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Visibility analysis in urban spaces: a raster-based approach and case studies

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Abstract. In this paper a method for the estimation of the visual impact of buildings with symbolic relevance, such as skyscrapers that are out of scale with their surrounding urban space, is discussed and applied. It is based on the viewshed analysis as developed in rural landscape studies, but it also takes into account the peculiarity emerging from the urban studies. In order to go beyond the sole information of whether a cell is, or is not, visible, which is typical of viewshed analyses, in this work the various factors that cause the visual attenuation with the distance are discussed and quantitatively assessed by determining various limit-of-visibility distances that may also be time variable. These factors are the visual acuity, the contrast between the target and its surroundings, the atmospheric visibility, and the recognition process of the subject. An application of this methodology is carried out on various case study buildings in the city of Turin, Italy (an ancient building, an urban landmark, the Mole, and a skyscraper under construction). From the visibility maps, under various conditions, it can be seen that the new skyscraper will be a major landmark not only for the entire city, but also for the surrounding municipalities.

Keywords: viewshed analysis, skyscraper, landmark, visual perception, urban landscape

1 Introduction

It is well known that a new development can modify the viewing conditions of a landscape. This is identified as a visual impact; however, it is seldom an easy task to determine the effect of the view obstructions and the reshaping of the skyline in both urban (Guney et al, 2012; Moser et al, 2010) and rural areas. In the first case it is necessary to take into account, besides the topography, the building elevations and the urban atmospheric visibility. In the scientific literature visibility studies for rural and forest landscapes are well established and have been developed further in recent years, but there are not many visibility studies for urban space, and most of them are based on a two-dimensional (2D) representation (eg, isovist) due to the difficulty of taking into account building heights and other factors. Other recent studies have concentrated on small parts of a city (Bartie et al, 2013).

In the design of a skyscraper the most important modifications to the urban landscape that should be studied are, for example, the variation of the skyline of the city, the visibility of the building from visual corridors of the main streets, and the compatibility with the surrounding architecture, especially when such projects are developed in traditional Italian cities that are characterized by a building height no greater than 20 m (De Rossi and Durbiano, 2006) and where buildings are easily seen by people on streets. In such cases there is the need to estimate the visual impact of a new building on its surroundings, in order not only to redesign the city

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skyline from some representative viewpoints, but also to understand where this building can be seen from and how much of it can be seen. In order to answer these questions, urban landscape studies are necessary. It is evident that these studies should be three-dimensional (3D). Also, a simple geometrical study which does not take into account atmospheric extinction, colour difference, visual acuity, and the visual psychological threshold may give unrealistic results, as will be discussed later. A comprehensive method, sufficiently simple but accurate, to generate visibility maps of symbolic buildings is presented and discussed in this paper. It is applied to various case studies in the city of Turin and, in particular, to a new skyscraper about 230 m high that is under construction.

2 Scope of the work and peculiarities

In order to study the visibility of an out-of-scale building within an urban environment it is necessary to use GIS procedures that consider together both terrain and built environment representations and model the interaction between humans and the space. However, visibility studies, especially those referring to rural and forest landscape analysis (Fabrizio and Garnero, 2013), are usually based on terrain representations only such as triangulated irregular networks or a regular square grid of elevations [digital elevation models (DEMs)] and require some simplifications in order to take into account vegetation and other obstacles that affect the visibility (eg, create a vegetation elevation model that is added to the DEM).

Another characteristic of this work is to go beyond the standard binary approach that is used in visibility analysis (an integer result to identify whether the cell of a raster is, or is not, visible), taking into account more realistic factors that depend on human vision and the outdoor environment (Garnero et al, 2013).

Finally, in this work we tried to perform the visibility analysis not on small areas or single hillsides like many viewshed studies, but on the area of the entire city of Turin, which covers an area of 130 km^2 and is one of the largest cities in Italy.

3 Materials and methods

3.1 From the isovist to the visual exposure

Visibility studies in urban space analysis were first conducted by means of isovists (Benedikt, 1979). An isovist may be defined as the visual field (set of points) that is wholly visible from a certain single point that is the feature of interest and is called the vantage point. If the isovist is computed on a plan, in a 2D representation the isovist is the set of points that are visible from the vantage point, disregarding the effect of the terrain morphology and the different heights of the surrounding buildings. In this case an isovist is mapped as the continuous area of a 2D polygon, as shown in figure 1, where the area that is visible from the point at the corner of two streets in an urban environment is indicated.

With the creation of isovist-generating computer applications (Dalton and Dalton, 2001), there has been the possibility of moving the vantage point along a path generating a field of isovists and studying how the isovist properties vary along the path. However, among the drawbacks of the isovists there is the fact that in two dimensions an isovist does not take into account the possibility of looking beyond an obstacle (Llobera, 2003).

The concept of isovist (Batty, 2001) has been employed in the study of spatial properties of indoor spaces (Arabacioglu, 2010; Franz and Wiener, 2005; Turner et al, 2001; Wiener et al, 2007) rather than urban spaces, but the visibility indices emerging from the rural and forest landscape analysis were preferred. In fact, as stated by Llobera (2003), apart from architectural and urban studies, the term viewshed tends to be used instead of isovist. In particular, Turner et al (2001) developed the concept of the visibility graph: that is, a graph of mutual visibility between locations, that can be useful in various spatial perception applications such as wayfinding.

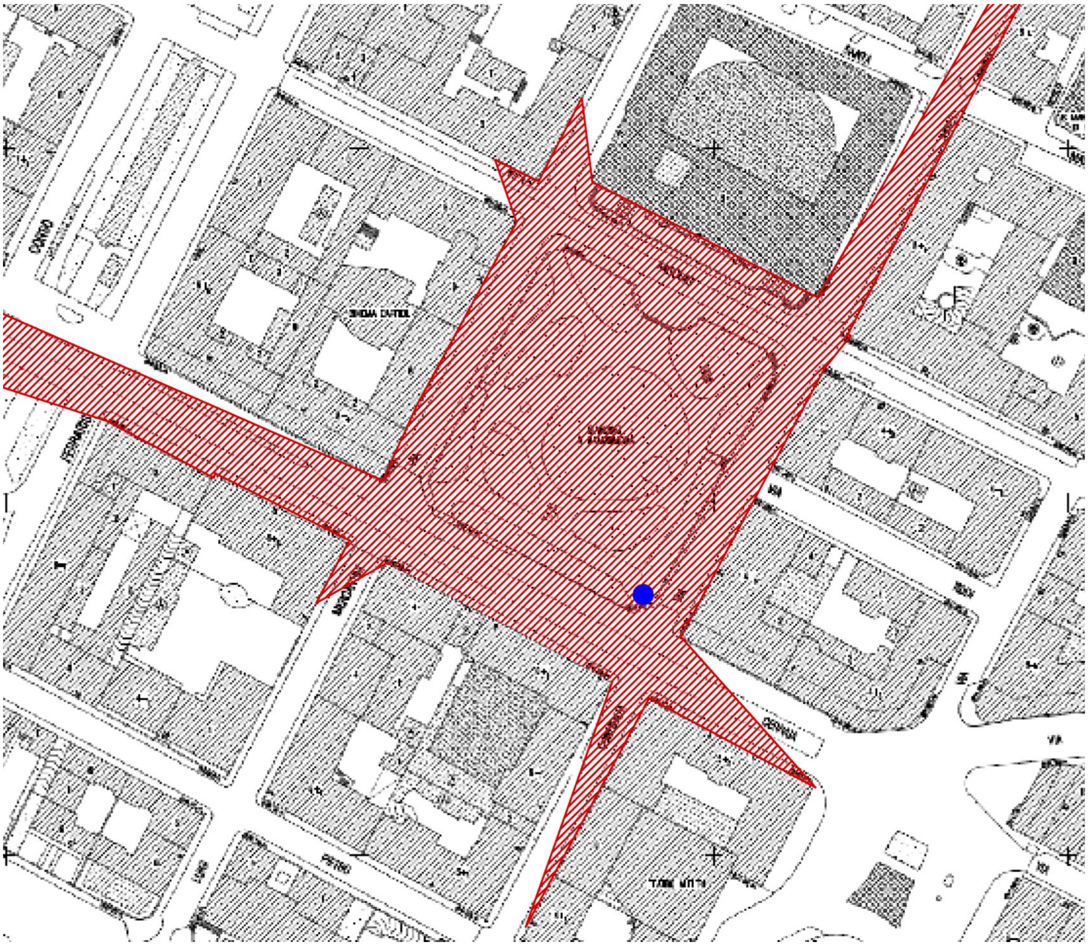


Figure 1. [In colour online.] Example of an isovist.

A viewshed is a binary representation of the visibility of a location from a certain viewpoint and is usually computed by means of standard functions of GIS software tools from the DTM (digital terrain model). The result is a Boolean variable that identifies whether each cell is visible (value 1) or not (value 0) from a certain viewpoint.

When the results of various viewsheds from different viewpoints are added together using raster algebra of GIS tools, the result is called the cumulative viewshed and is characterized by an integer result: in this way, the number of viewpoints that are seen from a cell can be identified.

In order to go beyond whether a cell is, or is not, visible which is typical of viewsheds, some authors have introduced visual magnitude, which also takes into account the amount of a specific feature that is visible to the observer. The first consideration on which this concept is based is that the visible size of an object diminishes as the viewing distance increases. The visual magnitude result is a floating point whose values are from 0 (no visibility) to 1 (complete visibility) and is computed taking into account the fact that the visible area decreases with the square of the distance. Different formulations for the calculation of the visual magnitude can be found in the literature (Chamberlain and Meitner, 2013; Grêt-Regamey et al, 2007). As can be easily understood, in reality, visual magnitude assumes very low values because it has the physical meaning of the amount of occupied area in an observer's view. Again, in the case of visual magnitude only geometrical aspects are considered. Other authors have introduced the concept of visual exposure (Domingo-Santos et al, 2011) in order to take into account the atmospheric extinction, the colour difference of the background, and the visual acuity.

Visual magnitude and visual exposure concepts have been widely used in rural and forest landscape analysis (Chamberlain and Meitner, 2013; Domingo-Santos et al, 2011; Jakab and Petluš, 2012; Kearney et al, 2008) but more rarely in urban environment landscape analysis. Bartie et al (2013) proposed a model for describing a visible cityscape; however, it was tested on a small study area.

A second line of research into urban visual analysis is of studies that are not raster based (like the viewsheds ones) but vectorial based, especially the ones related to the spatial openness index (Fisher-Gewirtzmann and Wagner, 2003; 2006; Fisher-Gewirtzmann et al, 2003; 2005; Shach-Pinsly et al, 2011) and the isovist matrices that were proposed by Morello and Ratti (2009) for large urban areas. Also Yang et al (2007) proposed a way to go beyond the 2D visibility for measuring visible urban space quantitatively using 3D visibility indices applied to an urban test site in Singapore.

In regards to the motion perspective of an observer, sky shape skeletons were investigated by Sarradin et al (2007) in order to quantify the morphology of urban open spaces along routes.

3.2 From geometric visibility to visual perception

Viewsheds and cumulative viewsheds can be easily calculated by means of standard GIS tools; however, they suffer from the limitation that they lack visual attenuation with distance, so when the distance increases the results of a viewshed analysis are merely theoretical.

The effect of the visual attenuation with distance is due, from a physical point of view, to three factors:
(1) the visual acuity of the human eye;
(2) the atmospheric visibility;
(3) the contrast between the target and the surrounding (eg, the sky).

Visual acuity is defined as the inverse of the minimum apparent diameter *a*, measured in minutes of arc (min). The arc *a* can be obtained from the distance of observation *d* and the object size *D* as

$$a = \frac{180 \times 60}{\pi} \arctan\left(\frac{D}{d}\right). \tag{1}$$

The visual acuity threshold value depends on the age of the subject, the illuminance level, and the contrast, and ranges from 2 (that is 0.5′) for young people with the greatest contrast, to 0.2 (that is 5′) for elderly people with the lowest contrast (Fortuin, 1951). Usually, a value of about 1, that is an angle of 1′, is considered to be a threshold value of visual acuity.

The limit-of-visibility distance due to visual acuity, d_{lv}, and is

$$d_{\mathrm{lv}} = D \Big/ \tan\left(a \frac{\pi}{60 \times 180}\right) \cong D \frac{60 \times 180}{a\pi} . \tag{2}$$

Considering an object that has a size of 20 m (that may be, for example, one of the two dimensions of a building plan), the maximum distance at which it can be seen is 69 km with a visual acuity of 1. This value may seem quite high; however, it should be noted that in many cases it remains merely theoretical because other factors (contrast, atmospheric extinction) becomes dominant.

Even though visual acuity sets a physical limit on the mutual view distance between two points in a GIS model, it is only in some particular weather conditions (eg, clear winter days) that the visual acuity limitation may be the predominant one.

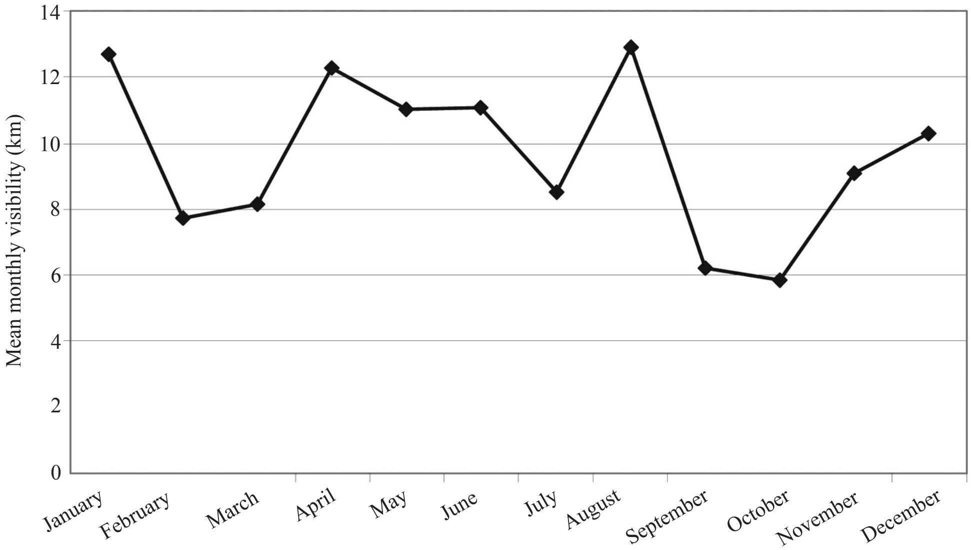


Figure 2. Mean monthly values of the visibility in the test reference year for the Turin location.

In fact, in practice in many cases the atmospheric visibility, rather than the visual acuity, may limit the maximum visibility distance. Weather registration stations usually measure the visibility in km, or at least the number of days when the visibility is less than 1 km and less than 100 m for at least 3 hours. However, rather than specific weather registrations, a typical behaviour of this parameter can be found in the test reference years (TRY) [(1)] used, for example, for energy performance calculations, where for each of the 8760 hours of a year a value of visibility is assigned and measured in km. For example, the mean monthly values of the hourly values of visibility for Turin are reported in figure 2, where it can be seen that the lowest values of visibility occur in September and October, while the highest values occur in August and January. Between the lowest and the highest visibility values there is a difference of 7 km. Atmospheric visibility sets a time variable limit-of-visibility distance, d_{la}, and is dependent on outdoor weather conditions.

The third aspect that affects the visibility of an object in the landscape is the colour contrast between the target and its immediate surroundings. In many procedures for visual impact assessment (eg, Chiabrando et al, 2011; Torres-Sibille, 2009) this aspect is taken into account by computing the colour difference—sometimes erroneously called contrast—expressed as the Euclidean distance between the two points in the CIELAB colour space. In visibility studies other authors calculate the contrast as the difference between the average lightness of the object and the background object (eg, Shang and Bishop, 2000), thus considering only a difference in lightness on a grey scale.

It is evident that in order to correctly take into account the visual attenuation with distance and to produce more realistic viewsheds that can be used to assess the visual impact of a new development, it is necessary to consider all three factors. Depending on the various boundary conditions of the study (eg, size of the study area, the atmospheric conditions) one of those three factors may be the one that limits the detection of a target.

Finally, not only the physical aspects of vision (eg, visual acuity, contrast) but also the psychophysical effect of perception should be considered. In fact, visual acuity regards only

[(1)] A TRY is a file that contains the 8760 hourly values of the various weather quantities representative of the mean climatic conditions of a location, see for example the TRY computed by the ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers, http://www.ashrae.org) within the international weather for energy calculation programme. They were initially developed to be used in order to determine the heating and cooling energy needs of buildings.

the possibility that an object is seen from a certain distance but does not assure that the subject detects and recognizes the object. To take into account this perceptive of vision, visual thresholds were introduced in psychophysics. A visual threshold is the minimal stimulus that can be perceived, a sort of a boundary between detecting and not detecting (Shang and Bishop, 2000).

The process of visual recognition of an object can be divided into detection, the informed recognition [subjects are asked to recognize a certain object knowing beforehand what they are expected to find in their vision] and uninformed recognition (the subjects do not know that there is such an object and have to name it). Medium visual impact thresholds were studied and defined for landscape settings by Shang and Bishop (2000) in field surveys using tanks and towers as objects. In particular, they found that there is a mutual relationship between visual contrast and visual size. The visual contrast C is the difference between the average lightness of the object and the background. The visual size (or magnitude) S is the portion of the field of view that is occupied by the object and is computed as the product of the two angles α and β that lie on the horizontal and vertical planes, respectively, and are subtended by the target object. It is measured in min^2. It is calculated as

$$S = \alpha\beta = \left[\left(\frac{180\times 60}{\pi}\frac{D}{d}\right)\left(\frac{180\times 60}{\pi}\frac{H}{d}\right)\right] = \frac{180^2\times 60^2}{\pi^2}\frac{DH}{d^2}\ , \qquad (3)$$

where D and H are the horizontal and vertical target dimensions.

There is a mutual trade-off between the C and S quantities. At high visual sizes uninformed recognition happens for low values of the contrast, but when the visual size decreases a greater value of the visual contrast is necessary. If the visual size approaches the value of $1'$ it is necessary to have a contrast of 100%: this point represents the usual visual acuity. Shang and Bishop (2000) have therefore plotted graphs which have visual size (in min^2) and visual contrast as the axes. These threshold curves express the trade-off between threshold visual size and threshold visual contrast for informed recognition, uninformed recognition, and uninformed detection. These curves, and the related logistic regression equations also derived, can be used in landscape studies to determine the visual impact of an object introduced into the landscape and they were adopted in our work.

It is worth noting that the concept of visual thresholds as defined by Shang and Bishop (2000) combines different factors that were introduced previously (visual acuity, contrast) together with psychophysical perception into a unique concept. It is, therefore, possible to determine a limit distance d_{lp} based on these thresholds. Once that the visual contrast is fixed, the limit-of-visibility distance for the psychological perception d_{lp} can be determined, from equation (3), as

$$d_{\mathrm{lp}} = \frac{180\times 60}{\pi}\left(\frac{DH}{S}\right)^{1/2}\ . \qquad (4)$$

For example, considering the uninformed recognition of a target characterized by object sizes equal to 20 m and 70 m, for a visual contrast of 30% the threshold visual size is equal to 50 min^2 and the limit-of-visibility distance for psychological perception is 18.19 km. If the contrast falls to 13%, the threshold visual size is 100 min^2 and the limit distance becomes 12.26 km, while at the lowest value of contrast (7%) considered by Shang and Bishop (2000), the threshold visual size is 250 min^2 and the limit distance becomes 8 km. Finally, it is interesting to note that for the maximum contrast (that obviously, under normal ecological conditions, is not attained), the threshold visual size is 1 min^2: that is, the standard visual acuity, and equation (4) gives 128.6 km.

4 Implementation of case studies

The following visibility analyses were conducted in the city of Turin, one of the largest cities in the northwest of Italy, and on three different targets: an ancient building, a symbolic building, and a future skyscraper. The general specifications concerning the study area are reported, followed by the analyses that were conducted for each case-study building.

4.1 Terrain model

The terrain height is the new DTM of the Piedmont Region which has a cell size of 5 m × 5 m. Data for our work were provided by the Regione Piemonte survey, which aimed at the production of a digital orthoimage at 1 : 5000 scale and a digital terrain model at level 4 in accordance with Intesa specifications (CISIS, 2011) as reported in table 1 (Godone and Garnero, 2013).

Table 1. Specifications of the DTM (digital terrain model) level 4 (CISIS, 2011).

Type	DEM [a] or DSM [b]
Accuracy: bare ground *PH(a)*	0.30
Height accuracy: with tree cover > 70% *PH(b)* (DEM)	0.60
Height accuracy: buildings (DSM) *PH(c)*	0.40
Height tolerance: bare ground *TH(a)*	0.60
Height tolerance: with tree cover > 70% *TH(b)* (DEM)	1.20
Height tolerance: buildings (DSM) *TH(c)*	0.80
Planimetric accuracy: *PEN*	0.30
Planimetric tolerance: *TEN*	0.60
Cellsize:	5

[a] DEM = digital elevation model.
[b] DSM = digital surface model.

A LIDAR survey was carried out using an ALS 50 II sensor (Leica Geosystems) with MPIA (multiple pulse in air) technology with the following features:

- maximum pulse rate: 150 000 Hz (150.000 points/s);
- maximum scanning frequency: 90 Hz (90 lines/s);
- four echoes (1º, 2º, 3º, and last);
- flying height: 200–6000 m above ground;
- field of view (FOV): 10º–75º;
- side overlap: 200–600 m;
- intensity measured for each echo.

In addition to the ordinary survey, in a portion of the Regione Piemonte, a more detailed survey has been required. It was characterized by the following parameters:

- FOV: 58º;
- LPR (laser pulse rate): 66.400 Hz;
- scan rate: 21.4 Hz;
- average point density: 0.22 points/m²;
- average point spacing: 2.12 m.

The study area is the city of Turin and counts nine sections at a scale of 1 : 10 000 which were jointed on a single DTM resampled at a cell size of 0.5 m × 0.5 m. Obviously, this resampling does not add any improvement to the quality of information, but was done in order to operate the following calculations. The representation of this DTM is reported in figure 3 where it can be noted that from west to east there is a gradual slope to the River Po, then there are the hills on the southeastern part of the DTM.

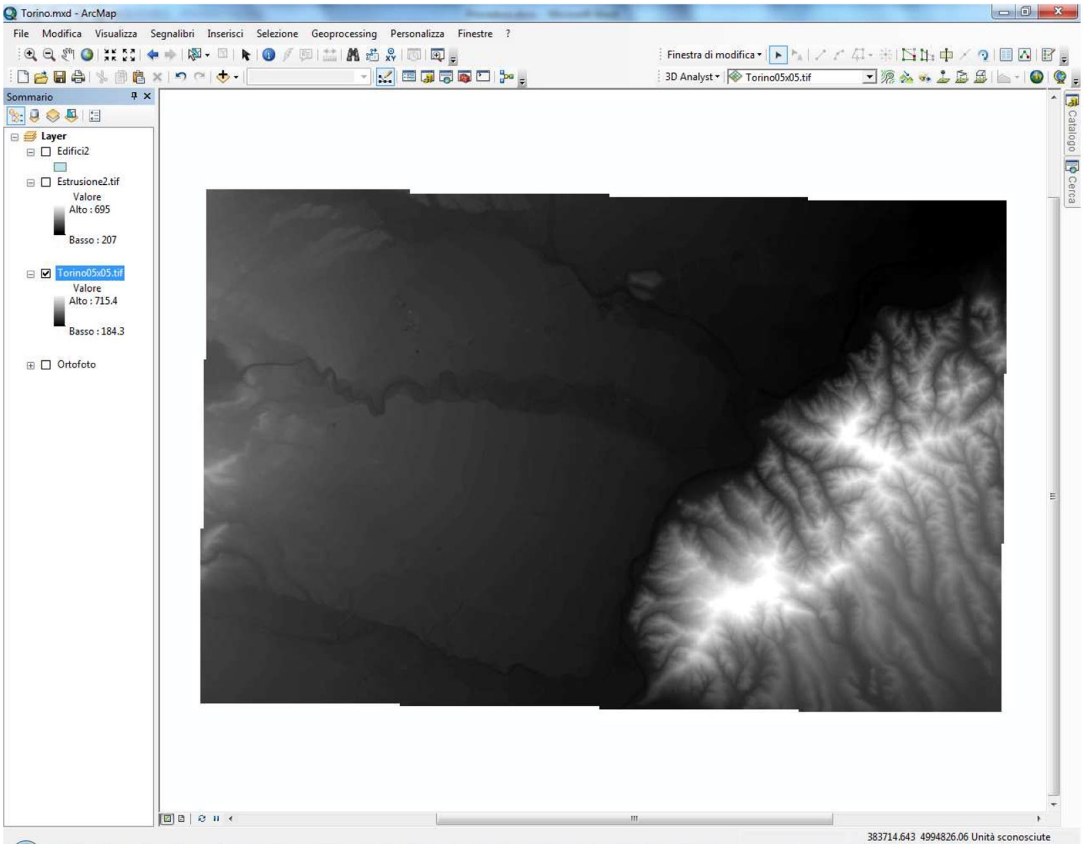


Figure 3. [In colour online.] Digital terrain map of Turin.

4.2 Buildings model

As regards the buildings, the information was taken from the Technical City Map of Turin, a cartography on a scale of 1:1000, updated each six months with topographic measures. It was obtained as a shape file and with the eaves height of each building. In particular, the 3D model of the city is subdivided into primary and secondary buildings, and every height is derived from aerophotogrammetry techniques. Secondary buildings are low-rise constructions like garages, sheds, and service buildings, next to a primary building. In particular, there are:

- 64 679 primary buildings, of which 3515 have eaves height equal to zero. In order to retrieve, at least approximately, the heights for these buildings, for which the information on the number of floors above ground was in any case available, the eaves height was estimated by summing the building height (as number of floors × 3 m) to the ground level.
- 65 334 secondary buildings, of which 28 870 have eaves height equal to zero; these are mostly low buildings and they were deleted.

4.3 GIS processing

The ArcGIS 10.1 tool was used in all the processing. In order to obtain information consistency between the two databases available, the vectorial data were transposed into raster data using the GIS ‘Polygon to raster’ command, which produces a raster with a cell size of 0.5 m, that reports all eaves heights of the buildings, and nodata where there are no buildings.

At this point, the two models (DTM and buildings) were merged using the raster calculator, generating a new raster that has the value of the regional DTM if the building raster is null, otherwise it has the value of the building eaves height. In practice, this is a sum of the buildings DTM and the terrain DTM that produces a DTM where buildings are ‘extruded’ with a cell size of 0.5 m. (See figures 4 and 5.)

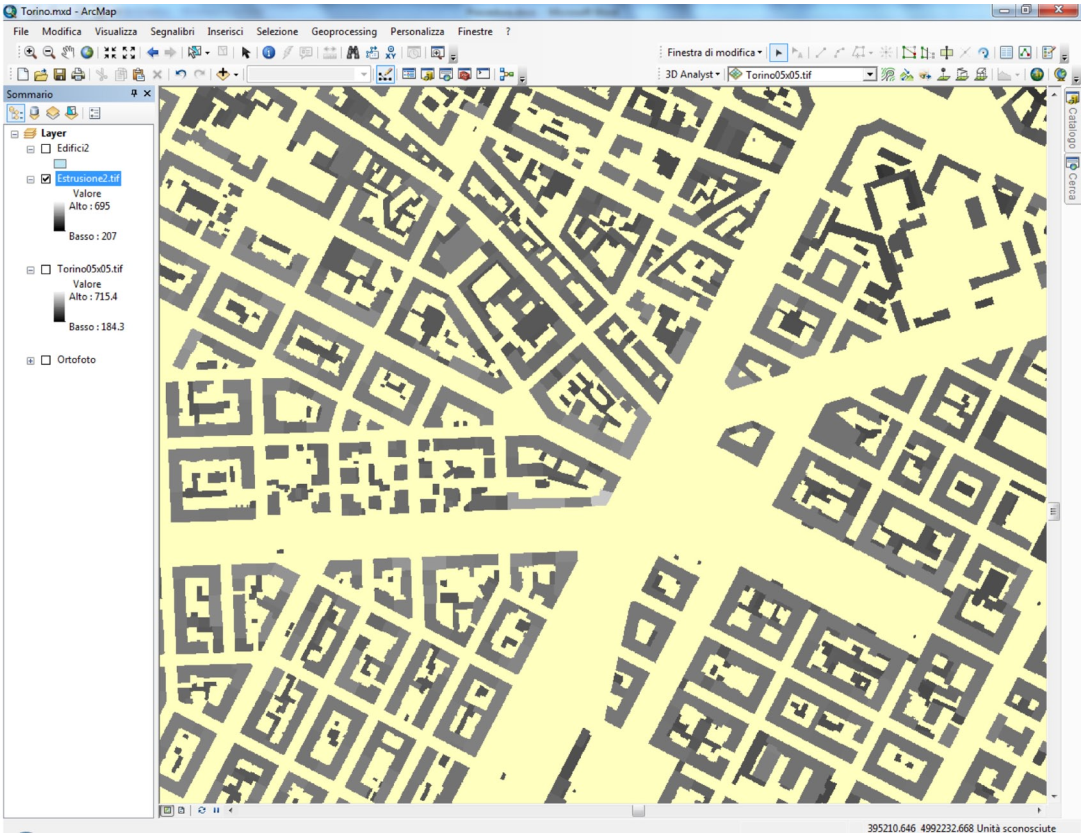


Figure 4. [In colour online.] Model of buildings.

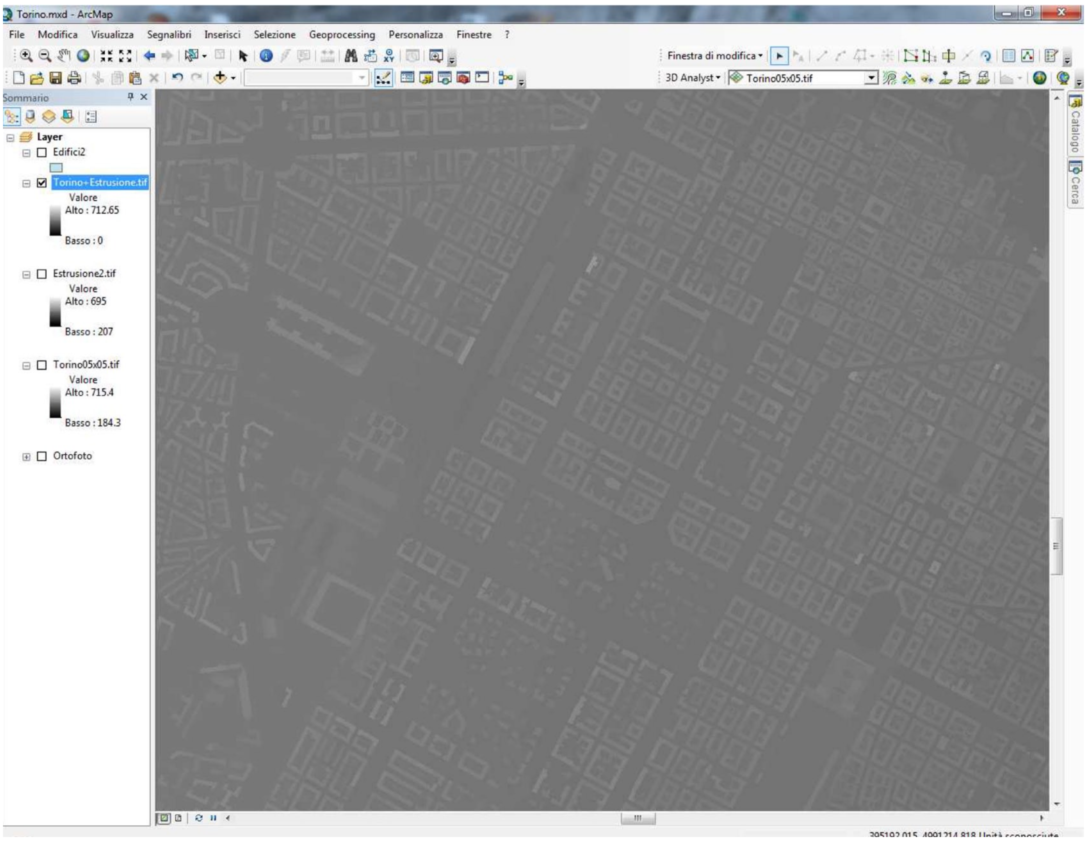


Figure 5. [In colour online.] Model of the digital terrain map and building.

In order to determine the cumulative viewsheds, the ArcGIS ‘Viewshed’ command was used, inputing as target points the eaves height of the building under consideration and introducing a maximum visibility distance in order to take into account the various limitations (visual acuity, atmospheric extinction, psychological perception).

A 3D view of the city model (where the heights of the buildings were not emphasized) is shown in figure 6, where the limit of the city is indicated with the fuchsia line. All buildings are coloured yellow while the skyscraper under consideration in the following paragraph is coloured brown.

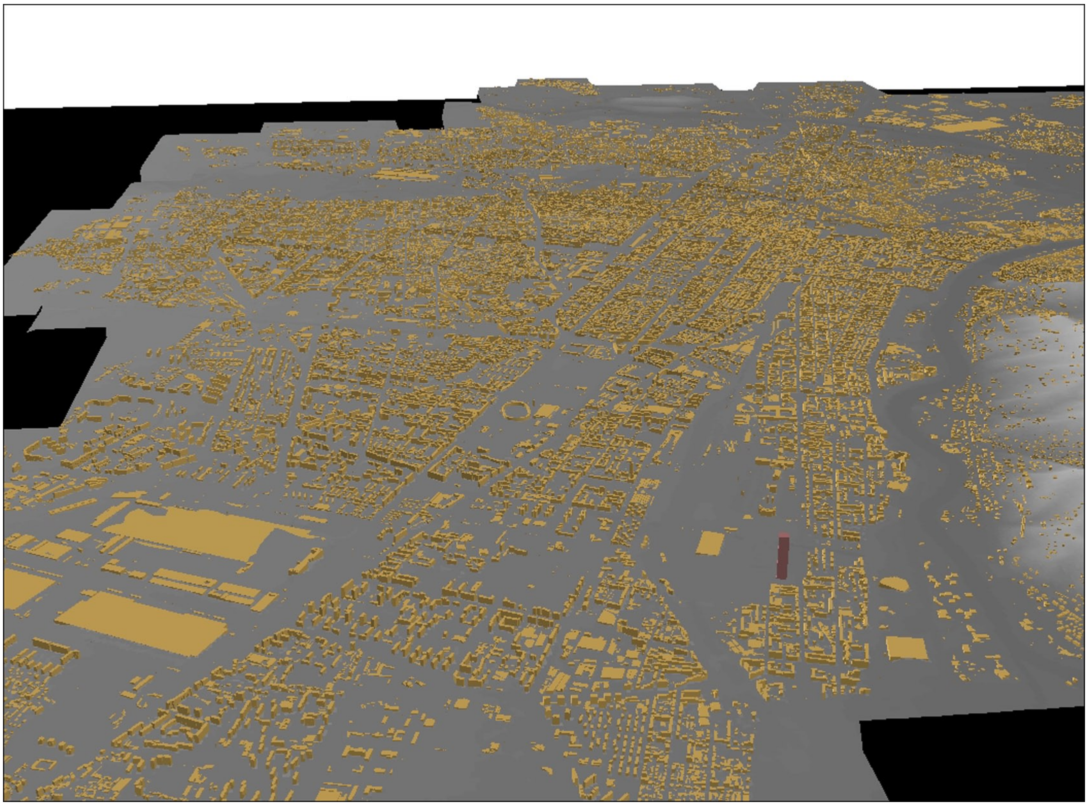


Figure 6. [In colour online.] A view of the 3D model of the terrain and buildings of the city of Turin, looking north.

4.4 The limit-of-visibility distance for atmospheric extinction

As it was introduced in subsection 3.2, a limit-of-visibility distance due to atmospheric extinction, typical of the location of the study area, should be introduced. In this work, in order to consider two different conditions characterized by a different behaviour, the two months with the highest and the lowest visibility values were selected. These are August, with a mean monthly visibility of 12.9 km, and October with a value of 5.8 km (figure 2). In figures 7 and 8 the frequency distributions of the hourly values of visibility for those two months are reported. It is easily seen that the frequency distribution of the month with the lowest visibility (October) is centred on low values with a maximum at 2 km, while for the month with the highest visibility (August) there is more than one maximum and the distribution presents values spread from 4 km to 35 km. In order to set the maximum value of the atmospheric visibility as the d_{la} distance to be used in the following analyses, the visibility value that is surpassed for 80% of the time was selected. These values are 5.2 km for August and 1.6 km for October. In particular, it is the value for October that will be used as a lower limit of visibility distance.

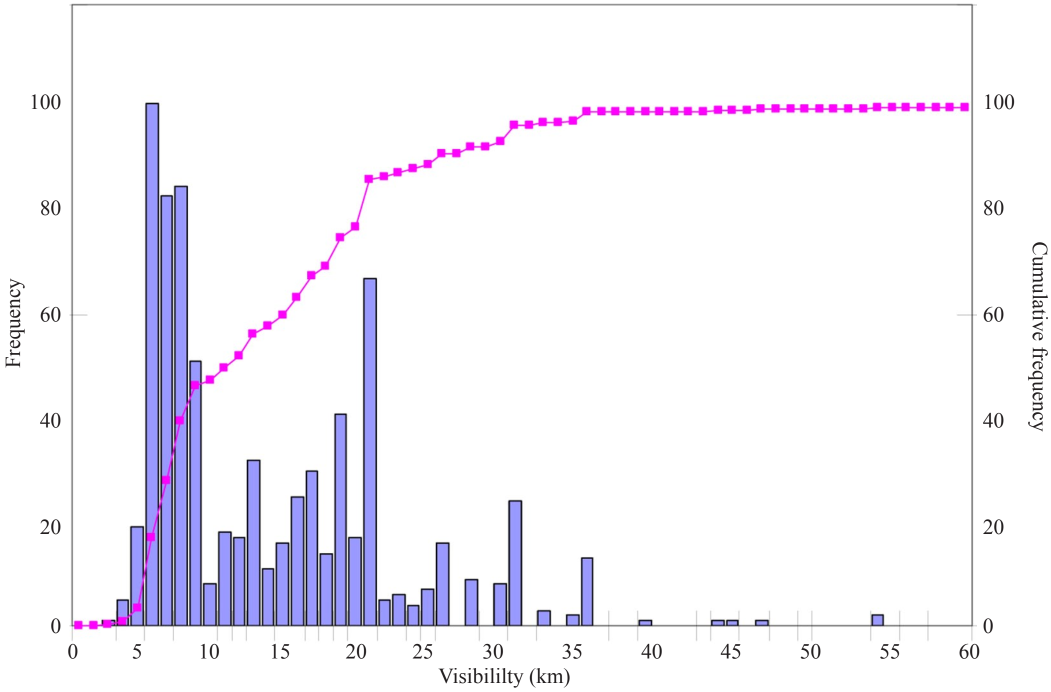


Figure 7. [In colour online.] Frequency distribution of the hourly visibility values for August of the test reference year for the Turin location.

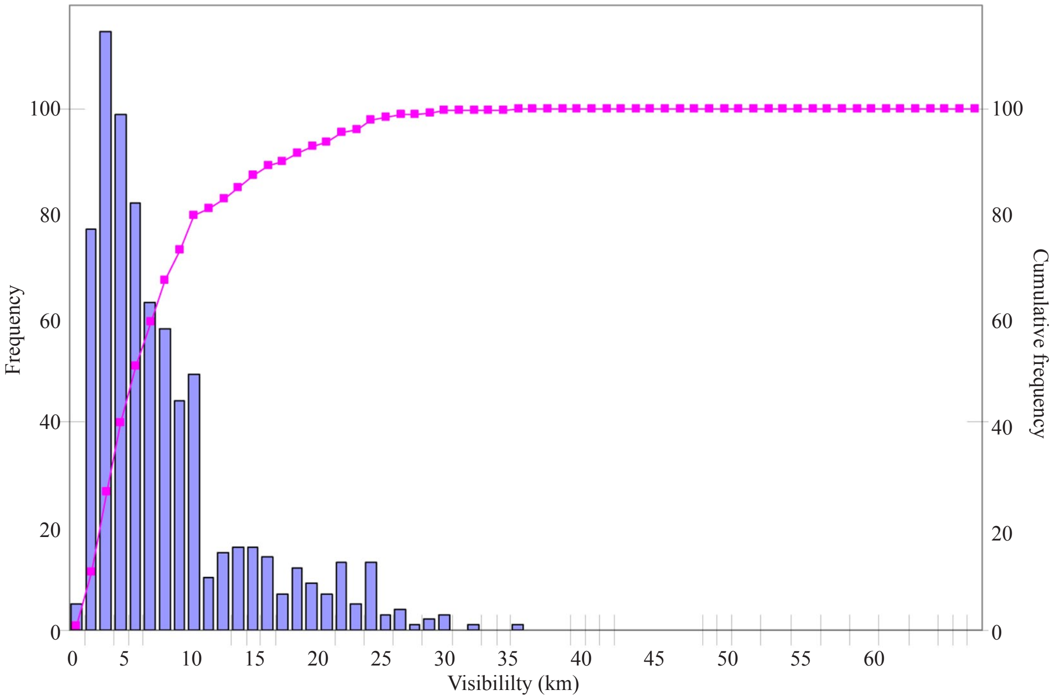


Figure 8. [In colour online.] Frequency distribution of the hourly visibility values for October of the test-reference year for the Turin location.

4.5 The Gran Madre church

4.5.1 *Description of the target*

This building is a neoclassical-style church located opposite Piazza Vittorio Veneto in Turin, close to the River Po and visible from one of the main streets of the city centre (see figure 9). Its architecture is based on the Pantheon in Rome and has a central round-shaped plane.

Figure 9. [In colour online.] Gran Madre church in Turin and its dimensions.

4.5.2 *Calculation of the visibility distances and visibility maps*

The visibility maps for the Gran Madre church are reported in figures 10 and 11. In figure 10 there is no attenuation with the distance, while figure 11 was determined with a low atmospheric visibility (1.6 km). Apart from the hill locations on the east, there is not a great difference in taking into account, or not, the limit-of-visibility distance.

4.6 The Mole

4.6.1 *Description of the target*

This building is a major landmark of the city of Turin, and was built between 1863 and 1889; originally intended as a Jewish temple, it later became a community building. Its height is 167.5 m and it is characterized by the shape of the dome, which is particularly high. It is located near the city centre of Turin. Since 60 m of its height is due to the spire, its visibility should be distinguished between the visibility of the dome and the visibility of the spire. In the following analyses the visibility of the spire was considered.

4.6.2 *Calculation of the visibility distances and visibility maps*

In this case, the limit-of-visibility distance for the visual acuity d_{lv} can be determined by considering the size of the spire as the object size D (figure 12). This was taken to be 2 m, which using equation (2) and a visual acuity of 1 gives a distance of 6.9 km.

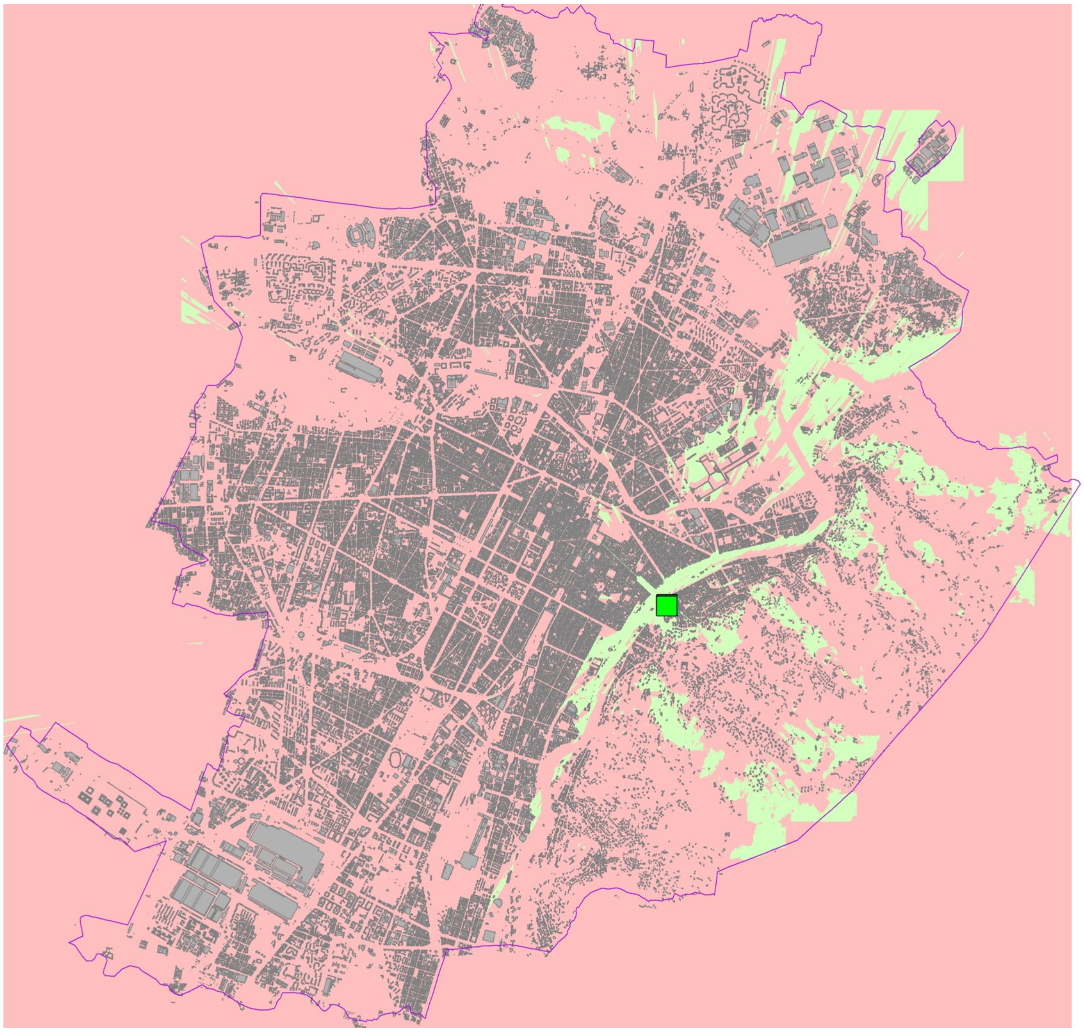


Figure 10. [In colour online.] Visibility map of the Gran Madre church.

The limit-of-visibility distance for the psychological perception d_{lp} can be determined by considering the D and H dimensions (figure 12) to be 1.5 m and 60 m, respectively. With a value of threshold visual size S equal to 100 (which is the uninformed recognition with a contrast of 13%), the limit-of-visibility distance for the psychological perception from equation (4) gives 10.3 km. This means that in clear atmospheric conditions (eg, visibility up to 20 km) the limit of the visibility of the Mole is set by the visual acuity (figure 13), but when the atmospheric extinction increases the limit of the visibility of the Mole is set by the d_{la} limit visibility of 1.6 km (figure 14). In the first case the Mole is visible from the vast majority of the rural areas of the city (figure 13), while in poor atmospheric conditions, it is visible only from a small part of the city centre and the River Po (figure 14).

4.7 The skyscraper

4.7.1 *Description of the target*

This skyscraper (figure 15) has a 45 m square building shape and is located in the south of the city of Turin, near a railway station and a large tertiary district that was once the largest factory in Turin (Lingotto area).

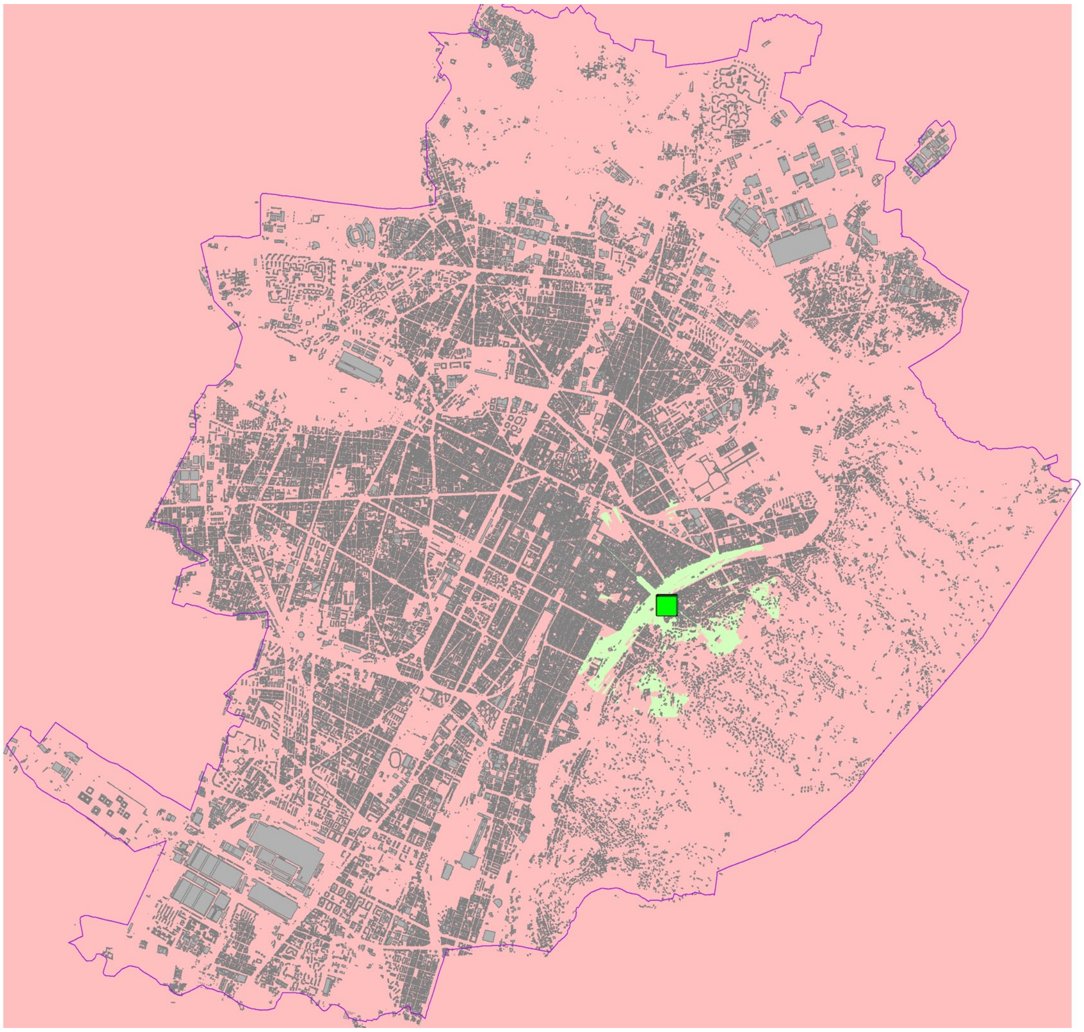
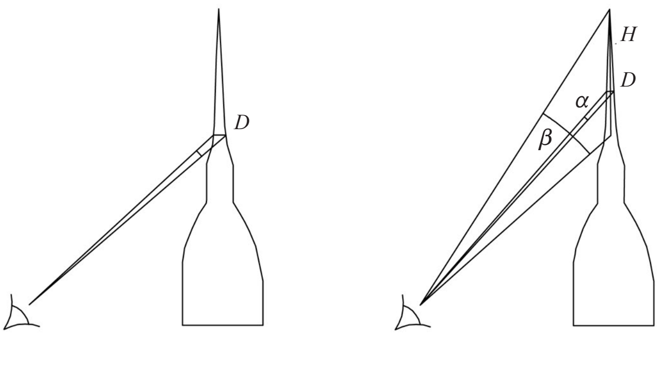


Figure 11. [In colour online.] Visibility map of the Gran Madre church in the case of low atmospheric visibility.

(a)



(b)

Figure 12. [In colour online.] (a) A photograph of the Mole; (b) schemes for the determination of the d_{lv} and d_{lp} distances.

Figure 13. [In colour online.] Visibility map of the Mole with a maximum visibility distance of 6 km.

Once completed, this skyscraper will be the tallest in Italy, with forty-two floors, two of them below ground, and at the forty-third floor there will be a wooden roof open to the public. The project has been amended several times, bringing the initial height of 220 m to the final height of 210 m. On the facades, 1000 m^2 of photovoltaic panels are going to be installed in order to ensure, as much as possible, the energy production of the building. The large windows are designed to reduce the need for artificial lighting.

The total land area on which the skyscraper is to be built is approximately 70 000 m^2; around 60 000 m^2 of retail space is planned, in order to promote the development of this urban district. This project is linked with another residential district for approx 5000 inhabitants and a new railway station (Lingotto) with a bridge structure that will connect the station to the skyscraper.

The terrain height of the DTM is 234.50 m; the building height was set to 210 m, thus giving the four upper vertices of the building an overall height of 444.50 m. Thus, the skyscraper is indicated by four points (the four vertices) placed at a height of 444.50 m.

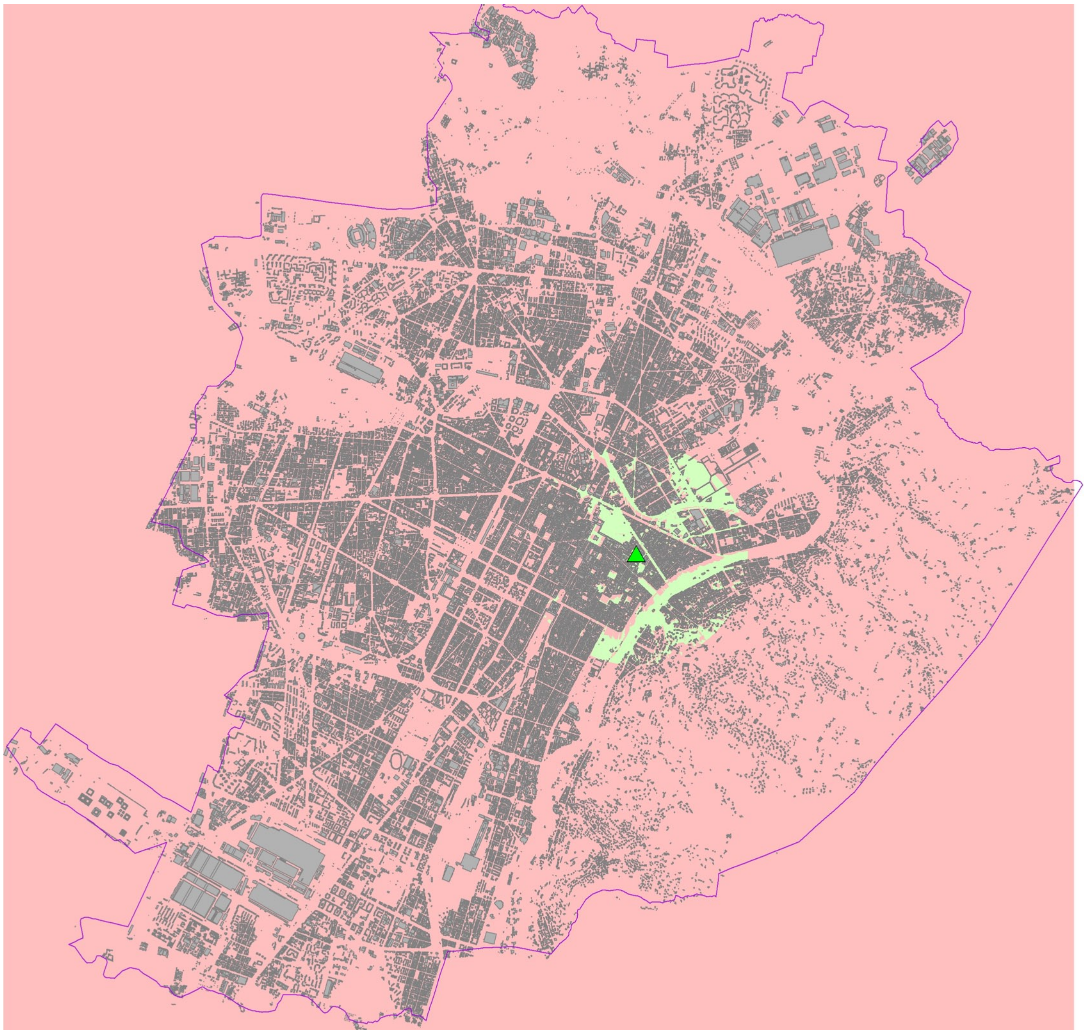
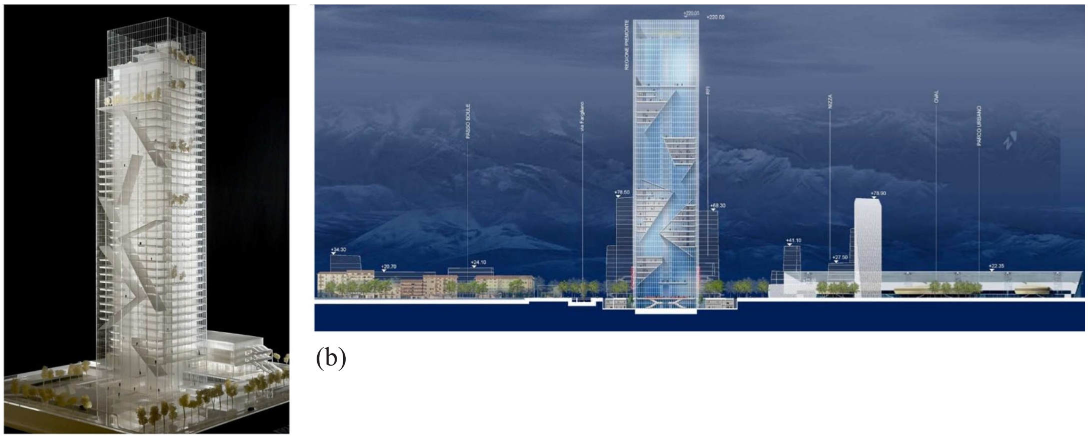


Figure 14. [In colour online.] Visibility map of the Mole in the case of low atmospheric visibility (visibility distance 1.6 km).



(b)

(a)

Figure 15. [In colour online.] Models of the new skyscraper.

4.7.2 *Calculation of the visibility distances*

For the calculations of the limit-of-visibility distances, the following parameters were selected:

- object size D equal to 63.6 m;
- object size H equal to 190 m;
- visual acuity of 1;
- threshold visual size S of 100 min^2 (uninformed recognition with a contrast of 13%).

The object size D was taken as the diagonal of the 45 m square, while the object size H is equal to the building height reduced by the height of the surrounding buildings, which are 20 m high The previous assumptions give a limit-of-visibility distance for the visual acuity d_{lv} of 218 km and a limit-of-visibility distance for the psychological perception d_{lp} of 37.8 km. Since the lower of these distances is greater than most of the visibility distances for atmospheric extinction (see figure 7), for such a building the visibility distance is always the atmospheric visibility distance. Since this distance varies as a function of the meteorological conditions, it is the weather that limits visual detection of the top of the skyscraper.

4.7.3 *Visibility maps*

The visibility maps in figures 16 and 17 were obtained with visibility distances of 20 km and 1.6 km, as discussed in subsection 4.4, respectively. In contrast to the visibility maps in figures 10, 11, 13, and 14, the visibility maps in figures 16 and 17 are cumulative viewsheds,

Figure 16. [In colour online.] Visibility map of the new skyscraper.

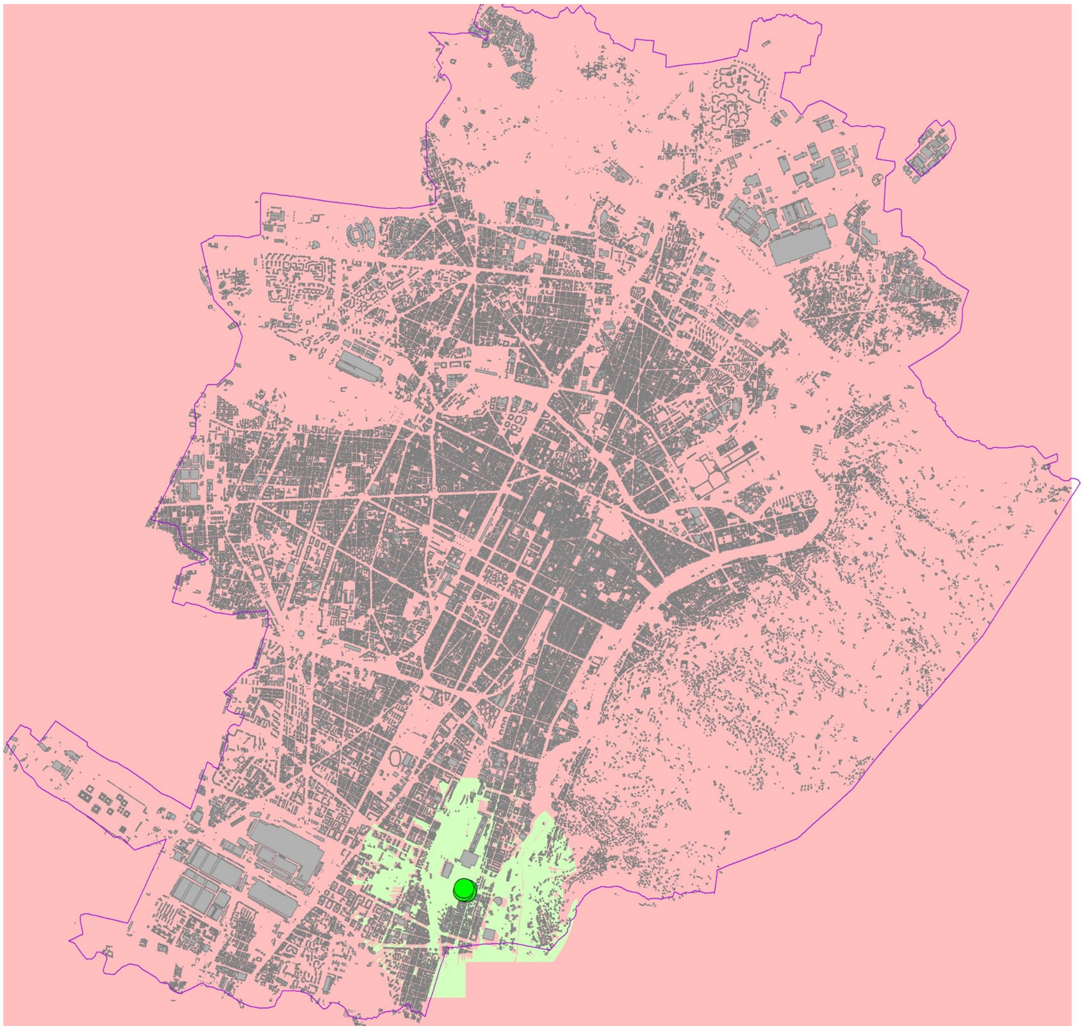


Figure 17. [In colour online.] Visibility map of the new skyscraper in the case of low atmospheric visibility (visibility distance 1.6 km).

determined using raster algebra and summing the results of the visibility for each of the four points of visibility into which the skyscraper was discretized. In order to give a quantitative evaluation of the visibility of the skyscraper, from the visibility map of figure 16 the percentage of streets that falls within the visible set was calculated. This was done considering the fact that the urban landscape is visible by people walking in the streets and that this parameter can be of interest in order to determine how much this new landmark building is, or is not, visible. From the analyses conducted on the shape files of streets, the total area of streets (which considers yards as well as streets) amounts to 2 575 802 m^2 (about 2% of the city's surface). Using raster algebra on the data for streets and visibility layers, it is calculated that it will be possible to see at least one point (vertex) of the skyscraper from 819 316 m^2 of the city. In percentage terms, this means that—in good atmospheric visibility conditions—in 32% of the streets of the city of Turin people will be able to see the new building. As can be seen from figure 17, these areas may be far from the skyscraper itself, which is located in the south sector of the city.

An analysis for the other neighbouring municipalities should be done in order to ascertain the degree to which the building will be seen from the municipalities that are located in the south of the city of Turin.

5 Conclusions

The urban visibility analyses presented in this paper were conducted for three buildings in the city of Turin, one of the largest cities in the northwest of Italy. This procedure can become a shared methodology for landscape analyses, not only in the urban settings, integrating both terrain and building models, that are now considered particularly in environmental impact assessment procedures. A knowledge that is not qualitative but objective, may be incorporated into the design process in order to suggest improvements and corrections to the visual impact analysis and mitigation measures.

Moreover, in the case of objects that, by their nature, cannot be completely mitigated from the point of view of their visual impact (eg, a skyscraper, but also a road viaduct), the tools and methodologies described here allow decision makers and the community to know how much and in what way the building changes will take effect on the perception of places. In the case that was examined, without entering into qualitative assessments such as ‘it is better now/it was better before’, the spatial distribution of the areas that will be visually affected by the new skyscraper makes this building a new landmark in the urban landscape. Besides, it can also be seen that the visual impact of this building will be much greater than that of the Mole, which is actually the landmark of Turin but, due to its location and the very small size of the spire, it is not as visible in urban areas as the skyscraper will be.

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