A Study of Visibility Analysis Taking into Account Vegetation: An Approach Based on 3D Airborne Point Clouds

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Abstract. *The visual environment is very essential for forming an urban image, therefore, it is necessary for authorities and urban researchers to quantify the visibility of urban spaces. To date, many traditional visibility analyses fail to take vegetation into account. With the development of LiDAR technology, there is an opportunity* to *use LiDAR point cloud data directly for visibility analysis. Point cloud-based visibility analysis can compensate for many disadvantages of traditional modelling and analysis methods. Such as a better inclusion of vegetation, which is used to be ignored in traditional GIS-based visibility analysis, can be implemented in point cloud-based analysis. This paper gives a brief review of related work and demonstrates the advantages of using LiDAR data for analysis, and also proposes an approach based on airborne point clouds taking in account the vegetation, then performs the proposed visibility analysis on a study case.*

Key Words: point clouds, visibility analysis, airborne point clouds, urban spaces, visual environment

Introduction

The study of visual landscape is an essential topic in the area of urban design. Researches reveal that 90% of the transmitted information in the human brain is visual, we can say we feel the world through eyes. As a result, the visual environment is a crucial element for people to know a city. A well-designed city can also make citizens feel happy and relaxed in their daily life. Therefore, it is very necessary to design a better visual environment for citizens. Before we start planning and designing, an analysis of the urban visual environment should be performed for obtaining the properties and characteristics of human visual space.

Geographic Information System (GIS) is the most common tool to explore human visual space. However, nowadays the use of GIS has been very limited in the study of human space. One of the main reasons is that many GIS operations are based on a traditional view of space which is essentially based on 2D raster or vector representation. To date, the absence of GIS procedures considering vegetation in the built environment remains an obvious limitation. With the development of LiDAR technology, there is an opportunity to use LiDAR point cloud data for compensating some disadvantages derived from traditional modelling and analysis methods.

Based on GIS technology, we propose a methodology that uses airborne point clouds directly to perform visibility analysis for obtaining the visual properties of urban spaces. This paper first gives a brief review of recent researches on visibility analysis, then introduces the methodology using point clouds to do the visibility analysis and presents the results from applying the methodology to the case study, finally illustrates main conclusions and expects the future work.

Motivations

Why visibility analysis?

As mentioned in the section of "Introduction", visibility analysis is a crucial process for designing a better visual environment. With rapid development of economics and to the urbanization, especially in China, mushrooming high-rise buildings as well as various styles architectures haven't been well organized and planned in the urban space under a high-speed construction. This has severely deteriorated the visual environment. A lack of reasonable visual management is the main reason leading to this problem. However, a good visual management method should be based on a reliable and quantitative visibility analysis, rather than on a visibility evaluation totally based on someone's opinions. For this reason, we would like to explore a relatively objective and reliable visibility analysis for urban spaces which is expected to be the foundation for designing a better visual urban space.

Why point clouds?

There are benefits for researchers to use point cloud data in visibility analysis, point clouds could be much more flexible and efficient than other models.

- Using a point cloud based model for visibility analysis can make it possible to skip the process of generating a surface object/vector or grid/raster representation model. It means that we can directly use observed/ surveyed point cloud data to perform visibility analysis, which can help in shortening the period of analysis.
- The point cloud data is collected in a high density and high accuracy, normally the density of points could be more than 10 point/m^2. That allows precise and accurate data usage for both visualization and analysis resulting in better quality visibility analysis.
- Moreover, point cloud data can provide much more detailed information than traditional raster data or a TIN/DEM model. Vegetation is usually neglected in traditional analysis using surface models because of the difficulty of representing trees or shrubs. But actually, we can't neglect the impact of trees in visibility analysis, especially in the summer time when trees would partially block the line-of-sight. Thanks to the comprehensive details provided by point cloud data, it is much easier to represent as well as analysis vegetation by using this kind of data.
- It is also proved that point clouds can be organised very well in different Levels of details (LoDs), which can improve the execution speed of analysis(van Oosterom, Martinez-Rubi et al., 2015).

Why airborne point clouds?

In this paper, an airborne point clouds downloaded from AHN3 (ref: www.ahn.nl), the Dutch Actual Height Map, is used to be the model for our visibility analysis. We used mobile LiDAR point clouds to perform the visibility analysis, but the result is not ideal because of some drawbacks of the origin mobile data. Even though we can gain beautiful and complete facades of each building from mobile point clouds, the missing information of roofs, especially missing slope roofs, will lead to an inaccurate result. In our previous study(Zhang, van Oosterom et al., 2017), we used solid cubes to represent the space which each point occupies and considered these cubes as the main blocking element in mobile point clouds. Since this approach really depends on the integrity and consistency of the input data, a point cloud without complete information of obstacle could result in unreliability and inaccuracy. The comparison of the visibility results from airborne and mobile point clouds can be seen in Figure 1.

Conversely, in airborne point clouds, the roof information is relatively complete*, but the density of facade points is too low to block the line of sight. However, we can still distinguish the space occupied by buildings through the rooftop information(Sun and Salvaggio, 2013). The rooftop features are enough for deciding which part of the model can be the obstacle blocking sight lines. In another word, if there is a roof, there is a wall(s) under the roof in most situation (architectures with underpasses or tilted walls or bridges are not included).

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Related study

Nowadays many researchers in the field of urban design, landscape planning as well as GIS technology focus on the study of visibility analysis. They have proposed different schemes for exploring visual properties of urban spaces or natural environments for different purposes.

The study of visual spaces

As the design of visual landscapes is a crucial procedure of urban design, several researches in the area of urban design and landscape concentrate on the study of visibility analysis. Because the topic of visibility needs multidisciplinary studies, many researches have made an effort to bridge the gap between GIS technology and urban studies.

Llobera (2003) introduced the concept of “visualscape” as a tentative unifying concept to describe all possible ways in which the structure of visual space may be defined, broken down and represented within GIS independently of the context in which it is applied.

Turner, Doxa et al. (2001) show how a set of isovists(Tandy, 1967) can be used to generate a graph of mutual visibility between locations. The measurement of local and global characteristics of the graph, for each vertex or for the system as a whole, is of interest from an architectural perspective: to describe a configuration with reference to accessibility and visibility, to compare from location to location within a system, and to compare systems with different geometries.

Van Bilsen and Stolk (2005) have established an open framework for Isovist-Based Visibility Analysis (IBAV) for urban design and planning. They performed the visibility analysis on several study cases, ranging from modern to traditional, rural to urban, and private to public to address and exemplify IBVA and the framework. They have gained rich results and also proposed a relatively complete framework for analysing visibility on urban streets. But unfortunately, they didn’t take vegetation into account.

Similarly, Weitkamp (2010) has proposed a method for landscape visual openness by using Isovist Analyst, an ArcView extension proposed by Rana (2006), and also performed the method on study cases for verification.

Visibility analysis based on point clouds

With the emergence of LiDAR technology, point clouds have been considered as a new model to perform visibility analysis. Researchers in the area of GIS and LiDAR technology also have done a lot of work for visibility analysis based on point clouds.

Guth (2012)calculates intervisibility of LiDAR instruments in forest for military purpose. He compared the efficiency and accuracy of grid data (DSM & DTM) with considering both situations with and without leaves. His results show that using the LiDAR point cloud can greatly

* Black roofs may not be detected and collected by the laser scanner.

improve both the visualization and quantitative computations of the vegetation blockage. But he only concentrated on the natural environment rather than the built environment.

Murgoitio, Shrestha et al. (2013) consider tree trunks as the primary visual obstacle. After converting point cloud data to raster, they computed viewshed of a specific viewpoint in a forest by using ArcGIS 10.0. In their research, they only took trunks into account because of the missing information of leaves.

Peters, Ledoux et al. (2015) use medial axis transform (MAT) of point clouds for visibility analysis in a built environment including trees and buildings. The medial balls are interior, i.e. inside building points. The computation of a point's normal is the most important part of this research, and in their paper, they also admitted that it is hard to define the normal of vegetation points.

Also, Iglesias, Díaz-Vilariño et al. (2016) have proposed an approach for automatic visibility analysis in interurban roads from point clouds, which is used to identify potential obstacles between the driver and the theoretical position of pedestrians and cyclists, including vegetation and man-made objects.

From the recent study of visual spaces, we can draw a conclusion that a visibility analysis combining terrain, vegetation and constructions remains a blank spot in the study of urban visual spaces. Building on related work of point cloud-based visibility analysis, we find that there is still a lack of integrate visibility analysis for urban spaces directly using point clouds.

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Methodology

We propose a methodology that use the point cloud-based model directly to perform visibility analysis for obtaining the visual properties of urban spaces. The vegetation which is always neglected in visibility analysis is took into account in this study. The overall workflow of our approach is presented in Figure 2.

The proposed approach starts with a process of data preparation to construct a 3D model for visibility analysis. After the data pre-processing, a visibility analysis is executed. The progress of the approach is illustrated in the following sections.

In the domain of architecture, landscape and urbanism, ArcGIS is the most popular software to use GIS technology. Besides, Arcpy allows us to customize and design analysis tools which might be absent in current version, especially analysis tools for point clouds. Therefore, ArcGIS 10.3 is chosen to implement the methodology with Arcpy.

Basic definition

A target point is an object that is defined as the symbol of a certain area, city, or nation, it should be the element (monuments, mountains etc.) can improve the visual environment efficiently. **A viewpoint** is a location where people has the possibility to see the target point(s). In this research, the visibility of public urban spaces is very crucial to the city image. Therefore, viewpoints are selected from urban open spaces only.

Data preparation

First step of the methodology is to extract different classes of the points from a well classified point cloud. In our approach, three categories of points are extracted separately in this analysis for different purposes – ground, buildings and vegetation.

Because we concern about the public space of the city, points of ground (outdoor space) are used to generate the viewpoints. These ground points are downsized by enlarging the average point spacing from 0.2m to 5m and added a height of 1.6m as an eye level.

The building and vegetation points are used as obstacles for the sight lines in addition to terrain itself. For evaluating the impact of vegetation in visibility analysis, we prepare two sets of data as obstructions – one including buildings only and the other one containing both buildings and vegetation.

After the process of point clouds, viewpoints and target points are prepared to be analysed.

Visibility analysis model design

Based on the construction lines between viewpoints and target points, a set of searching points with a certain increment is used to trace along the line. Each searching point involved in an occlusion detection. As mentioned before, an airborne point cloud is used in our approach. We assume that if there are enough rooftop points above a certain space we can say that the space are occupied by buildings themselves, as shown in Figure 1 (b).

Let's assume we have given a point cloud of building rooftops and a set of searching points generated from a line of sight. We want to find the number of points surrounding a searching point on XY plane to detect if the point is blocked by buildings. Assuming that we use a k-d tree structure for doing the range searching, for a certain line of sight LoS, the algorithmic steps would be:

1. create a k-d tree representation for the input point cloud dataset P;
2. create a set of searching points $P_S \in LoS$;
3. set up an empty list of obstacle candidates O_C;
4. for every searching point $p_i \in P_S$, perform the following steps:
    a. search for the set P^i, in every point $p_k^i \in P^i$, the z value of p_k^i is higher than the z value of p_i, see Figure 3 (b);
    b. for every point $p_k^i \in P^i$, check if the point is in a XY-plane searching range of p_i with radius $r < d_0$, if so add the point to O_C, see Figure 3 (c);
    c. calculate the number n_i of points in O_C, if the number is less than a critical value continue process, and if not the algorithm terminates and LoS is marked as invisible;

    when the list of all points in O_C has been processed and $n_i < n_0$, reset O_C and continue to the next point p_{i+1}, the distance between p_i and p_{i+1} is d_0. If $n_i > n_0$, LoS is marked as invisible and the algorithm terminates;
5. The LoS is marked as visible when every $n_i < n_0$ for all points $p_i \in P_S$.

The number of obstructive candidates n_i inside the **searching range** with a radius d_0 of each searching point p_i is considered as a judgment of the occlusion. As long as n_i exceeds a critical value n_0 , the searching point can be considered to be inside a building, i.e. occluded. Consequently, the line which the point belongs to will be marked as invisible, meanwhile, the analysis will stop searching and detecting. Vice versa, if the number fails to reach the critical value, the obstructive candidates inside the searching range of p_i can be considered as non-occlusion, the analysis will continue to the next point p_{i+1}.

Parameter determination

a) The searching range for each searching point

The size of the searching range d_0 should be changed based on the distance like a cone according to the visual system of human eyes. But for simplifying the computation, a fixed size is considered in this study.

According to the physiology of the human eye, we can distinguish an object with a diameter of 0.3m in a maximum distance of 1km. In another word, we can see a 0.3m-length object clearly

within 1km. In our case study, the length of the longest sight line between the viewpoint and the target is about 225m which is much less than 1km. Therefore, a round searching range with a diameter of 0.3m ($d_0 = 0.15m$) is chosen in our case.

b) The number of points that can be considered as occlusion

The criteria value n_0 used to estimate whether a searching circle is occlusive should be assigned based on the density of points. CloudCompare v2.6.3 is used to calculate the density of the obstruction points. Due to the average surface density of the point cloud in our study case is about $14.2\ \text{points}/\pi R^2$†, R = d_0 (the searching radius of the point), n_0 should be 14 in this case.

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Case study

For applying the methodology, a small area in Delft, Netherlands is considered as a study case to perform visibility analysis base on point clouds. The dome of the tower of the Faculty of Architecture and the built environment in TU Delft is chosen as a landmark, and also as the target of visibility analysis (Figure 4(a)).

The input data

The origin airborne LiDAR data is downloaded from AHN3 (ref: www.ahn.nl, see Figure 3(a)), the point cloud is well classified into ground, building, vegetation etc., where we can easily extract points in different classification. The range of the original point cloud is $300 \times 300m$. There are 2,581,639 points in total, the number of points in each category is described in Table 1. After extracting ground points, we randomly reduce points to a minimum spacing of 5m and an extra-height of 1.6m. The total number of viewpoints is 3184 and the number of target is 40. Consequently, 127,360 construct lines are generated and used to compute the inter-visibility between the viewpoint and the target.

The use of k-d tree

For reducing the execution time, the idea of k-d tree is used to re-construct the point cloud data in occlusion detection. The process has been speeded up remarkably by using the k-d tree, the computation time is 155 times less than before. In our case, it only takes 0.2s-0.5s for computing the visibility of one construct line. Scipy, which is a Python-based ecosystem of open-source software, is used in this study for constructing the k-d tree and doing the range searching.

Visibility map

Applying our visibility analysis based on the point cloud, a set of visible sight lines between viewpoints and target points is obtained. Processing on these visible lines, we can generate those points which we can see the target from. In this section, we have computed visibility based on two different models of the built environment (obstructions), see Figure 4.

- Model 1: Obstructions contain building points only;
- Model 2: Obstructions contain not only the buildings but also the vegetation.

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† A point with no neighbour in the spherical neighbourhood will have an invalid (NaN) density

a) The impact of vegetation

Figure 4 also shows the comparison of results from model 1 and model 2. Because of the abundant information of vegetation in model 2, areas covered by trees are exclusive from the visible area in visibility computation. We can see from the figure that the visible area from model 1 is much larger than model 2 due to the ignorance of the vegetation blockage. Specifically, only 1/3 of the visible area from model 1 remains in the result from model 2 (see Table 2), and the rest is blocked by tree and considered as invisible in model 2. From the comparison, we can come to a conclusion that the impact of vegetation can't be neglected in visibility analysis.

b) The accuracy of visibility from point clouds

We have also took a "ground truth" to test the accuracy of our methodology. By taking pictures from the viewpoints and contrast the picture with our result, we find that the distribution of visible and invisible areas from model 2 is considerably reliable. A contrast of photos taken on site and visibility map of model 2 can be found in Figure 5.

Potential applications

Using the original result of visible lines, we can classify the visible viewpoints according to their frequency of seeing target points. In this case, we put visible viewpoints into 5 classes, the classification can be seen in Figure 6. In the process of urban design, we can take different strategy for different visible classes. For instance, points in class 5 and class 4 are defined as the best location to see the target landmark, because in the result of our analysis they have the most amount of visible target points. Therefore, the construction around these points should be controlled strictly to ensure the view of landmark.

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Conclusion

In this work we propose a point cloud-based visibility analysis which can not only quantify the visibility in urban space but also measure the impact of vegetation. The main idea of our analysis is detecting the occlusion along the line between the viewpoint and the target to check if the line is block by obstructions or not and to find where the location of the best view is. A study case is also used in this work to apply the proposed approach, from the results, we can draw several conclusions:

- It is possible to perform visibility analysis directly on point clouds to obtain detailed and reliable results without any procedure of modelling. Besides, the approach we proposed can result in an accurate visibility result by taking the impact of vegetation into account, which can compensate for the neglect of vegetation in traditional viewshed or visibility analysis.
- There are many potential applications for us to use point cloud-based visibility analysis in the progress of urban design, such as estimating the visual blockage of vegetation in urban areas before plant planning for the city. A quantitative visibility result can be very useful for many purposes, for example, different levels of visibility can be helpful to find the best location to enjoy the landmarks or natural sites, and the space between these locations and the landmark should be controlled reasonably for the protecting the view.
- Although a point cloud based visibility analysis could result in better quality, it also requires a significantly large and well classified dataset to perform analysis.
- For the analysis of vegetation blockage, it is also expected that using a different strategy to present the semi-transparency of trees. In the reality, even a leafy tree fails to entirely

block the line of sight. For this reason, it is not accurate to define the visibility of those sight lines passing through trees as “visible” or “invisible”, there should be an intermediate statue(s) between them.

In future research, we plan to apply our method in a larger study case to find the visual properties of large scale urban spaces as well as some essential features behind the urban form. And a different treatment of vegetation, buildings with underpasses or tilted walls and bridges in the visibility analysis should be implemented. Moreover, a merge of airborne and mobile point clouds is considered to obtain a more complete model. Furthermore, a faster point cloud-based visibility is also expected by reducing the redundancy of data. A well-organized point cloud and the idea of level of detail (LoD) can help in filtering useless information in the process of analysis.

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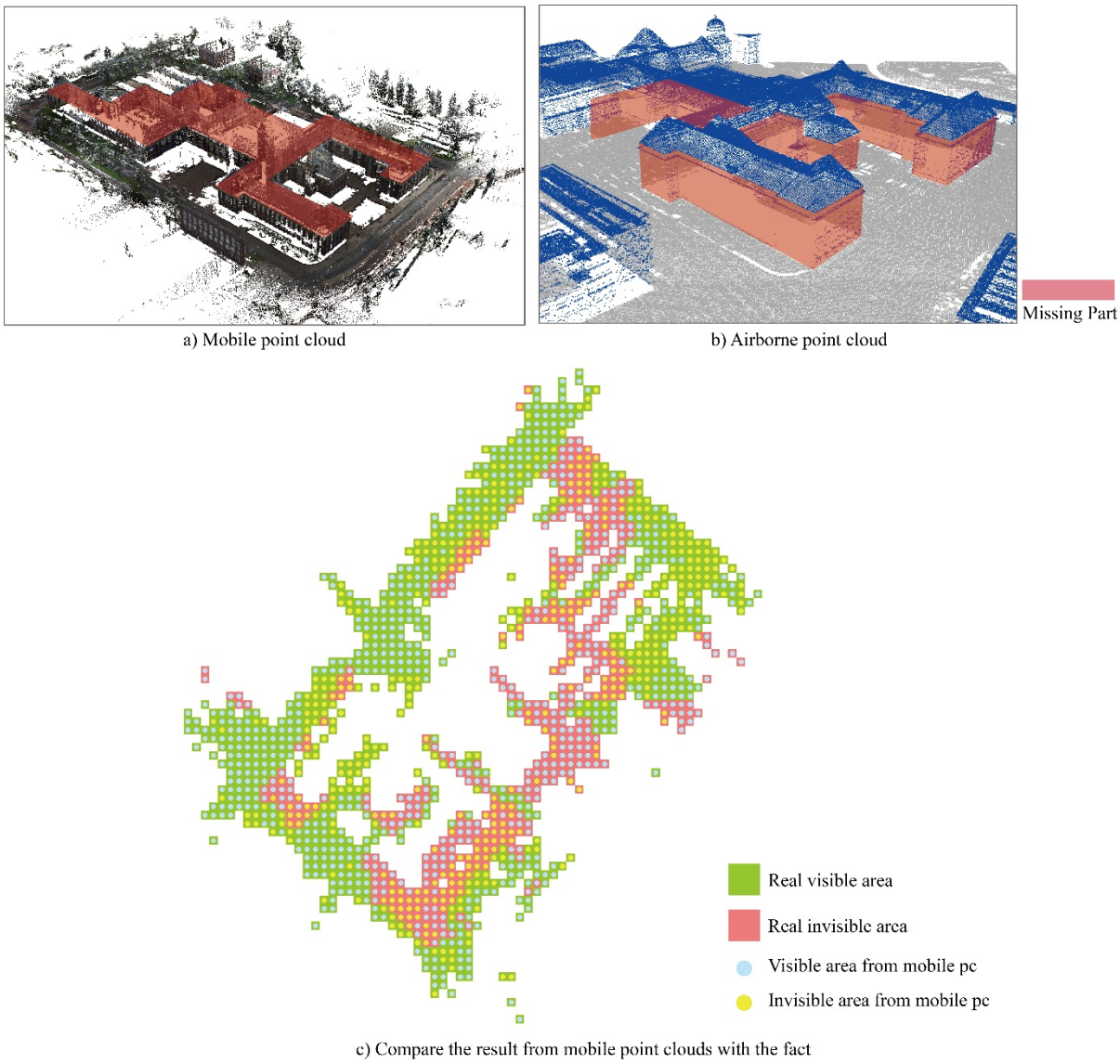
Illustrations and tables



a) Mobile point cloud

b) Airborne point cloud

c) Compare the result from mobile point clouds with the fact

Figure 1 Mobile point cloud vs. airborne point cloud

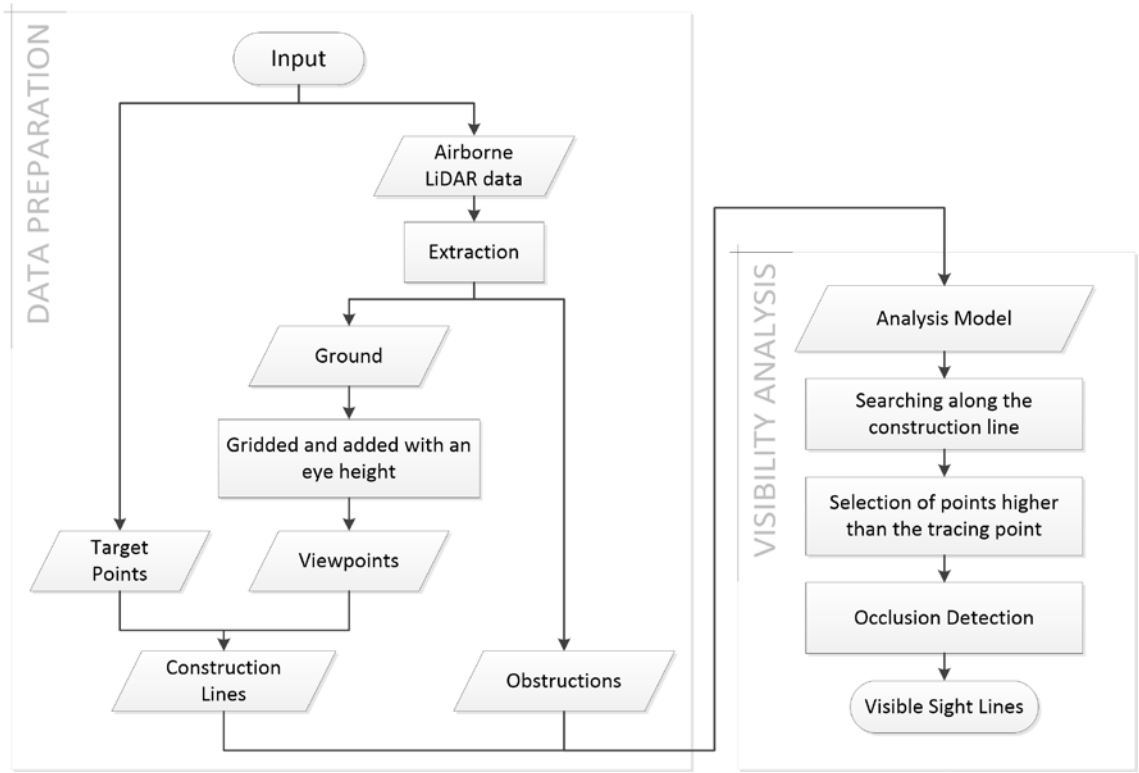


Figure 2 The flow chart of the proposed methodology

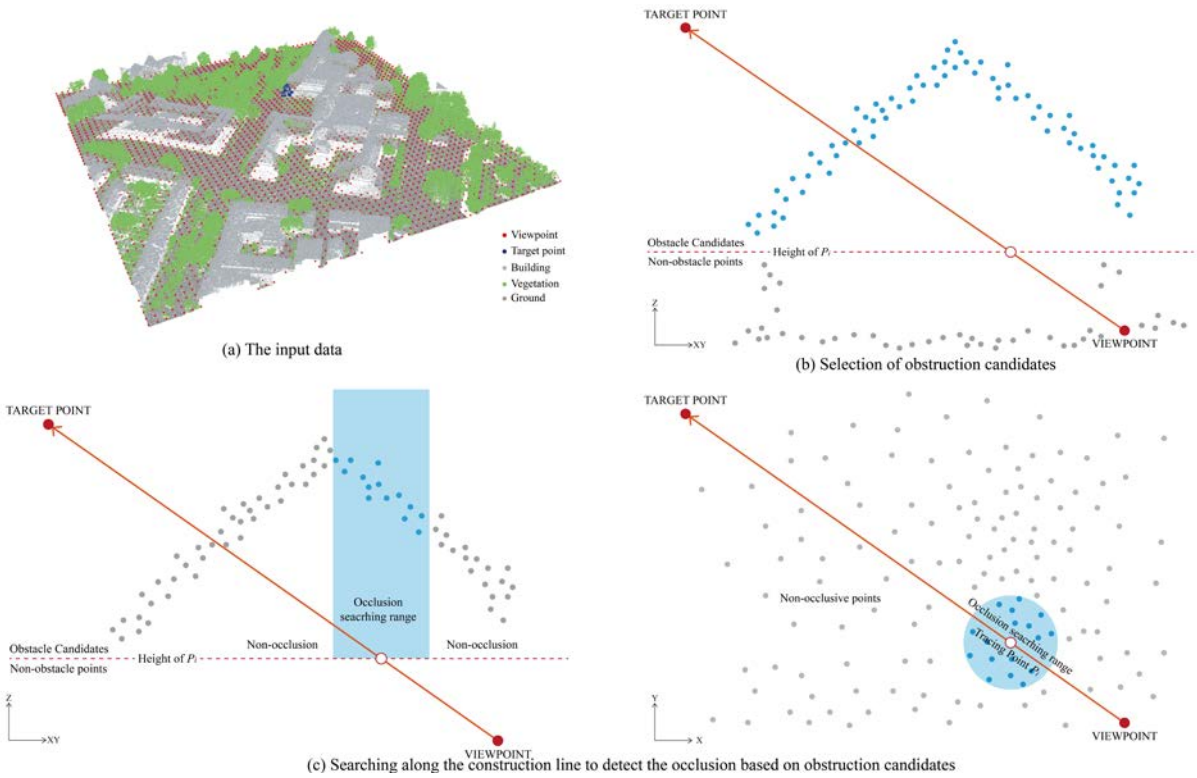


Figure 3 Main procedures of the proposed analysis

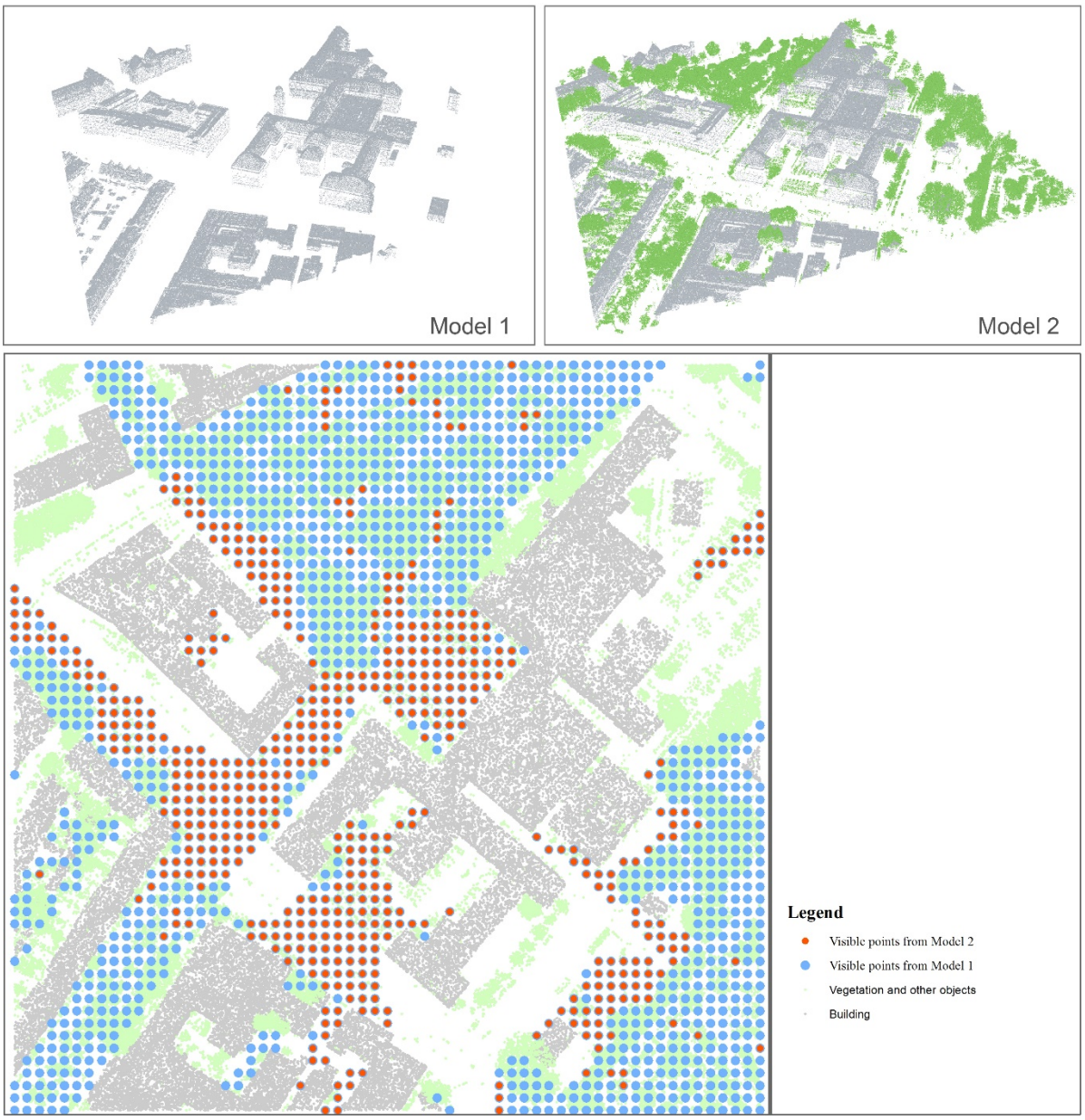


Figure 4 Compare the results from different models

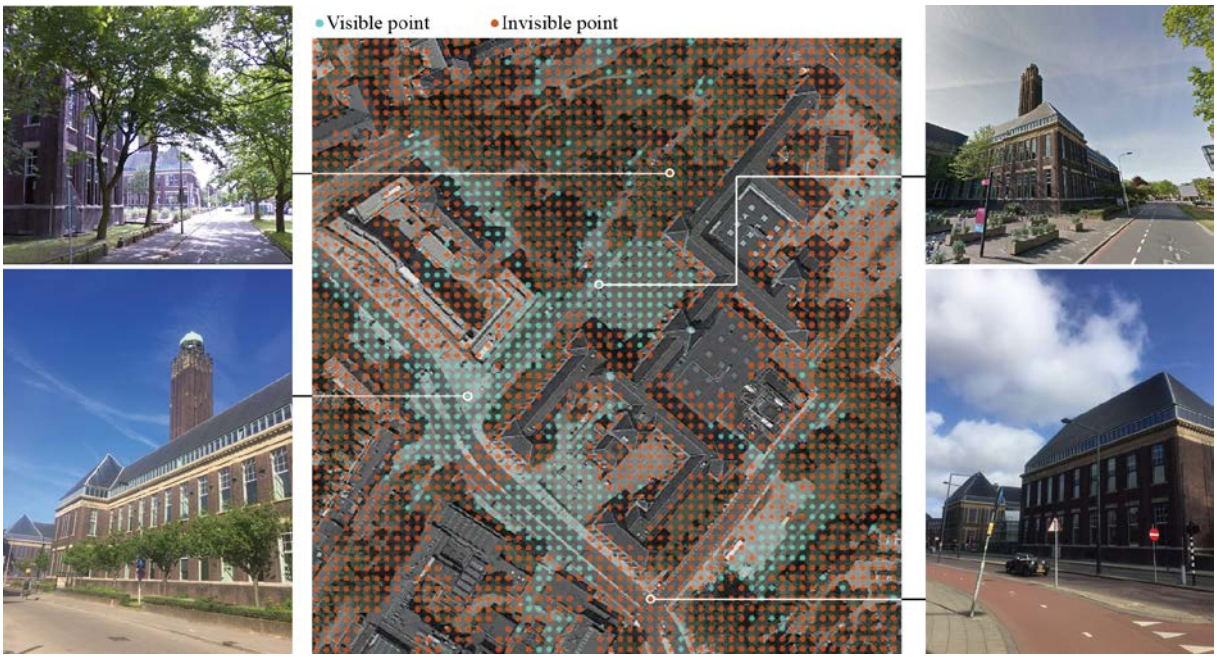


Figure 5 Ground truth testing

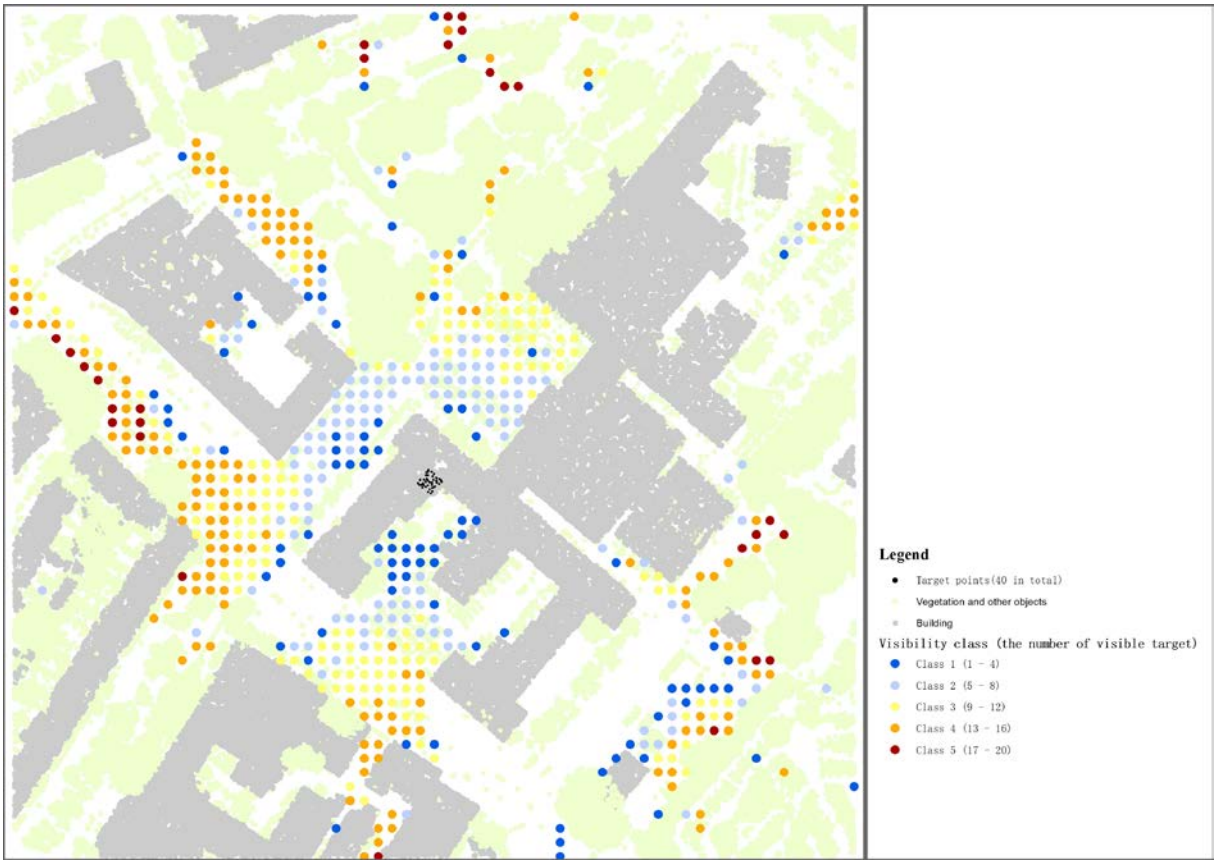


Figure 6 Visibility classification based on the result from model2

Table 1 The information of the input point cloud

Category	Number of points	Highest elevation (m)	Lowest elevation (m)
Ground	1,074,195	1.555	-3.346
Vegetation and other objects (cars etc.)	529,167	28.495	-1.706
Buildings	978,238	52.911	-0.313
Water	39	-	-
whole data set	2,581,639	52.911	-3.346

Table 2 The statistics of the results

Number of Input viewpoints	3184			
Number of Input target points	40			
Model	Number of viewpoints can see at least one target point	Number of target points can be seen from a certain viewpoint		
		Maximum	Minimum	Mean
Model 1	1676	20	1	13.17
Model 2	576	19	1	9.79