Article

3D Space Syntax Analysis: Attributes to Be Applied in Landscape Architecture Projects

António Ascensão [1,*]**, Laura Costa** [2]**, Cláudia Fernandes** [1,3]**, Franklim Morais** [4] **and Catarina Ruivo** [5]

1. Faculdade de Ciências da Universidade do Porto, 4169-007 Porto, Portugal; cofernandes@fc.up.pt
2. Department of Forestry and Landscape Architecture (CIFAP), Universidade de Trás-os-Montes e Alto Douro, 5001-801 Vila Real, Portugal; lauracosta@utad.pt
3. Research Center in Biodiversity and Genetic Resources (CIBIO InBio)/Landscape Planning, Design and Management Research group (LPDM), 4485-661 Vairão, Portugal
4. Escola Superior Artística do Porto, 4050-545 Porto, Portugal; franklim@cyberoikos.com
5. Research Center for Architecture, Urbanism and Design (CIAUD), Faculdade de Arquitetura da Universidade de Lisboa 1349-063 Lisboa, Portugal; catarinaruivopereira@gmail.com
* Correspondence: a.ascensao93@hotmail.com; Tel.: +351-93519-4336

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Abstract: The article delves into the potential application of space syntax methodology to landscape architecture. Anticipating the complexity of the landscape architectural design process, the use of 3D space syntax analysis made it possible to better understand the relations between urban space shapes and their functions. The application of an iterative process of project improvement optimizes the fulfilment of the landscape architect vision, through changes in ground shaping, selection of tree species and their spatial distribution. This article explores the vegetation attributes of vegetation that are necessary to consider in landscape architecture projects in the context of the DepthSpace 3D software, using the case study of an urban park in Maia—Portugal. To achieve this, it was necessary to define the attributes to be inserted in the software. The main attributes of vegetation that can be employed in landscape architecture projects are form and dimension, growth speed, and visual permeability (opacity) of the crown in winter and summer. The software proved itself a useful tool, not only in studying and evaluating the effects of the final design, but also during project development.

Keywords: space syntax; DepthSpace3D; landscape architecture; visibility; vegetation attributes; vegetation parameters

1. Introduction

Public space plays a major role in the quality of life of citizens. Many public spaces are green spaces, rendering it essential to understand the relations and actions between people and the spaces they use, as well as how spatial elements in green spaces influence these relations. In green spaces, ground modeling, vegetation, and time are the elements that promote these major interconnections. Together, these elements have an unequivocal impact on visibility, connectivity, and accessibility, offering different experiences to users and, to the same degree, granting different usage as time advances.

1.1. Space Syntax

Space syntax is a set of methods with an underlying set of theoretical ideas [1], which are in continuous development. It is a well disseminated instrument in architecture and urban design studies.

Bafna (2003) [2] describes it as a research method that studies the relations between society and space from the perspective of a general theory of the structure of inhabited space in its various forms, meaning buildings, cities, landscapes, etc. It contains a large semantic network of quantified concepts. This research will focus on isovists and visual connectivity. According to Bafna (2003) [2] an isovist is a polygon created by delineating the area visible to an observer in that position, assuming a 360-degree field of vision. Alagamy et al. (2018) [3] define visual connectivity as the extent to which a place can be viewed from other places.

1.2. Space Syntax in Landscape Architecture

Space syntax methodology provides tools to analyze the linguistic characteristics of space – configuration [4], visibility [5], and accessibility - and their functional relations to the physical, social, and psychical environment. Existing space syntax research from several authors related to landscape architecture demonstrates the benefits of assessing green spaces. Some of these studies evaluate the effects of planting design in urban parks concluding that it has a significant effect on visibility, but also, that other spatial attributes such as tree height and form could be used for a better understanding of the space [6,7]. Other studies analyze pathway configuration characteristics and their relation to senior walking behavior [8]; evaluate accessibility aspects in nature parks [9]; analyzing people's spatial distribution and predicting pedestrian trail use in natural parks [10]. Green spaces do not always have clear and easy to define boundaries. Zhai and Baran (2013) [11] noted the difference between defining boundaries among parks and other urban constructions, where sightlines are mainly blocked by buildings, while in parks people can look through branches of trees and shrubs.

The design process is generally the same in architecture and landscape architecture. It starts from a general/conceptual view of the design and moves towards a more detailed final product where the configuration of space and materials is well defined. The choices made for a design are a result of experience and continuous study. Space syntax as a tool that has been developed and studied throughout the years can provide an efficient method of aiding the design process. Dursun (2007) [12] explores the contribution of space syntax in this endeavor, concluding that it can be an efficient method of aiding in design choices through "evidence-based design" with various tools to evaluate design choices. Li et al. (2009) [13] studied this matter with the addition of BIM (Building Information Modeling) showing that users can use it in the development of the design at the same time they assess the outcomes and consequences of each choice.

1.3. Three-Dimensionality in Space Syntax

Although space syntax analyzes mainly 2D space, space is actually perceived in three-dimensions (3D). Therefore, to be able to fully understand the space, namely the visibility in the urban space/architecture/green spaces, the third dimension should be added. Kim et al. (2019) [14] defined visibility as the representing the size of a space that is visually perceived by people and can also be referred to as isovist. Schroder et al. (2007) [15] describe a methodology and implementation of 3D space syntax with the aim of creating a visibility surface that summarizes the varying degree of visibility values among a set of buildings, but do not consider altimetry nor the visibility on modeled buildings. Kim et al. (2019) [14] experimented with an urban space and various combinations of building heights, showing that the heights of buildings gradually affect the spaces around them, but does not also consider altimetry of the terrain. These authors do not consider the attributes of vegetation. Morais et al. (2017) [16] introduced a general notion of tree transparency on the 3D visibility analysis of Casa da Música in Porto and the surrounding areas, considering a difference in visual permeability of the tree crowns in summer and winter and the general form and dimensions of trees, showing relevant differences in the global visibility and permeability of the space. These attributes were studied further by Ascensão et al. (2018) [17], complementing them with parameters that could be inserted in the DepthSpace 3D software for each species of trees and large shrubs and considering

new attributes and parameters. These studies and authors did not consider visual permeability in the analyzes made with the software.

1.4. 3D Space Syntax Software - DepthSpace3D

In recent years, three-dimensional analysis has been a focus of research in space syntax, as is reviewed by Ruth and Conroy Dalton (2015) [18]. However, this had not yet materialized in the development of open-use software for three-dimensional space syntax analysis before DepthSpace3D was released, expanding on concepts developed in space syntax theory, particularly those regarding augmented visibility graph analysis (AVGA) [19]. DepthSpace3d is a software developed by some of the authors of the present paper and is freely available at http://opoarch.com/ds3ddownload/ for academic use. How space syntax concepts were adapted for three-dimensional analysis was developed in earlier research by Morais (2018) [20]. The research reported in this paper uses this software, as three-dimensional analysis seems to have some advantages over current two-dimensional syntactic analysis in situations which are particularly fitting to the study of landscape architecture, such as:

- Rough altimetry of the terrain, either natural or sought by the designer;
- Dynamic volumetric geometries, in size, configuration, elevation, and interpenetration, such as those created by vegetation;

3D analysis could very well be a powerful tool in formalizing the classical theoretical and aesthetical space concepts such as proportions and scales, hierarchy, or rhythm.

1.5. Objectives

The main objectives were to adapt and improve the DepthSpace 3D software to suite the special requisites of landscape architecture discussed in this section and further in the document and evaluate if the developed research is suitable for application to landscape architecture. This research will introduce and describe attributes and parameters to be applied in the aforementioned software, aiming to set a foundation that allows continued development of 3D space syntax in the application to urban parks and gardens, while also attempting to optimize the design process. A trial application of these attributes and parameters in the DepthSpace3D software is developed under the case study urban park in Maia, Portugal.

This paper attempted to answer the following questions: What do people see? What do people see more often? What do people see throughout the year? What do they see throughout time?

1.6. DepthSpace3D Developments for Landscape Architecture

To be able to apply this software to landscape projects and analyses, it was necessary to define a set of attributes to be applied in ground modeling and vegetation, due to the underlying complexity of green spaces. The paper focused on the aforementioned attributes, expanding on the work of Morais et al. (2017) [16] and Ascensão et al. (2018) [17]. The proposed attributes are presented in Section 2.

2. Materials and Methods

2.1. Methods

Firstly, it was necessary to delimitate the study area for the model creation. The study area was based on the plans for the project of the urban park in Maia, located in Portugal. Two types of approach were considered: (a) Relations between the interior and exterior of the park which led to the inclusion of a model area that extends beyond the limits of the project; (b) Relations within the interior of the park.

Following the delimitation of the study area, it was necessary to evaluate which elements had to be present in the model. This specific case study integrated buildings, as well as altimetric differences

and vegetation. Since space syntax analysis is usually bidimensional, it rarely or never considers the last two elements, making it necessary to define them in the context of DepthSpace 3D. Attributes and parameters were then defined for vegetation and are explained further in the Section 2.3.1.

Finally, the model was created taking into account the previously mentioned factors and analyses were made to evaluate and determine their interest in three-dimensional space syntax analysis considering the different vegetation attributes. The diagram represented in Figure 1 synthetizes the key aspects of the research method.

Figure 1. Research method diagram.

2.2. Case Study

The case study presented in this research is a landscape architecture project of the urban park in Maia, Portugal. It is located in the city center and connects to several of the city's main services through the projected path system. Along these paths are several open spaces such as squares, training field, lawns, a skating area, and a lake, also connecting to the parks sports buildings which are a big presence in this space. Some areas have a great density of trees, a diversity of trees species, and different altimetry.

The relevance of this case study lies in the importance of these elements as they have direct implications on the visibility of people, some pre-existing (buildings) and others proposed (terrain modeling, vegetation, lake, lawns, etc.) along the year and time.

2.3. Attributes and Parameters

Aiming to study the aforementioned instances in the context of landscape architecture, it was essential to decide on a set of attributes and parameters to apply to vegetation. Due to the complexity that involves the natural development of plant life, it had to be investigated to achieve a set of summarized concepts to be employed in the analysis.

2.3.1. The Distinctive Case of Vegetation Conceptualization

Plants are live and continuously evolving structures, showing great variability, affecting visibility and the use of space through time. These parameters enable the assessment of space considering time.

To obtain the attributes and parameters for landscape architecture it was necessary, at an initial stage, to understand which could be applied to 3D space syntax analysis. To fulfill this endeavor, an extensive literature review to find the possible attributes and parameters to apply in the development of this software was undertaken. From this review, Ascensão et al. (2018) [17] defined four attributes to be applied for trees and large shrubs:

1. Dimension [17], involving three parameters: Height, width, and trunk height, defined by Moreira (2008) [21]. Trunk height is considered from the ground to the first branches.
2. Form [17], defined by Moreira (2008) [21]. 5 simple volumes/forms were chosen: Conical, rounded, wide, pyramidal, and columnar (Table 1).
3. Growth speed [17] was considered as slow, medium, and fast based on Viñas et al. (1998) [22] and Costa (2015) [23] considering the dimensions after 20 years of plant growth (Table 1).
4. Visual permeability of the crown in winter and summer [17] was considered opacity applied to deciduous and evergreen plants. For the latter, the opacity values were considered the same in winter and summer. The method used for evaluating the permeability of the crown encompasses three phases:

    (1)   Picking images that represent naturally, well-developed adult specimens for each species;

(2)　　Determining crown transparency, adapting the methods of Clark, Lee, and Araman (2003) [24] and Borianne et al. (2017) [25] consisting of a simple delineation of the crown, acquiring the total number of pixels (Tp) (100% of the crown area) and acquiring the visible light area through the crown (Sp) (number of pixels corresponding to the visible light/sky area, through the crown);

(3)　　Finally, visual permeability (P) was calculated through the following formula:

$$P = 100 - \left(\frac{\text{Sp} \times 100}{\text{Tp}} \right) \tag{1}$$

All these attributes were studied, quantified, and applied for a set of trees and large shrubs [17]. The species of trees and large shrubs present in Table 1 were chosen because they are listed in the planting design of the case study—urban park in Maia, Portugal.

2.4. DepthSpace 3D Model Creation

The model developed in DepthSpace3D comprises three conceptual types of spaces - the viewed, the viewing, and the obstacle spaces.

- The viewed space has 2 components: (a) The ground, buildings and vegetation surfaces (physically identical to the obstacle spaces but conceptually different); (b) The global volume, corresponding to the 'air' modelled by a tridimensional grid, vertically ten meters apart; and horizontally three meters apart.
- The viewing space is the space where the viewing subjects can move, as opposed to the entirety of the studied volume.
- The obstacle (to visibility) space is modelled by the surfaces of the ground, considering the curved topography, the facades and other solid surfaces (buildings, trees, and large shrubs, etc.).

The 3D model was created in the DepthSpace3D software, considering the attributes and parameters presented in Table 1. It was modelled according to the project plans which include proposed vegetation and its attributes (Figure 2), ground modeling, and the preexisting structures such as buildings.
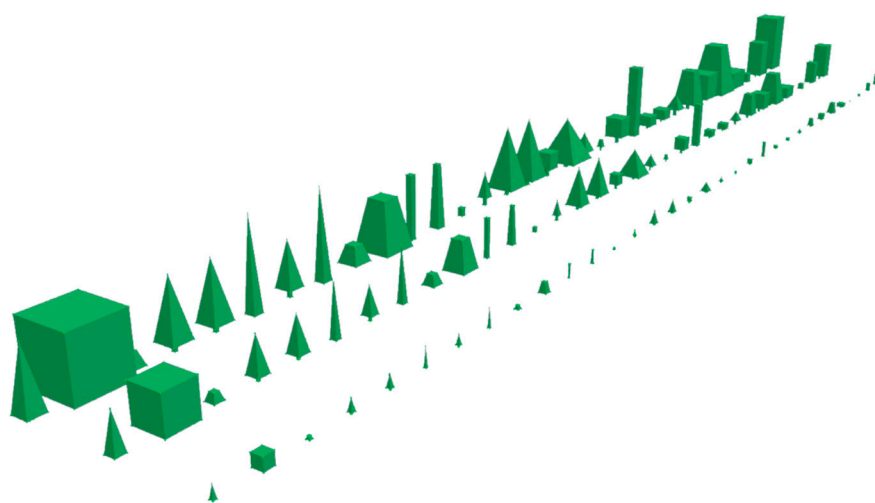
Figure 2. Trees and large shrubs created in the DepthSpace 3D software, according to the attributes shown in Table 1.

Table 1. Classification of trees present in the case study considering: (1) Dimensions (m) at maturity age; (2) Form; (3) Growth Speed and dimensions (m) after 20 years of development; (4) Visual permeability of the crown [17] (p. 220).

| Trees and Large Shrubs	Ultimate Dimensions			Form	Growth Speed Dimensions after 20 Years			Visual Permeability		
	Height (m)	Width (m)	Trunk Height	Classification	Classification	Height (m)	Width (m)	Classification	Summer	Winter
Alnus glutinosa	25	8	4	conical	fast	17	5	deciduous	83	49
Acer pseudoplatanus	30	25	4	rounded	slow	10	8	deciduous	88	60
Arbutus unedo	8	8	2	wide	slow	3	3	evergreen	92	92
Betula pendula	25	10	4	conical	fast	17	7	deciduous	76	44
Betula verrucosa	25	10	4	conical	fast	17	7	deciduous	76	44
Casuarina equisetifolia	20	8	4	conical	fast	13	5	evergreen	73	73
Cedrus libani	25	18	4	pyramidal	slow	8	6	evergreen	75	75
Cercis siliquastrum	10	10	3	wide	medium	5	5	deciduous	86	41
Chamaecyparis lawsoniana	40	5	-	pyramidal	fast	27	3	evergreen	99	99
Cupressus sempervirens 'sempervirens'	30	3	-	columnar	fast	20	2	evergreen	99	99
Frangula alnus	5	5	-	wide	fast	3	3	deciduous	83	62
Laurus nobilis	12	5	3	conical	slow	4	2	evergreen	83	83
Ligustrum japonicum	4	2,5	-	columnar	fast	3	2	evergreen	97	97
Liquidambar styraciflua	30	14	4	conical	fast	20	9	deciduous	81	23
Magnolia grandiflora	22	20	4	conical	slow	7	7	evergreen	87	87
Magnolia x soulangeana	10	8	4	rounded	slow	3	3	deciduous	86	34
Nerium oleander	6	3	-	wide	fast	4	2	evergreen	90	90
Melia azedarach	13	8	4	rounded	fast	9	5	deciduous	77	50
Olea europaea	15	10	3	rounded	slow	5	3	evergreen	87	87
Picea abies	40	6	-	columnar	fast	27	4	evergreen	87	87
Pinus pinaster	24	9	6	conical	fast	16	6	evergreen	77	77
Pinus pinea	25	14	6	wide	medium	13	7	evergreen	92	92
Prunus cerasifera "Pissardi"	8	8	3	rounded	fast	5	5	deciduous	84	46
Quercus coccinea	20	15	4	rounded	fast	13	10	deciduous	84	32
Quercus robur	35	22	4	wide	medium	18	22	deciduous	83	33
Quercus suber	15	20	4	rounded	slow	5	7	evergreen	76	76
Salix atrocinerea	6	5	-	rounded	fast	4	3	deciduous	85	46
Salix alba 'Vitellina'	25	10	2	rounded	fast	13	7	deciduous	77	57
Ulmus procera	40	15	4	rounded	fast	27	10	deciduous	86	58

3. Results and Discussion

In landscape architecture, visualizations create a view of what the space can eventually become and what will be seen from a certain point of view, but these visualizations try to represent what the space will become in the idea of the designer and, in a majority of cases, are centered on the best views. To represent objectively what is, or will be seen throughout the space, year, and time, a 3D model was created in DepthSpace 3D considering the attributes of vegetation and terrain modeling. The trial application for the urban park, can define what will be seen through all of the space. The images present a gradient of colors that goes from dark blue to red, which represent the amount of visibility on a certain location. A dark blue color indicates that the space has no visibility from the chosen points and a red color indicates that the space is very visible from the chosen points.
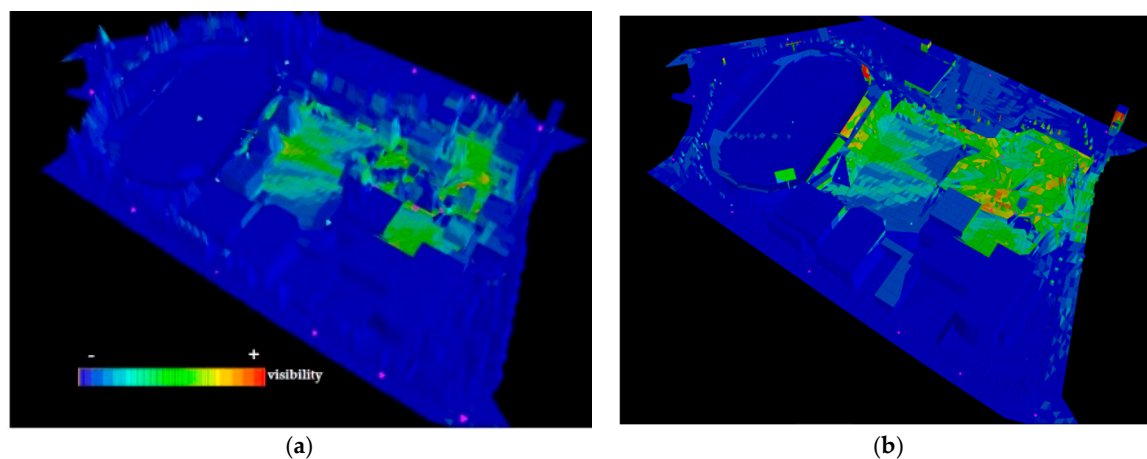
3.1. Effects of Time on Visual Connectivity

One of the most important attributes related to vegetation is time. In Figure 3, it is possible to visualize the effects of time on the park's global visibility, by considering vegetation growth. The differences in visibility are clear. As vegetation grew the spaces appeared more defined opening and closing and offering different views of space, creating variability over time. Considering the importance of planting design and visual permeability of the trees and in an initial and global exercise, simulations were developed where it was possible to understand the influence of this attribute in visual connectivity.

| (a) | (b) | (c) |
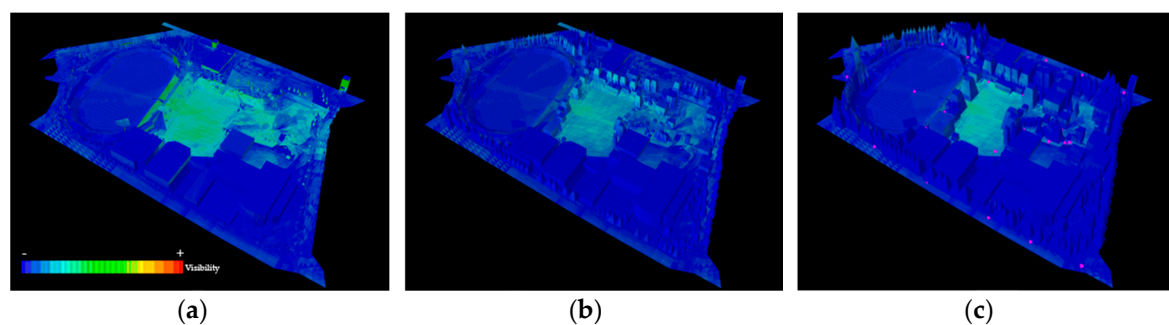
Figure 3. Visual connectivity maps of the effects of time in trees. (**a**) initial growth; (**b**) expected growth in 20 years; (**c**) full growth [17] (p. 222).

The presented results originated from inserted viewpoints which were predicted as important points and paths inside the park. These included notable viewpoints from higher places in the park and various paths on the exterior and interior of the park. The introduction of the growth speed attribute to vegetation allowed a close to realistic notion of the visibility of the space throughout time, demonstrating its effects on visual connectivity throughout time.

The case study of Maia Park (Figure 4), showed low levels of visibility from the interior to the exterior of the park but showed good visibility to the spaces inside it, while not completely disclosing the whole park.

Figure 4. Visual connectivity maps of the effects of tree opacity in summer from the interior pathway. (**a**) full growth; (**b**) initial growth.

3.2. Effects of Visual Permeability in Winter and Summer on Visual Connectivity

The analysis also contributed to understand the spatial design in winter and summer months (Figure 5). Subtle manipulation of vegetation and topography could be experimented with until the design expectations were validated through visibility analysis, resulting in the final design. It was also possible to verify that the main entrance behaves as a logical entry, allowing high levels of visual permeability between the park and its immediate surroundings.
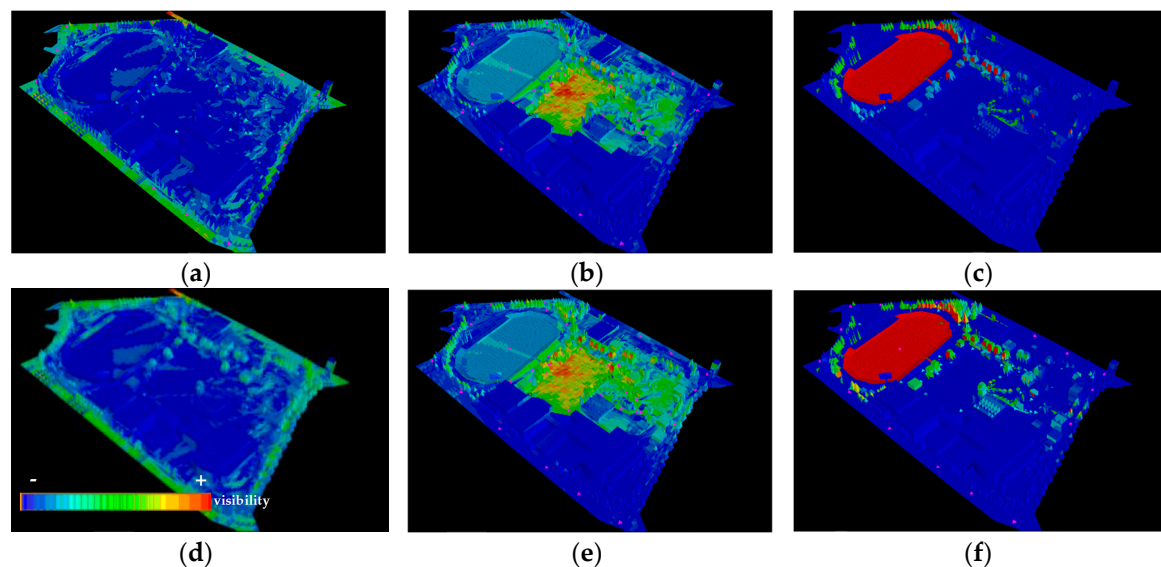

Figure 5. Visual connectivity maps of the effects on visibility of opacity in trees throughout the year, trees at 60% growth. (**a**) From the exterior of the park in summer; (**b**) from the interior of the park in summer; (**c**) isovist from inside the municipal field in summer; (**d**) from the exterior of the park in winter; (**e**) from the interior of the park in winter; (**f**) isovist from inside the municipal field in winter.

3.3. Other Analyses

Visibility maps for additional zones were created (Figure 6) with the objective of understanding the definition of the designed spaces. During the project phase, it was the intention of the landscape architect that the park should not be grasped in its entirety from a single point but only through meandering inside the park. As it is perceptible from the images, this objective was successful mainly due to the proposed terrain modeling and location of the different species of trees and large shrubs.

It must be noted, however, that the loss of visual connectivity happens mainly due to the existence of buildings and altimetry, because vegetation always allows some visual permeability, adding to the visual connectivity values. The spaces appeared clearly defined, showing variations between high and low levels of visual connectivity, appealing to movement along the park.
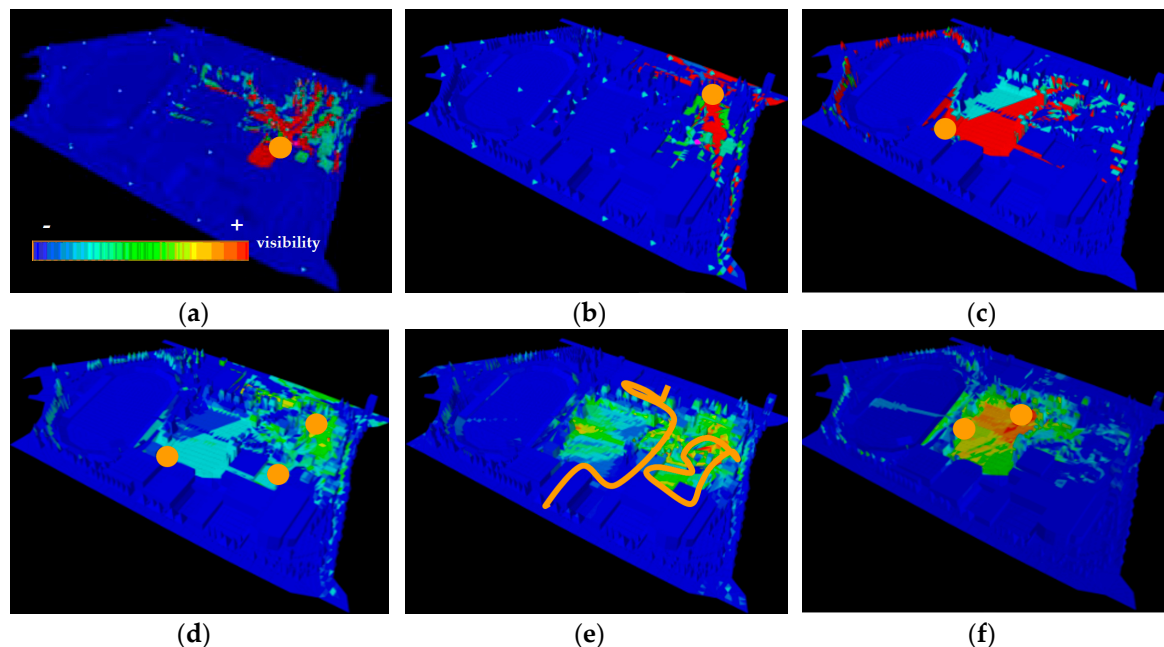
Figure 6. Visibility analysis of particular spaces and definition of differentiated spaces. (**a**) Isovist from the walkway; (**b**) isovist from the gazebo; (**c**) isovist from the bar; (**d**) visibility from the three referential points: walkway, gazebo, and bar; (**e**) visibility from a meandering path in the park; (**f**) visibility from the informal stands [17] (p. 224).

Three-dimensional analysis was an essential contribution to understanding how the trees and large shrubs affected visibility throughout the year, by allowing for a visualization of the differences between summer and winter in the park's visibility. Although in some cases the differences were visible at ground level, they were most discernable at the higher points in space (Figure 5a,c,d,f). This happened because the visual permeability is calculated through the crown of the trees and also relates to form, as trees in the simulation, had different trunk heights and they allowed the passage of visibility below their crowns. Visibility changes were most perceptible at ground level, when points that generate visibility were located at higher points in space (Figure 5b,e). In (Figure 5a,b,d,e) it is possible to visualize a reduction in visibility from the inside to the outside of the park and vice versa, visual connectivity is low meaning people inside the park will barely be able to see the outside. Contrary to what happens with buildings, trees, and large shrubs never show full opacity allowing for visual permeability even during summer months. Deciduous trees and shrubs are the ones which present lower values of opacity in winter and summer months, contrary to evergreens, meaning that the presence of distinct species implies different visibility values.

Regarding the design process, upon testing the vegetation attributes it was possible to understand the visibilities from the static areas (gazebo, bar) and dynamic areas (pathways) and apply corrections to the design. In these simulations it was possible to understand that the presence of an overlooked element, in this case a tree in the space cutting visibility from the bar to the training field of the park. It was intended that the people from the bar could watch what was happening in the field in its totality. Our method allowed for this small change to be made so as to address this issue. This example shows the possibilities of DepthSpace 3D in aiding the design process. It must be noted that, since the software is still in development, iteratively changing the design in the 3D model takes some

time due to the recalculation time. It is expected that this issue will be resolved with the continuous development of the software.

4. Conclusions

This paper set out to contribute to both the elaboration and evaluation of landscape architecture projects by developing and expanding on space syntax tools. The methodology was twofold and iterative.

1. Three-dimensional space syntax software was used throughout the design process of a park as an aid for objective assessment and decision making. Space syntax methodology allows for an immediate understanding of visibility, thus proving effective in answering a series of questions about the initial design of the park - What do people see? What do people see more often? What do people see throughout the year? What do they see throughout time? As a result, it was possible to understand the relationship between the interior and exterior of the park to assure convergence with natural movement, trees were moved and replaced to accentuate the visibility of certain points while ensuring the privacy of other areas.
2. The attributes from landscape architecture, some related to problems arising from the design process, were integrated into DepthSpace3D. The experimental application of the attributes and parameters in the DepthSpace3D software allowed for an understanding of the interest of this software during the development of the landscape architecture project. It proved itself to be a useful tool, not only in studying and evaluating the effects of the final design, but also during project development. The software was developed along with the urban park project, working to accommodate specific necessities that had not been foreseen. This allowed for the development of a series of tree-objects with varying growth patterns and opacities, as well as fundamental alterations in the way the software works.

The main challenges of this research concerned the obtainability of the attribute values. Fortunately, there is extensive literature for most of the proposed attributes (dimensions, form, and growth speed). The most complex issue lies with obtaining visual permeability values that translate close to reality values into the software. The visual permeability implies extensive work to evaluate each species and obtain the values as explained previously. It is a process in continuous progress, but the results obtained in the experimental application lead us to believe that the attributes and parameters relating to vegetation are of great interest, not only for landscape architects but also for a wide community of professionals of diverse areas in urban design.

The connection between analysis and design proved a useful step both towards the development of a successful design, and the furthering of a useful tool for landscape architecture. Future work should expand this even further. In addition, space syntax theory provides designers with other quantified concepts that relate to a spatial configuration for understanding expected movement and interaction in space which can contribute to understanding the designed spaces.

Further work should evolve to include a larger database of vegetation to be utilized inside the software allowing for a wider application of the software in other landscape architecture projects such as parks and gardens, but also in urban design to evaluate the effects of trees and topography on a tridimensional spectrum at an urban scale.

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