, technicians could resize pipelines, planners could rethink the position of rescue stations or select public transport routes that show fewer deviations from nominal travel time.

The aim of this contribution is to set up a structured framework that describes the integration of uncertainty information for accessibility analyses. For this purpose, categories of uncertainties are developed in the context of their modeling (Section 3), taking into account uncertainties in the input data, processing, target variables, and through final visualization. Particular attention is paid to the impact of the uncertainties on the target values, as these are of central importance for the interpretation and decision-making. Section 4 gives a systematic overview of options for the visualization of uncertainties. Using selected examples, and with the help of a new software tool, the application of this framework is shown in Section 5.

## 2. Previous Work

### 2.1. Applications

The wide range of applications and the relevance of accessibility analyses was already shown in the introduction. In the following, the presentation of selected examples is intended to further support this statement.

Accessibility analyses are very often used in the context of describing and optimizing traffic and transport route networks, with the goal to improve the efficiency with which people or substances can get to their destinations [5]. Examples of this are planning for public transport stops or train stations (e.g., [12,13]) with the aim of creating the largest possible catchment areas for people in a clearly defined environment (e.g., 10 min on foot).

Furthermore, temporal variations of such networks can be determined by calculating the accessibility for different time segments [14,15]. In this way, time-variable properties of the network can also be modeled (such as traffic jams, construction sites, opening hours, etc.). A combinatorial challenge arises from the consideration of multi-modal means of transport (such as reaching a destination by car, public transport and on foot).

In addition, medical or emergency care is an important application in which the availability of locations with doctors, pharmacies, rescue services or fire departments is checked against given standards. In Hamburg, for example, fire brigades require eight minutes to leave and arrive [16,17].

Accessibility analyses are also of fundamental importance for other infrastructure facilities such as schools, supermarkets, bank branches, petrol stations or e-charging stations. This is also where the interface to geo-marketing becomes evident [18]. In urban planning, but also in the field of tourism, access to recreational areas or sights plays an important role [19]; for example, [20] investigate the accessibility of green spaces.

### 2.2. Methods

Accessibility analyses can be based on a variety of accessibility models such as distance, cumulative, gravity, place rank or space-time; for an overview refer to [21]. Another view is the distinction between place-based and people-based models, where the latter directly considers individuals' behavior in space [22]. In this contribution we will rely on cumulative measures because they can be applied to different modes, are simple to analyse and to present [3] and follow our idea to focus on the summarized effect on target variables.

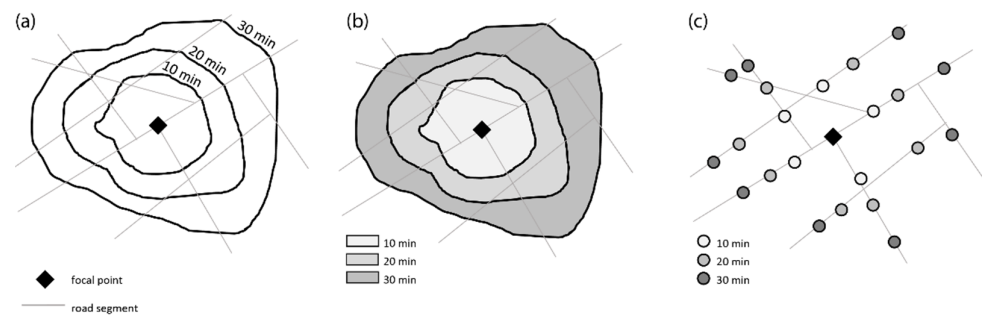
It is possible to determine the accessibility starting from or leading to a focal point with concentric circles around it. A much more reliable variant, however, is the calculation based on actually existing routes. For these analyses it is necessary to use graph theory to determine the topology of the (traffic) network, i.e., to generate the nodes and edges from given geometrical information.

Different weights (also referred to as impedances or costs) can be assigned for the edges. They describe various properties of the network such as distance, time, consumption, costs, attractiveness, or affected persons. From a mathematical point of view, the modeling of these weights can follow different deterministic approaches (inversely proportional, negative exponential, Gaussian distribution, etc.). [3] and [23] give detailed overviews of accessibility measures.

On the basis of this graph network, optimal routes (e.g., with the help of the Dijkstra or A \* algorithms) from or to the focus point (in the topological sense, the focus node) can now be calculated. This produces points on the edges that represent a certain accessibility (e.g., for a certain travel time).

For visualization purposes, the points of equal weights can be connected (e.g., using the convex hull method). Lines of equal cumulative weights are obtained, which are referred to the general term of isovarones (from the Greek: "iso" equal, "varos" weight) in this contribution (Figure 1). The most important special case of these are isochrones, i.e., lines of equal time difference. Additionally, regions can be determined for a given weight

interval, either as a polygon between given isochrones or by buffering around isovarones [24]. With that, isovarone areas (or more specifically, isochrone areas) are obtained. In order to avoid interpolation errors that occur when determining isovarones and isovarone areas, network isovarones can also be determined: Here the edges themselves (or points on these edges) are symbolized or colored according to their weights. This gives a direct reference to the network, instead of visualizing those regions through the linear or polygonal connection of points that cannot be reached in reality because they are not part of the network.



**Figure 1.** Visualization of accessibility: Isovarones (a), isovarone areas (b), network isovarones (c).

Hardware and software developments have led to significantly faster calculations of isovarones in recent years, which enables, for example, a finer granularity of the weight intervals (e.g., every minute instead of ten minutes) and the consideration of time-variable weights (e.g., traffic flows at different times of the day) [6].

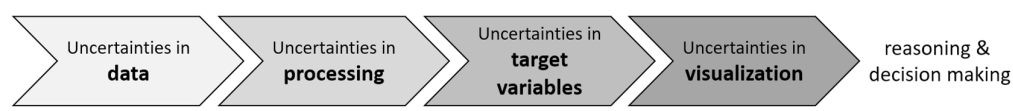
When analyzing previous work with regard to the methodical implementation of accessibility analyses, it is noticeable that uncertainty information is not explicitly taken into account. There are only few comparative considerations between different methods or programs (e.g., [25,26]) that indirectly take this aspect into account. This research gap will be addressed in the remainder of this paper.

### 3. Modeling Uncertainty Information for Accessibility Analyses

There is no generally applicable or complete method for determining uncertainties in geographic information system (GIS) analyses in general and in accessibility studies in particular. In the following, a framework for the special case of accessibility analyses is presented, which pursues two main ideas:

- The description of the uncertainties requires not only the consideration of the input data, but also the propagation or additional uncertainties through the processing and visualization of the data. This constitutes a chain of uncertainty [27].
- For users, it is not so much the uncertainties in the input variables that are relevant for interpretations and decisions, but those in the target variables. Therefore, special attention must be paid to the effects of the uncertainties on the analyses' result [28].

In the following, the mentioned categories of uncertainty information (see also Figure 2) and possible variables for the application of the accessibility analyses are dealt with in detail. From a methodological point of view, the framework is based on a literature analyses and a follow-up systematization. The resulting lists of uncertainties are structured according to the necessary input parameters (Section 3.1), possible parameters during processing (Section 3.2), possible outcomes (Section 3.3), and typical uncertainties known from cartography (Section 3.4).



**Figure 2.** Chain of uncertainties.

### 3.1. Uncertainties in the Data

The necessary input data for accessibility analyses are network points (e.g., road crossings), network connections (e.g., street segments) and the weights for the connections (e.g., time requirement, CO<sub>2</sub> consumption, visual attractiveness). Accordingly, geometric or thematic—and also combined or time-dependent uncertainties—can occur on a categorical or cardinal scale. Typical variables in this context are:

- Inaccuracies in the position of intersection points—given for example as a systematic offset or standard deviation of the position, derived from the comparison with ground control points;
- Inaccuracies in the length of connections (for example, due to too few intermediate points)—expressed by systematic shortening, standard deviation of the length, or others.
- Inaccuracies in edge weights, caused for example by:
  - deviations from a nominal value (e.g., the ratio of actual to nominal speed due to high traffic, traffic jams, construction sites, etc.);
  - modeling deficiencies in the model as such—in particular due to a deterministic weighting model (such as invers proportional, negative exponential, etc.);
  - the lack or fuzziness of quantitative data. In this context, the uncertainty values can also derived from linguistic approximators (“about”, “approximately”, etc.) that reflect the accuracy in a verbal sense [29,30]. The study by Ferson et al. [31] serves as a template for the translation of a linguistic uncertainty description into a numerical uncertainty values, by assigning mathematical functions to linguistic expressions;
  - missing information about weights.

### 3.2. Uncertainties through Processing

The necessary processing steps in accessibility analyses are building topology, calculating optimal routes and combining equal connections to isovarones or isovarone areas (in the case of time: isochrones or isochronous areas). Accordingly, the following uncertainties arise:

- Uncertainties in building the network topology—for example, missing topological integrity, or model errors in the determination of edge weights (such as the weighted combination of segment weights to create edge weights);
- Uncertainties in the calculation of the routes—due to the use of different and possibly suboptimal algorithms;
- Uncertainties due to the interpolations to isovarones and isovarone areas: in the case of isolines, the points as calculated by routing algorithms are linked on the basis of uncertain assumptions (e.g., by a linear connection between points; see also [32,33]). Furthermore, not all points on the isovarones or within the isovarone areas can necessarily be accessed because only a minority are actually identical with the nodes and edges of the network.

### 3.3. Uncertainties in Target Variables

The complexity of the uncertainties resulting from the input data and their processing (Sections 3.1 and 3.2) makes it clear that a differentiated view is almost impossible and usually not practical. However, the cumulative uncertainties in the target variables are more relevant for the application of the accessibility analyses. The respective values

result from simulated or statistically based multi-criteria analyses. Following the approach of [34], the uncertainties of the target values are carried out parallel to the actual calculation of the target values. There are two types of target variable uncertainties in accessibility analyses:

- **Spatial variance:** when the focus node and the weights are fixed (e.g., when a fire station and a time budget of eight minutes are specified), the spatial uncertainty of accessibility is of interest. This can be expressed by the general feasibility of the connections under the given conditions (i.e., the focus point or certain target regions may or may not be reached). Alternatively, spatial variance can also be expressed by means of distance buffers (e.g., calculated from the value range, or a multiple of the standard deviation) or distance classes that describe the grades accessibility of regions.
- **Variance of the cumulative weight:** if the spatial elements are fixed (e.g., if the fire brigade station and fire location are specified), the effect of the uncertainties of the associated weights (e.g., the temporal variance for reaching the fire location) is of interest. A typical example for expressing the variance of the total weight is a time interval (as a range or a multiple of the standard deviation of time) for individual selected locations. Alternatively, it can be specified whether the focus node can be reached within the time budget; either on a binary scale (reachable or not reachable) or on an ordinal scale (safely reachable, probably reachable, etc.).

### 3.4. Uncertainties in the Visualization

By default the result of an accessibility analyses is communicated through a cartographical representation. Independently from the modeling and calculation, new uncertainties arise in the step of visualization, for example:

- information loss due to cartographical generalization (e.g., the limitation on some discrete symbols or the use of isovarones with certain value differences);
- missing explanations for introducing the complex topic of uncertainties;
- limited monitor or print resolutions;
- general problems of legibility due to inappropriate design (such as color choice or placement of legend).

## 4. Visualization of Uncertainties in Accessibility Analyses

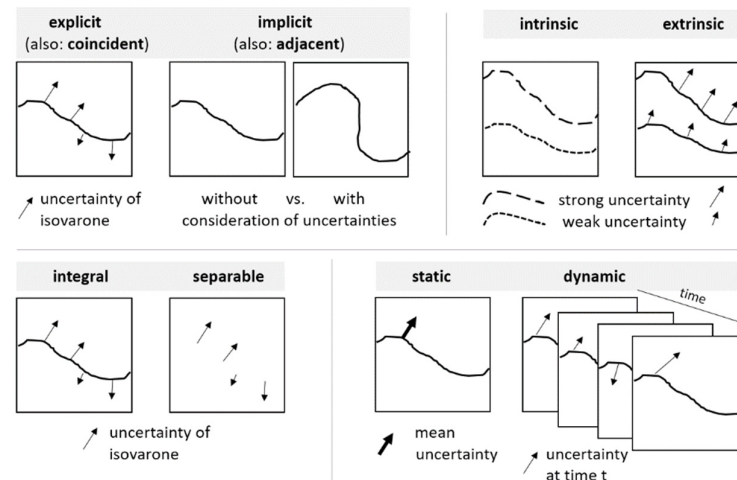
The following types already mentioned (Figure 1) can serve as a **basis** for the visualization of accessibility i.e., without taking into account the uncertainties:

- isovarones (with the special case of isochrones);
- isovarone areas (isochrone areas);
- network isovarones (network isochrones).

On this basis, uncertainty information has to be added. An overview of methods for the visualization of uncertainties is, for example, given by [35]. The authors group these methods according to the following inter-related dichotomous categories (Figure 3):

- **Explicit** (i.e., use of glyphs or symbols like deviation arrows) vs. **implicit** (i.e., displaying different isochrones maps as outcomes): The implicit option normally requires adjacent views that, however, should be avoided due to eye movements and a “mental separation” between variables and their uncertainties [35].
- **Intrinsic** (i.e., integrated into symbols of values, basically through manipulation of visual variables such as color lightness or usage of differently dashed lines) vs. **extrinsic** (i.e., the use of additional elements and applying specific color schemes or the noise metaphor such as dashed lines or so-called noise annotation lines for polygon features[36]).

- Coincident (i.e., integrated in one map) vs. adjacent (i.e., using multiple views)—with the general recommendation to use latter option in order to avoid eye movements and “mental separation”.
- Integral (uncertainty cannot be perceptually separated from the data significance, for example by showing isochrones plus deviation symbols) vs. separable (uncertainty can be read independently from data, for example by displaying symbols only).
- Static vs. dynamic, where dynamic are only meaningful if there is actual change over time and overall tendencies (i.e., changes in one direction) are clear.



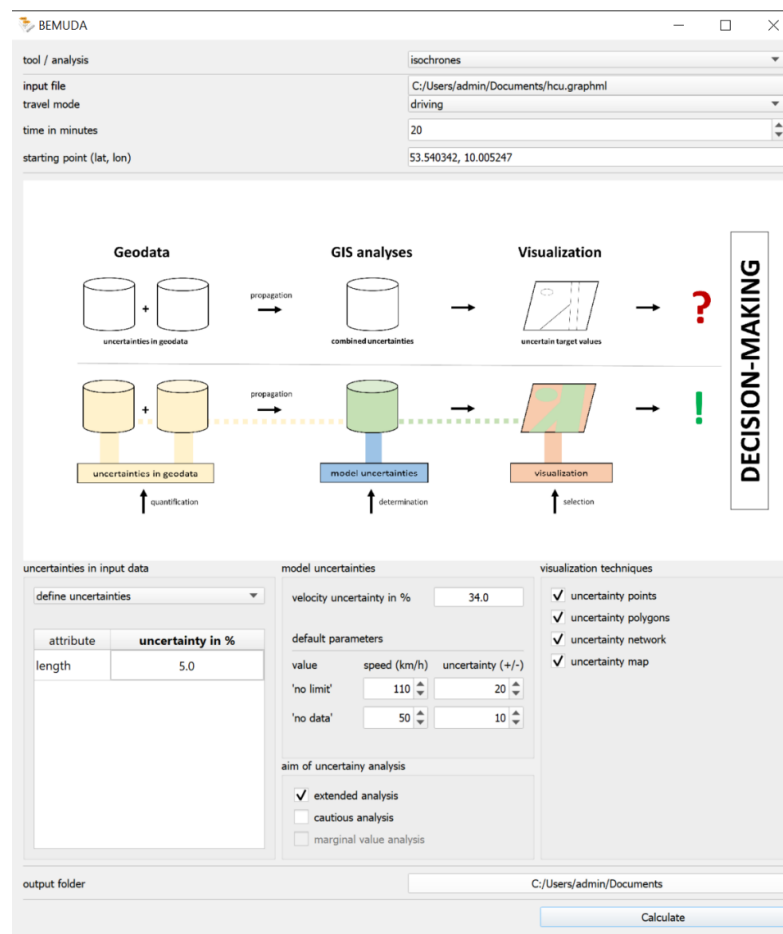
**Figure 3.** Dichotomous categories of uncertainty visualization.

## 5. Implementation and Examples

### 5.1. BEMUDA Software Tool

As stated in Section 3, there is no complete and generally applicable method for uncertainty determination in GIS analyses especially considering a chain of uncertainty consisting of data acquisition, propagation through modeling and visualization. As a result, widely-used uncertainty-related software tools are missing. Nevertheless, there are multiple models and concepts in the research literature dealing with parts of this chain of uncertainty, with some of them furthermore being implemented in software tools. For the domain of spatial analyses, DUE [37] and spup [38] can be mentioned, while tools like OpenTURNS [39] and DAKOTA [40] focus more on statistical uncertainty treatment in general. All of these tools have in common, however, that they have not evolved from specific applications for geoscientists to integration into widespread GIS software products. Also, the most common GIS operations like buffering, intersection or union, are not implemented in these software tools.

Therefore, the open source software tool BEMUDA (<https://gitlab.com/g2lab/bemuda> (accessed on 9 February 2021)) was introduced, implementing a new framework by [27] that enables the treatment of uncertainties over the entire workflow of spatial analyses, even for non-experts and GIS laypeople. It includes the description of uncertainties in the input data, the implementation of methods to determine the propagation of uncertainties during typical GIS operations, and the derivation of visualizations that determine the impacts of uncertainties on the target values (see also Figure 4). The tool follows a task-based approach. Based on the framework presented here, the task of isochrone calculations has been added to the tool. It can be used with selected road and traffic data (see Section 5.2) not only for real-world applications, but also for general demonstration and awareness purposes.



**Figure 4.** Graphical User Interface of the BEMUDA tool with common isochrone parameter input on the upper part of the interface and uncertainty quantification of input data (left), model parameters (center) and visualization techniques (right) on the lower part.

The tool has been developed in Python, uses network libraries networkx [41] and osmnx [42], and generates maps and geometries as outputs. It is planned to develop a QGIS extension after more user tests. A migration of the existing tool to QGIS will be possible so that the development efforts are reduced.

To lower the level of access for users without extensive statistical knowledge and GIS laypeople, uncertainties in the input data can be quantified without taking the source of the uncertainty into account. This can be stated directly with a numerical value, or using one of the linguistic approximators. In the outlined case of isochrones, the tool allows the users to describe the uncertainty of maximum speed, the length or the level of congestion of each edge (see also Section 3.1).

The result of the parallel modeling process is a combination of the actual target values of the analyses, which can also be computed with a common GIS software, and an additional value that reflects the cumulative effect of uncertainties in the analyses. For isochrone calculations, the propagated uncertainties lead to different spatial distances accessible from the focus point, while some additional restrictions to road network and calculation have to be considered, e.g., the maximum speed of a vehicle, which cannot be exceeded.

Finally, with respect to the aim of the task, different uncertainty visualization should be taken into account. For example, considering traffic congestion, a conservative approach would highlight the negative impact of congestion uncertainty to the target value



as the main subject of the visualization, while other visualizations could emphasize the certainty of which the chosen target could be reached within the given time.

## 5.2. Examples

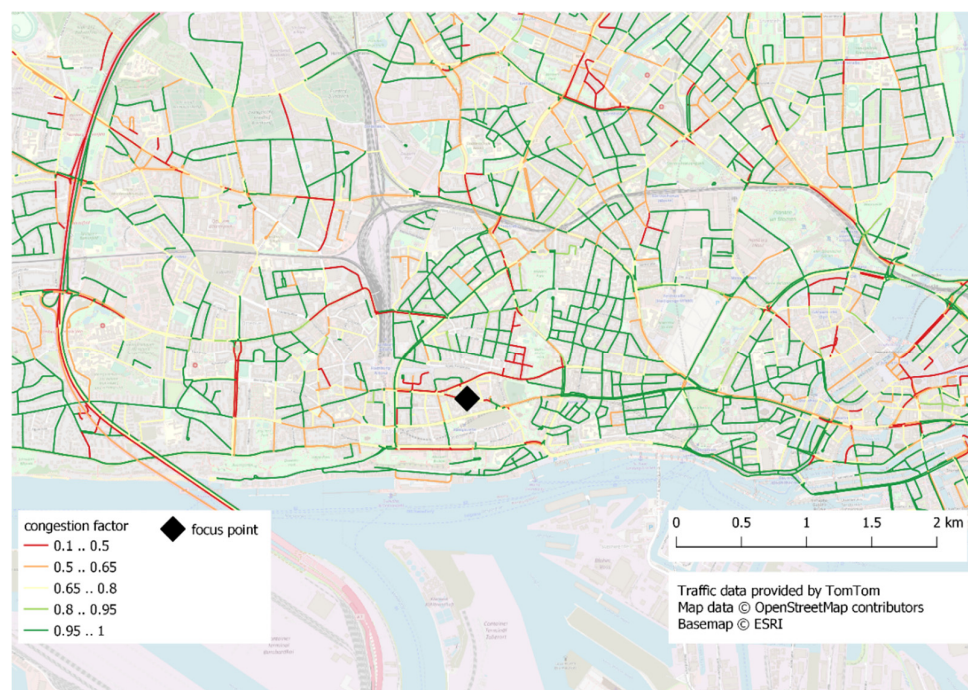
The framework for modeling and visualizing uncertainties mentioned above leads to a rather large and complex set of possible combinations of uncertainty categories. Five selected examples based on real data that cover important combinations are given in the following for demonstration purposes.

In all cases road network data of the City of Hamburg (source: OpenStreetMap (<https://www.openstreetmap.org> (accessed on 9 February 2021))) is used together with open traffic data as offered by the TomTom company (sources see below).

Example 1 (Figure 5) shows deviations in actual speeds (data provided by TomTom (<https://developer.tomtom.com/products/traffic-api> (accessed on 9 February 2021))) as a function of time and current traffic. These values are normalized by nominal speed values for street segment (which results in values in the range of  $[0, 1]$ ), which leads to uncertainties in the edge weights. In this case no target value is shown, but rather the measure can be used for an in-depth spatio-temporal analyses of potential bottlenecks in the traffic network.

The visualization uses the network as a basis. With regard to the five visual uncertainty categories (Figure 3), this example is explicit and extrinsic (by the use of explicit edge coloring), coincident (uncertainty information integrated in the base map), separable (uncertainty is depicted and can be interpreted independently from accessibility information as such) and static.

Beside the identification of bottlenecks, this visualization also provides an overview to the speed-related uncertainty of *all* edges in the area, so predictions about the overall situation in a certain direction from the focus point or the area in general are possible. This is helpful for motorists for re-arranging their individual routes, but also for traffic planners for implementing traffic guiding measures.



**Figure 5.** Example 1: Ratio of actual and nominal speed on street segments, using the example of the 16h afternoon rush hour in Hamburg, on 10 December 2020 (lower congestion factor stands for lower speed, or longer travelling time per edge, respectively).

Example 2 (Figure 6) shows the target variable „spatial variance“. The isochrone (red line) represents the accessibility for eight minutes' drive by car that already considers an average 34 % loss of speed on Hamburg roads (TomTom Traffic Index 2019 ([https://www.tomtom.com/en\\_gb/traffic-index/](https://www.tomtom.com/en_gb/traffic-index/) (accessed on 9 February 2021))). In addition, the uncertainty buffer reflects an uncertainty of the lengths of roads (plus/minus 5 %) that are transformed to speed and distance differences.

The visualization uses the isochrone as a basis, on which the uncertainty symbolization is applied as follows: explicit, extrinsic (transparent, single-colored polygon showing distance buffer with regard to isochrone), coincident, integral, and static.

With only two attributes shown, an advantage of this visualization is the low complexity due to the combination of fast calculation and a large range of opportunities to integrate the uncertainty information into general map products. Looking at the calculated isochrone, as well as on the best and worst case of cumulated uncertainties as borderlines for the uncertainty area, the user can easily estimate the part of uncertainty compared to the overall distance from the focus point. The example in Figure 6 can be related to the aforementioned requirement that fire brigades in Hamburg shall arrive to any destination within eight minutes (see Section 2.2). Large deviations for the interior buffer identify critical problems and, in a city-wide context, might lead to the requirement of additional stations.

However, the low complexity of this visualization leads to the introduction of new uncertainties, e.g., through interpolation to isochrones areas (see Section 3.2) or cartographic generalization (see Section 3.4).



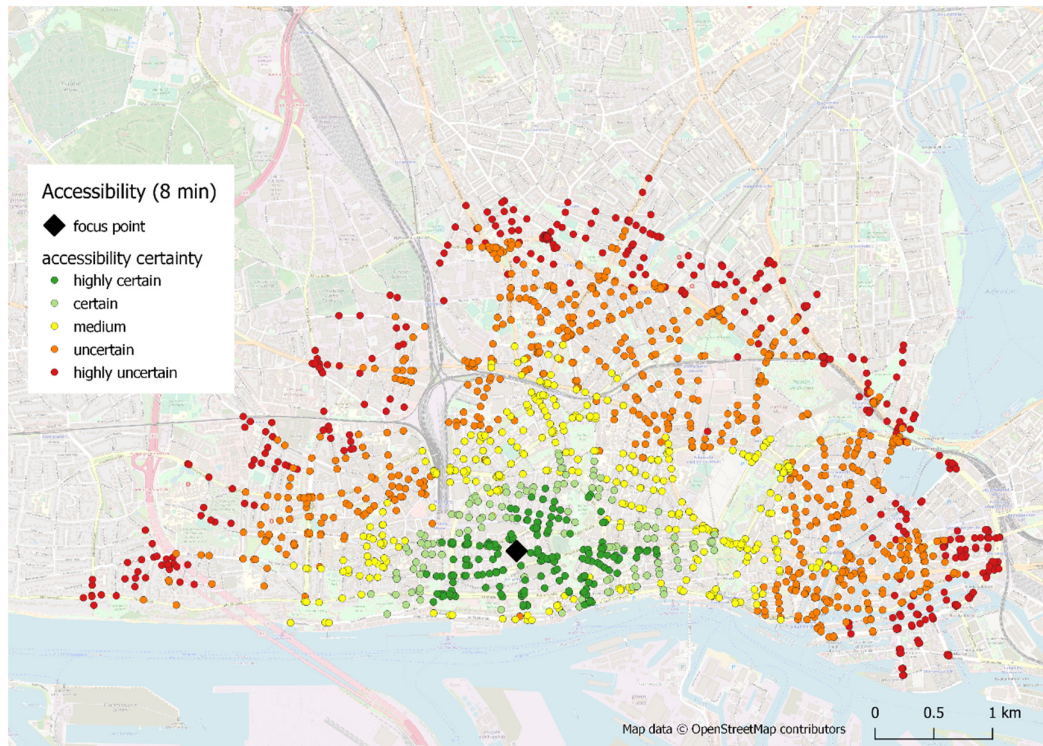
**Figure 6.** Example 2: Spatial variance around eight minute's isochrones, expressed by single buffer.

Example 3 (Figure 7) is similar to example 2, including the potential application of fire brigade accessibility. Again, the resulting spatial variance is shown as caused by the variance of speed. In this case, however, the accessibility is shown in five different classes.

The visualization is based on network isochrones. The uncertainty symbolization is applied as follows: Explicit and extrinsic (point symbols, using a color scheme for distance classes), integral, coincident, and static.



Compared to the previous example, this visualization is much more precise regarding the exact nodes accessible from the focus point during the eight-minute timespan. In the transition areas between classes in particular, the visualization is much more detailed and allows distinction between nearby nodes, while it is not as convenient as example 1 when it comes to more general conclusions about the overall accessibility in this area.



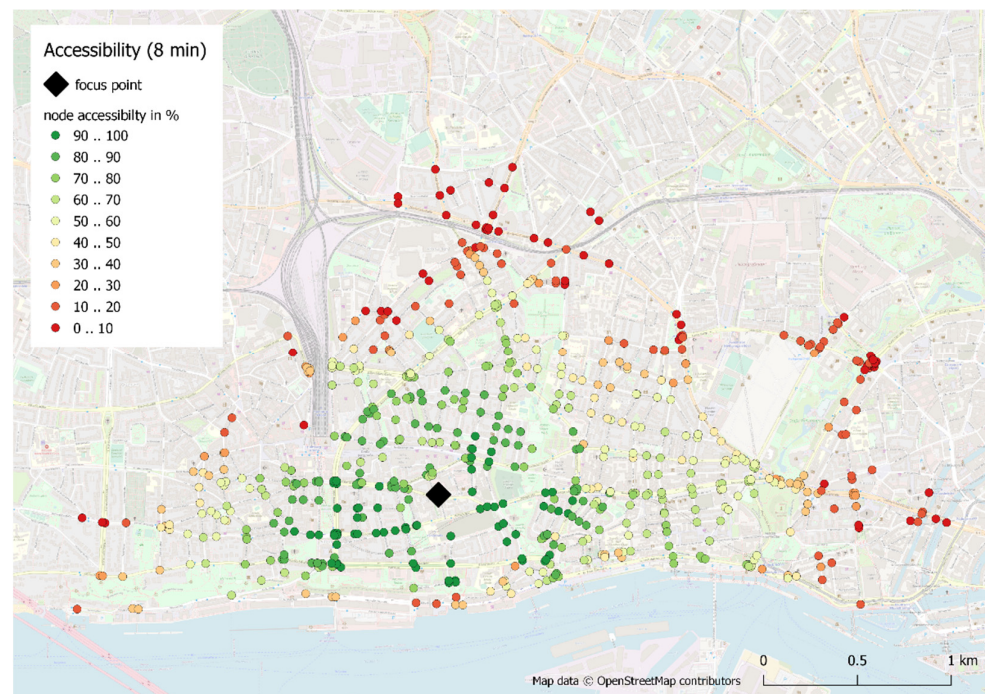
**Figure 7.** Example 3: Spatial variance around eight minutes' isochrones, expressed by network isochrone symbols.

Example 4 (Figure 8) is also based on uncertainties in the edge weights. In this case a simulation took place in which for the given isochrones and a time budget of eight minutes 100 times 10 % of roads were deleted on a random basis, simulating road closures. Shown is the target variable “spatial variance”: the color of points represent the frequency with that these points could be accessed in eight minutes.

The visualization is based on the network as such. The uncertainty symbolization is applied as follows: explicit and extrinsic (colored point symbols colored according to frequencies), integral, coincident, and static.

By simulating road closures, more resilient accessible nodes within the isochrone can be identified, as well as those which are important to their neighborhood or potentially vulnerable. This is important information for planners, e.g., for the preparation of emergency plans in the course of extreme weather events, bomb disposal, etc.

Nevertheless, a straightforward simulation as the one conducted introduces new uncertainties to the user, e.g., when possible traffic jams due to the closed roads are not considered, or road closures of more than one lane have no effect due to the second lane being an alternative. Also, the impact of one-way roads could be rather high.



**Figure 8.** Example 4: Spatial variance around eight minutes' isochrones, expressed by frequency with that points could be accessed within eight minutes although randomly placed closures occur.

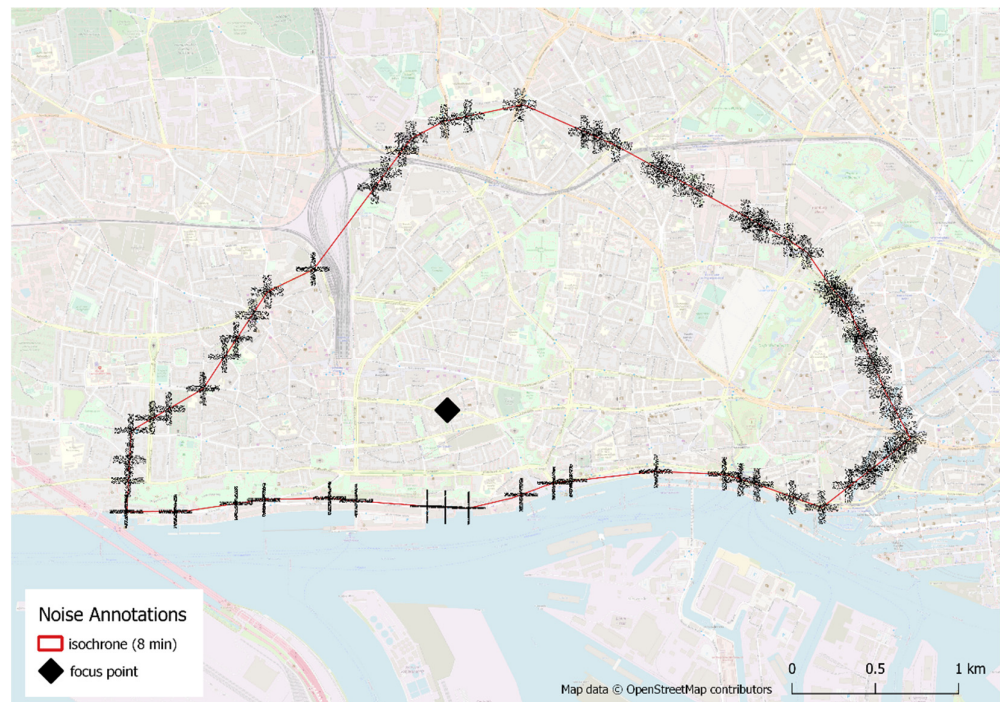
Example 5 (Figure 9) shows the target variable “time variance” (i.e., a variance of the cumulated weights). In this case, this has been modeled in a very simple manner just by considering the number of potentially red traffic lights on the shortest path between the focus point and intersections between the isochrone and the roads.

The visualization is based on the isochrone (for a traveling time of eight minutes). The uncertainty symbolization is applied as follows: explicit and extrinsic (here, noise annotation lines show the time variance as a function of location through different degrees of noise within the crosses), integral, coincident, and static. While these noise annotation lines are well suited for point or polygon features, sketchy lines are appropriate for line features [43].

This example offers the combination of a sharply defined line with a symbol visualizing the uncertainty of this information. Taking up the application for example 2, the uncertainty for reaching a destination in eight minutes from a fire brigade station or other points of interest is described. Based on this information, the placement of critical institutions such as hospitals or power plants can be assessed in a detailed manner.

Compared to example 2, this visualization requires even less map space when combined with other map information. On the other hand, the use of noise annotation is rather abstract and can be misinterpreted by the user, as well as adjacent symbols which overlay each other and lead to cluttering annotations.





**Figure 9.** Example 5: Time variance due to red traffic lights, expressed by noise annotation crosses (noisier appearance stands for larger number of traffic lights on the shortest path).

## 6. Summary and Conclusions

Accessibility analyses are an elementary and important type of geospatial processing for assessing and planning urban infrastructures. Previous approaches to solutions and implementations in geographical information systems (GIS), however, have not or have hardly taken into account inaccuracies in the input data and the results. In order to make a contribution to closing this research gap, this article presents a structured framework that describes the integration of uncertainty information for accessibility analyses.

This framework takes uncertainties in the input data, the processing step, the target variables, and in final visualization into account. Particular attention is paid to the impact of the uncertainties in the target values, as these are key factors for reasoning and decision making. Two major types of uncertainty are named at this stage: spatial variance (e.g., expressed by a buffer around an isochrone that can be accessed in given time) and cumulative variance of weights (e.g., temporal variance for a fixed destination). The accessibility as such is visualized by isovarones (with the specific case of isochrones), isovarone areas or network isovarones. Based on these, the uncertainties can be depicted by various methods for which a dichotomous classification has been applied. Five map examples were given that have been generated with a new software tool and that cover important combinations.

Applying this framework, it turns out that, as with other GIS analyses, the modeling of uncertainties in the context of accessibility analyses is a very complex task. From a practical point of view, a detailed and complete description of all uncertainties is hardly feasible, so that selected or cumulative uncertainty information is used. In order to do justice to a specific application, it is necessary that the purpose of the accessibility analyses (with regard to the target variables) is defined as precisely as possible, instead of just showing the resulting set of isovarones.

The examples presented also showed that every type of visualization has advantages and disadvantages. Here, too, it is therefore strongly recommended that the purpose of the presentation has to be defined as precisely as possible in advance and that the visual-

ization is adapted accordingly with the visualization options shown. In this context, further automatization of the presented framework, for example with the help of machine learning approaches, is an interesting and challenging aspect for future work.

An interesting aspect for future investigations will be whether and how conclusions can be drawn about the relevance (and thus further treatment) of individual sources of uncertainty based on the visualizations. A first prototype of such an analysis, showing the most significant source of uncertainty for each network edge, is already implemented in the BEMUDA tool and will be subject to further research regarding usability and usefulness.

Finally, there is the general problem of reasoning and decision making under uncertainty, for experts and laypeople [44]. This statement certainly also applies for accessibility studies. Hence, in the future, empirical research will be required to test the effectiveness of different types of visualization as a function of the target variables and the desired map purposes. It is to be expected that other symbolization options than the noise metaphor proposed here (noise annotation lines/crosses) will be further discussed.

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