École des Ponts ParisTech - Digital Building Design

Encoding Spaces:

Voxel Grid Framework for Quantitative Evaluation of Visual Perception in Indoor Spaces

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A significant portion of an individual's time, estimated between 85-90%, is spent in indoor spaces. Previous studies have shown the impact of indoor environments on various aspects of human well-being, such as sleep patterns, energy levels, mood, and productivity, shedding light on the influence of space and architecture on the psyche. However, tangible, real-world architectural solutions driven by such considerations are still very scarce. Among the reasons, strong subjectivity and lack of quantitative data strike as one of the main factors behind the struggle.

This paper examines a potential framework for assessing spatial configurations from a visual-spatial perspective by using measurable indicators. A part of the research focuses on identifying the properties of indoor spaces that are linked to the visual perception of occupants, such as exposure to sky and greenery, field of view, visual connectivity, and others. Another section of the paper is dedicated to explaining how these attributes can be quantitatively assessed within a defined scope using computational methods.

To achieve the objective, the indoor space is divided into discrete spatial units, and each unit is evaluated in terms of specific space features. This approach allows the grouping of different features in the form of numerical values, thus encoding the space and its induced conditions in a digital and operable format. To this end, the following body of work discussed a toolkit for the grasshopper 3D suite that evaluates indoor space characteristics via data collection, storage, and analysis. Finally, a case study is introduced to showcase a beginning-to-end real-world application for the discussed framework.

Keywords

Spatial Cognition, Perception, Isovists, Space syntax, Visibility, Visual comfort, View quality, Visual connectivity, Space Encoding, Navigation, Wayfinding, Voxel grid analysis, Spatial units, Indoor space, Spacio-visual perception.

1 Introduction

"Architecture is basically a container of something.
I hope they will enjoy not so much the teacup, but the tea."

Yoshio Taniguchi

In Europe a significant portion of an individual's time, estimated between 85-90%, is spent in indoor spaces [1]. The conventional understanding of buildings is that they provide a comfortable and safe environment by creating a protective barrier against potentially dangerous outdoor conditions. However, the Covid-19 pandemic has highlighted that the concept of well being and comfort is not solely reliant on temperature or square footage. Environmental Psychology research underscores the profound influence of one's surroundings on their mental states. Therefore the well being of individuals depends on the different parameters of indoor spaces.

This paper focuses on visual spatial properties of the indoor environment and possible variables impacting its perception. This paper is organised as follows: The first section provides an overview of established spatial assessment methods. The second section describes the methodology and a framework applied in this study. The third section presents the case study and its results. , while the fourth section discusses the case study results, methodology limitations and implications of the applied framework.

1.1 From perception to cognitive maps

The human species has evolved to analyse their environment, a skill crucial for survival. The Human brain perceives information about the environment through five senses. (Hearing, Sight, Smell, Touch, Taste) Most of the input (about 80%) comes from vision and hearing (about 10%) [2]. The brain processes visual information and integrates it with other sensory inputs to create a coherent representation of the external world. Understanding object positions and distances aids navigation, threat assessment, and social interaction. Indeed, specialised cells in the hippocampal region of our brains, known as place cells and grid cells [3], are finely tuned to the geometry and arrangement of the spaces we navigate and inhabit. These cells play a critical role in creating cognitive maps of our surroundings. The formation of a cognitive map involves the integration of various sources of information from sensory inputs, experiences, and memory.

Spatial cognitive maps are closely connected to our emotional experiences of the physical world. As the brain constructs a sense of space, it relies on this spatial perception to assist us in thinking and remembering. The connection between mental space and physical space is complex and mutually influential. Our mental states are shaped by our experiences of the physical world, and, in turn, our mental processes influence how we perceive, interact with, and shape the physical environment. In other words, our behaviour is driven by our feelings, our feelings are driven by our perception and our perception is driven by our context. Thus the configuration of physical spaces can influence our state of mind by affecting emotional responses, stress levels, cognitive function, and overall well-being.

Architects and urban planners have long acknowledged the significance of the built environment in influencing human emotional experiences. Contemporary research continues to examine how spatial geometry can affect various aspects of human behaviour.

1.2 Theories and practices

There have been several stages in exploring the relationship between humans and their environment, from Gibson's "The Perception of the Visual World" (1950) to the entire field of Neuro-architecture - a discipline in which architects partner with neuroscientists to scientifically investigate the connection between individuals and the built environment in terms of human response to it [4]. The findings in this field contribute to creating environments that can affect people's emotions and mental states, influencing design practices in various areas from healthcare to video games.

In video game design, understanding the psychological impact of the virtual environment on players is crucial for a player's emotions and engagement [5]. Just like a game, a space has its own rules that provoke the player to exhibit certain behaviours. The job of a game designer involves defining the spatial attributes that contribute to specific types of interactions within an environment. This aligns with the principles of the Prospect and Refuge theory, which suggest that certain spatial characteristics resonate with human survival instincts.

1.2.1 Prospect and refuge theory

Prospect and refuge theory was proposed by Jay Appleton, a British geographer, in his 1975 book "The Experience of Landscape." [6] According to Appleton "prospect" involves having a broad view, creating a sense of openness or exposure. In contrast, "refuge" involves concealing, often linked to a shelter that gives a feeling of being enclosed. The theory suggests that humans are naturally drawn to environments that offer a balance of open "prospect" spaces where they can see and survey their surroundings and enclosed "refuge" spaces where they can feel safe and protected. Besides Prospect and Refuge the Theory encompasses two additional components: Complexity and Mystery. Complexity measures how much information a space contains and Mystery how much you can't see (a promise of new information).

1.2.2 Evidence based design

Recognizing and addressing the emotional aspects of the environment led to more empirical understanding of design principles and their application in healthcare The medical field which has always referred to the evidence based approach has come up with the notion of "evidence based design" (EBD), a concept that originated in the field of healthcare and healthcare facility design as healthcare professionals and architects began to recognize the importance of incorporating empirical evidence and research into the design of healthcare environments. It was particularly influenced by Ulrich's study (1984) [7] that showed the impact of a window view on patient recovery. The goal of EBD is to create healthcare facilities that not only look aesthetically pleasing but are also optimised for patient well-being, safety, and healthcare outcomes. This approach ensures that design choices are based on proven best practices and contribute to the overall well-being and functionality of the space.

1.3 Research background

Most studies predominantly employed human evaluation via questionnaires to assess space, using qualitative notions such as beauty, openness etc. resulting in subjective outcomes. Nevertheless, some of these studies introduced space assessment methods based on mathematically defined metrics, enabling more objective variables.

1.3.1 Isovists and Isovist Fields

An example of using mathematically defined metrics is isovist. Isovists and isovist fields are concepts used in the analysis of spatial properties within built environments. One of the key figures associated with isovist analysis is Michael Benedikt, an architect and researcher, who made significant contributions to the understanding of spatial perception and the analysis of visual connectivity in architectural spaces. An isovist is a geometric representation of the visible space from a specific point or “the set of all points visible from a single vantage point in space with respect to an environment” as it was defined by Benedikt in his 1979 paper ‘To Take Hold of Space’ [8]. Isovists are used to analyse visual connectivity and the perception of spaces.

Isovist fields are a way of visualising the aggregation of multiple isovists within a given space. Instead of analysing individual viewpoints, isovist fields provide a holistic view of visibility and connectivity across an entire area or environment.

1.3.2 Space syntax

Space syntax, a theory and method, originated in the 1970s at The Bartlett School of Architecture, University College London, by Bill Hillier and his colleagues. In their 1984 book, "The Social Logic of Space," [9] Hillier and Hanson introduced 'space syntax' as a method to evaluate spatial relationships and employ various approaches and analytical techniques for studying urban spatial configurations and their impact on human behaviour and movement. The core concept is breaking spaces into parts, analysing them as networks of choices and showing how connected and integrated they are. Key methods and tools in space syntax analysis include:

1.3.2.1 Graph Theory:

Space syntax draws heavily from graph theory, which involves the mathematical analysis of the urban layout as a network of spaces (nodes) and paths (connections).

1.3.2.2 Axial Analysis:

Axial Analysis involves creating a graph of the street network by connecting key points, called "axial lines," which represent streets, paths, and corridors. The analysis considers how these lines intersect and the level of connectivity between them helping to identify the most central and integrated parts of an urban layout.

1.3.2.3 Depthmap Analysis:

Depthmap software is used to calculate the "depth" of each space within a network, considering the number of steps it takes to reach different parts of the layout from a given location. This method helps reveal patterns of accessibility and connectivity.

1.3.2.4 Visibility Graph Analysis (VGA):

VGA examines what can be seen from a specific location within an urban environment. Visibility graphs are constructed to determine lines of sight and visual connections between different spaces. This analysis is crucial for understanding how visibility influences social interactions and how easy or difficult it is to orientate and navigate through neighbourhoods.

1.3.2.5 Integration Analysis:

Integration analysis quantifies the level of integration of each space in the network. Spaces with higher integration are more centrally located and tend to have more connections to other spaces. This measure can help predict the flow of people and movement patterns.

Space syntax framework also uses Angular Segment Analysis, Route Analysis: GIS (Geographic Information Systems), Cumulative cost and flow models when applied to larger scale environments like urban or natural spaces . This layer of information adds a depth of insight that is challenging to obtain through other means.

1.3.3 Spatial network analysis software

The practical application of these methods led to the appearance of specific tools known as Spatial network analysis software such as Axman (axial line analysis), TransCAD(transportation), GIS (planning and geography), Depthmap , OmniVista (isovist measures), Mindwalk (axial maps), Ajanachara (visibility graph analysis), OverView Autocad plug-in (isovist analysis), UNA Toolbox for Rhino (spatial networks), DecodingSpaces (architectural and urban planning) and SpiderWeb (graphs) for Grasshopper and others. These software applications are commonly used in various fields, including urban planning, transportation, geography, and architecture, to study how objects or locations are connected and the flow of information, people, or resources through these networks.

1.3.4 Space discretization: The Grid

While Hillier and Hanson (1984) proposed metrics for individual nodes, they also introduced a broader concept called "depth." Depth refers to the effort required to travel from one point to another within a city or building and can be measured using various factors like straight-line distance, the number of turns or changes in direction. However, these abstract methods didn't work well for indoor spaces [10]. To address this issue In 2001 Alasdair Turner et al. suggested using a lattice grid system with one-metre units placed all over the analysed space, which is supposed to be related to how people experience those spaces. This grid created a regular spatial unit and allowed for more detailed descriptions of the spatial configuration [11]. Turner used the concept of the isovist from Benedikt (1979) to connect the vertices of the grid creating thus a graph, similar to Hillier and Hanson (1984). An isovist is all the points visible from a specific point in space [10]. Turner views isovists as tools for understanding local visual perception but not for grasping the bigger spatial picture.

That methodology had several problems related to grid resolution and until recently, had been a time consuming procedure. In his lecture given to the UCL Space Syntax Laboratory Research Seminar on 25th February 2021 Sam Griffiths [12] mentions “Architectural plan features often occur at scales of less than one metre, and so researchers now tend to adopt multi-various grid resolutions to suit their work. Beyond requiring exponentially extra hours of computation, such variation disregards the fact that grid resolution itself has a distortional effect on the resultant value of integration at any given point. This is challenging, to say the least, for a metric that was originally designed to allow normalised comparison between complex spatial systems”. However, he adds that this grid established a consistent spatial framework and enabled more in-depth explanations of the spatial arrangement. Turner initially created a software application named "Depthmap," [11] which underwent further development by Tasos Varoudis at the Space Syntax Laboratory and evolved into an open-source version called DepthMapX for multiple platforms. Within this application, the method can be implemented on 2D plans.

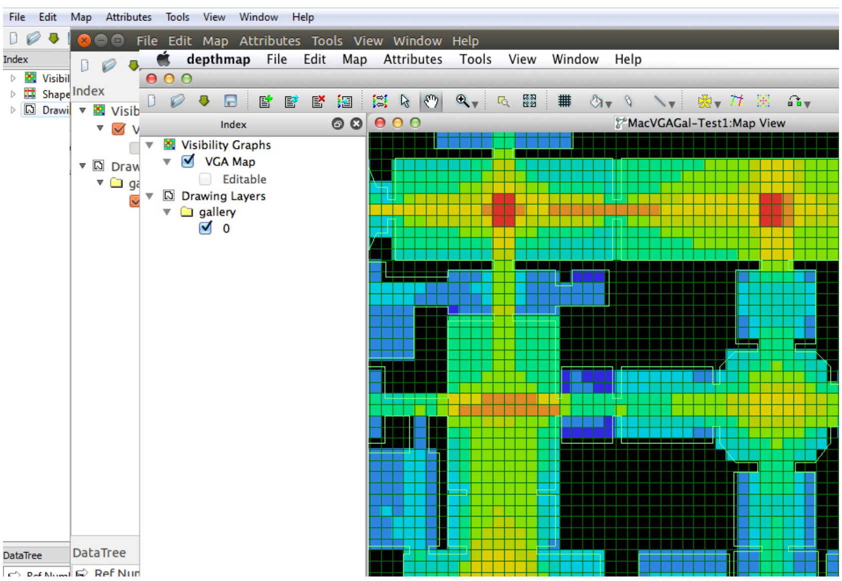


Figure 1. DepthMapX application (UCL Space Syntax © 2023)

Originally, this approach was primarily applied in urban settings, examining human interactions within cities. Today, it also finds utility in indoor spaces. Tools like Climate Studio and Pollination (formerly LadyBug Tools) use a grid-based framework for environmental analysis in buildings. Climate Studio, in particular, also assesses visual quality using a grid-based approach. These tools work with 3D models and climate data, allowing complex calculations, including daylight assessment, thermal analysis, and energy modelling.

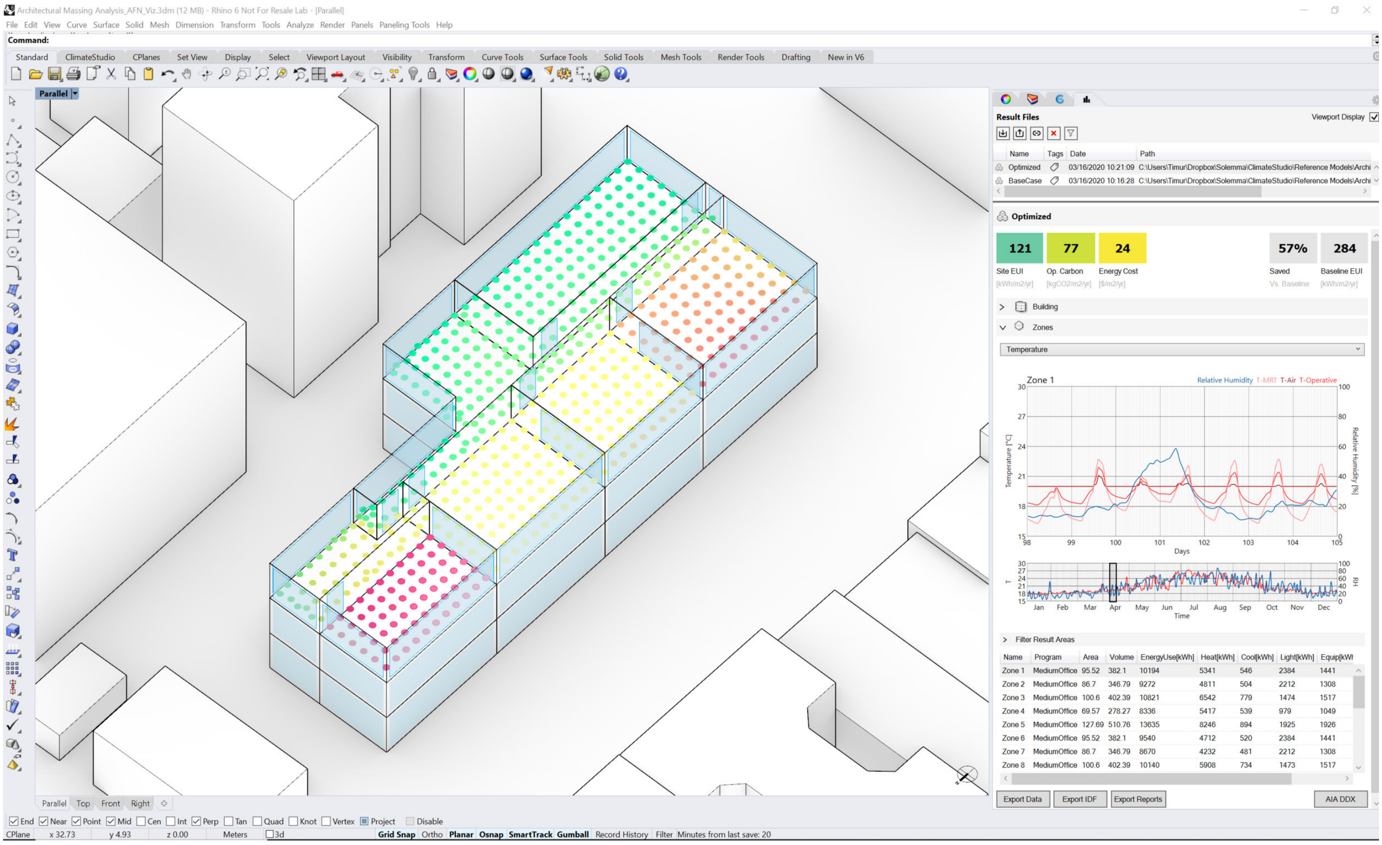


Figure 2. Spatial thermal comfort analysis in Climate studio Solemma LLC ©

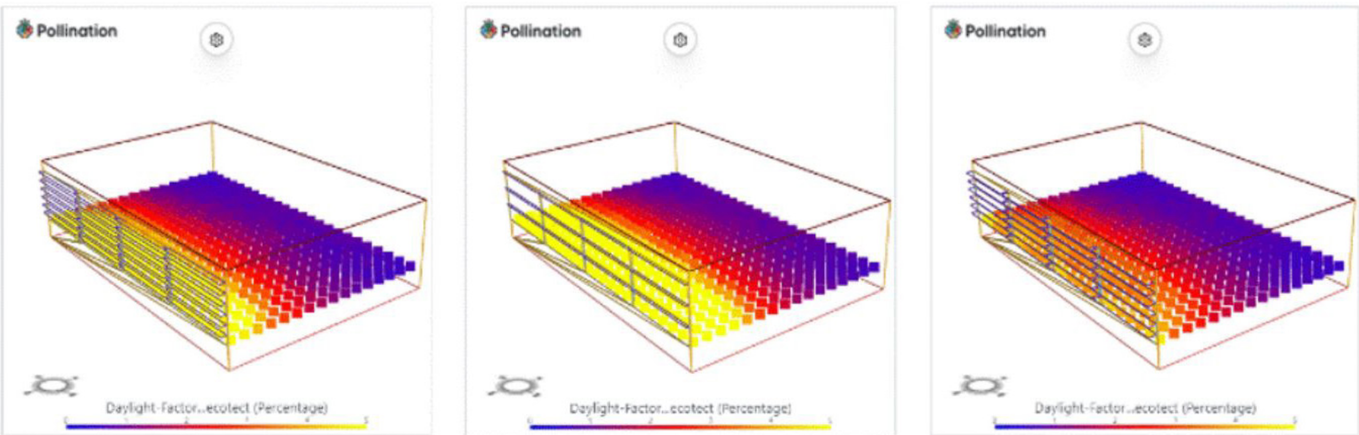


Figure 3. design-explorer results based on Daylight factor analysis made with Poillination tools. Pollination ©

In the realm of three-dimensional modelling, the 3D equivalent of a pixel (a 2D point) is a voxel. When working with 3D models, the conventional 2D grid extends into a three-dimensional grid, commonly referred to as a Voxel-based grid.

Thus space discretization based on a grid framework provides a systematic methodology for evaluating the wide range of space properties, enabling visual, navigational, environmental, organisational, and user-related aspects. In addition to the analysis itself, this approach facilitates quantification through a structured and systematic method for measuring and analysing diverse spatial elements.

2 Research

2.1 Research design

The study employs quantitative data collection and analysis methods within a standardised voxel grid framework. Expanding upon the previously described approach, the indoor space is conceptualised as a collection of uniform entities—spatial units. Each unit, symbolised by a voxel (TestPoint), undergoes evaluation based on specific spatial properties (metrics). The resultant values are then assigned to their respective units.

2.1.1 Spatial unit

A spatial unit functions as an abstract entity representing a distinct fraction of space, serving as a fundamental building block for spatial analysis. In contrast to the physical elements of the building, spatial units offer a granular representation of the environment, providing a more detailed perspective on spatial characteristics

2.2. Methodology

2.2.1 Scene preparation

To proceed with the calculation, the 3D scene must be constructed, incorporating the simplified building and contextual geometry. The scene's orientation is important.. Given the research's focus on vision-related properties, it is essential to differentiate between transparent and opaque elements within the scene. The building geometry should encompass structural elements and the envelope, and it may also include partitions and other geometrical elements considered as visual obstacles. Following this, the interior space is represented as a grid of voxels, where each voxel serves for generating spatial units.

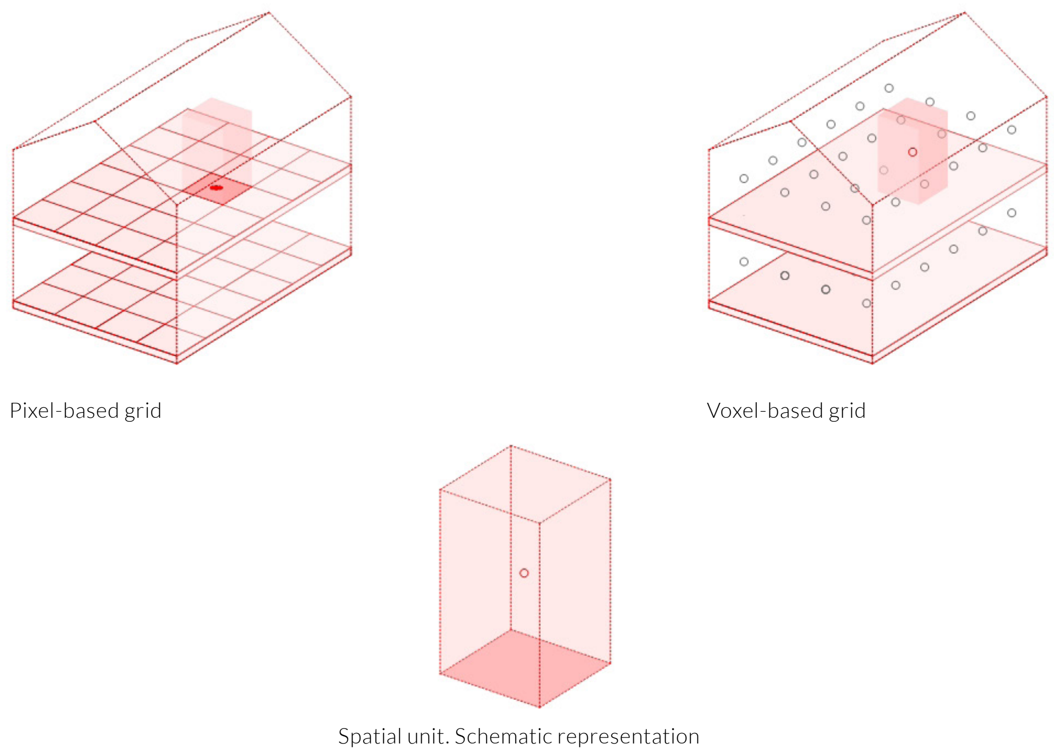


Figure 4. Spatial unit schematic representation.

2.2.2 Evaluation

2.2.2.1 The tool

Despite the enlarging number of applications using grid framework it might be challenging to analyse the particular location in the scope of different aspects. Especially considering that not all of the mentioned applications possess open-source code and the capability to calculate custom properties, this research employs a proprietary tool that provides complete control overcalculations. Given the growing significance of Grasshopper in the AEC industry, the decision was made to build a Grasshopper based toolkit.

Grasshopper is a visual programming language and environment that operates within the Rhinoceros 3D CAD software. It features a user-friendly graphical interface, particularly designed for individuals with no programming background.

The toolkit discussed consists of a Grasshopper plugin comprising 9 custom components, or modules, to be arranged in ananalytical pipeline in three main sections: Map, Harvest and Query.

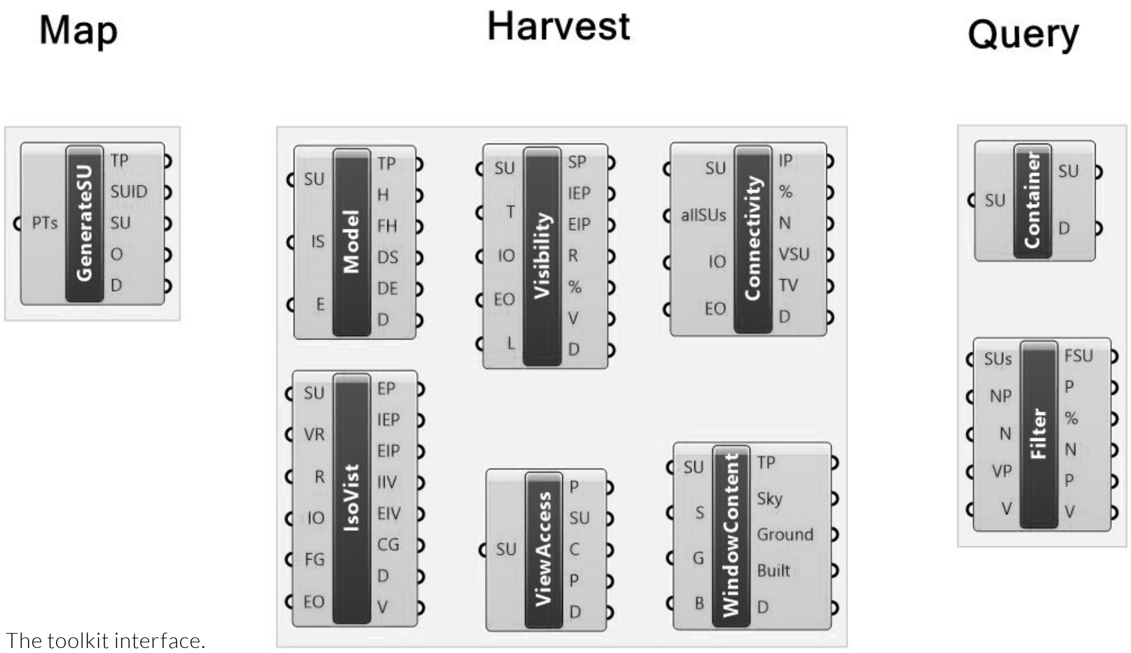


Figure 5. The toolkit interface.

Preprocessing module, **Map** is dedicated to the generation of the Spatial units (SUs) - the elementary representational portions of the interior space under study. Map section consists of a single component that creates a set of SUs from a given set of 3d points.

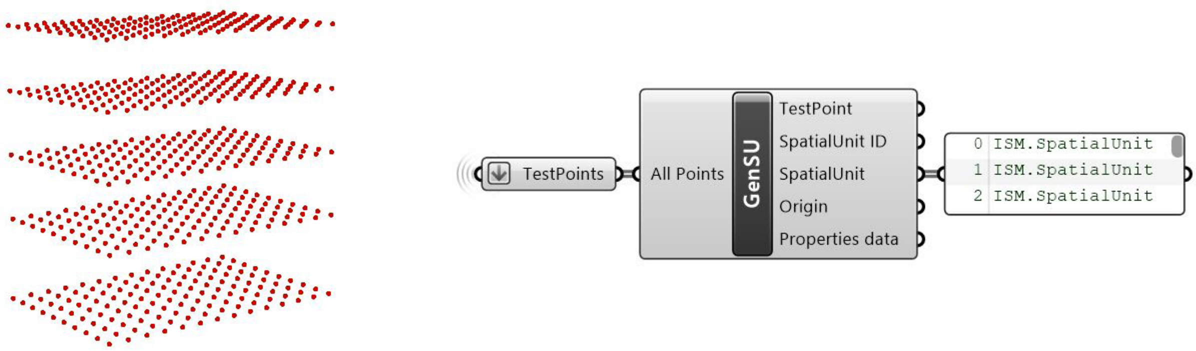


Figure 6. “Generate Spatial Units” component interface.

Harvest includes several components to run calculations for a specific set of properties for the provided spatial units. More detailed information is provided in the Properties description.

Finally, **Query** enables exploring the properties by applying filters or by reading data directly from the units. It consists of two components: Container and Filter.

Container shows all calculated properties for the given units. This data can be exported to csv format with the means of grasshopper native components.

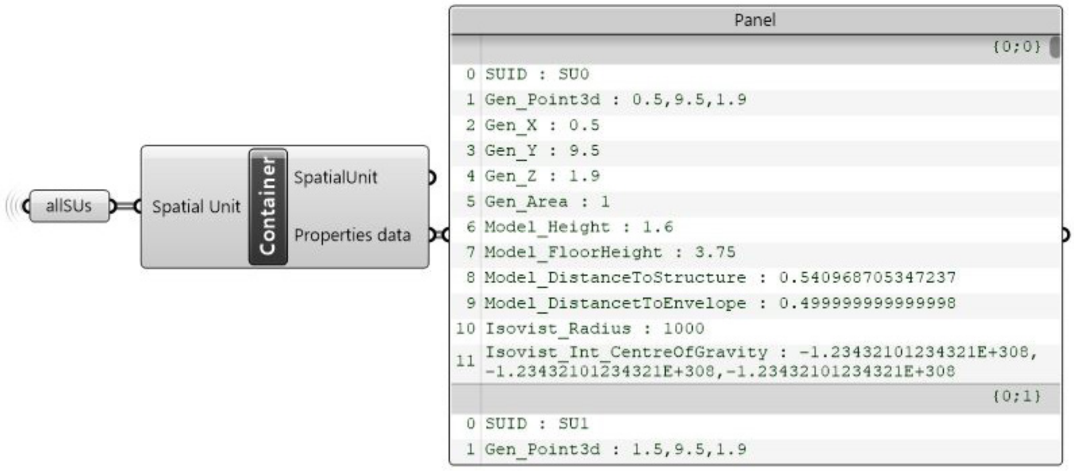


Figure 7. “Container” component interface.

The Filter component operates in the following manner: it receives a list of Spatial Units and four additional inputs that collectively form a condition statement. The provided units are then filtered based on the specified condition.

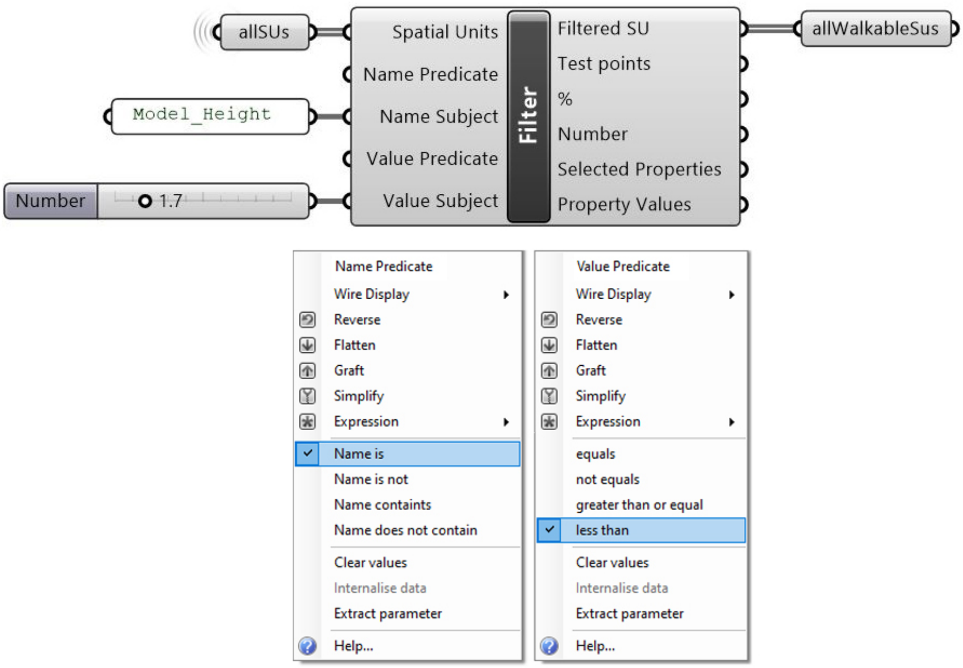


Figure 8. “Filter” component interface.

2.2.2.2 Selection of Variables

In order to evaluate each spatial unit the Metrics were selected based on two key criteria: the metric is known for its association with human perception, the metric is measurable. Some of the metrics are not directly associated with human experience but are necessary for the calculations. Once calculated a metric is assigned to the unit as a property. The current version of the tool allows for yielding the following list of categorised properties:

SUID

Gen_Point3d
Gen_X
Gen_Y
Gen_Z
Gen_Area

Model_Height
Model_FloorHeight
Model_DistanceToStructure
Model_DistancetToEnvelope

Visibility_Percentage

Connectivity_Percentage
Connectivity_NumberOfVisibleSUs
Connectivity_VisibleUnits
Connectivity_FarthestVisibleSUs
Connectivity_ThroughVision

Isovist_Radius
Isovist_Ext_PerimeterCurve
Isovist_Ext_MinVista
Isovist_Ext_MaxVista
Isovist_Ext_Area
Isovist_Ext_Perimeter
Isovist_Ext_Compactness

Isovist_Int_PerimeterCurve
Isovist_Int_MinVista
Isovist_Int_MaxVista
Isovist_Int_CentreOfGravity
Isovist_Int_Area
Isovist_Int_Perimeter
Isovist_Int_NumberOfVertices
Isovist_Int_DriftDirection
Isovist_Int_DriftMagnitude
Isovist_Int_Compactness

ViewAccess_Ext_EastScore
ViewAccess_Ext_NordEastScore
ViewAccess_Ext_NordScore
ViewAccess_Ext_NordWestScore
ViewAccess_Ext_WestScore
ViewAccess_Ext_SouthWestScore
ViewAccess_Ext_SouthScore
ViewAccess_Ext_SouthEastScore

ViewContent_SkyPercentage
ViewContent_GroundPercentage
ViewContent_BuiltPercentage

2.3 Properties description

2.3.1 Generic metrics

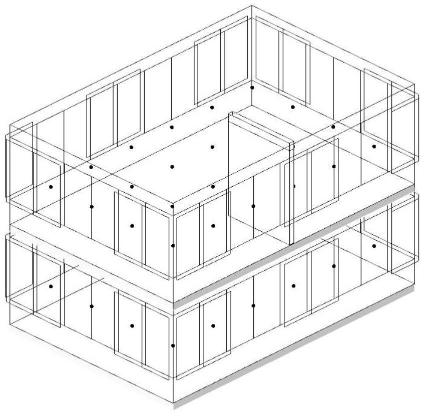


Figure 9. Grid of 3D Points .

The generic properties are initialised upon the creation of spatial units and serve as a repository of essential information necessary for the identification of individual spatial units. These properties include a distinct identifier, as well as grid-related data, such as the global XYZ coordinates of test points and the unit's area:

SUID
Gen_Point3d
Gen_X
Gen_Y
Gen_Z
Gen_Area

2.3.1.1 SUID - The (Spatial Unit Identifier) serves as a distinct name for a given spatial unit.

2.3.1.2 Gen_Point3d. This property signifies the voxel that serves as the source for the generation of the spatial unit

2.3.1.3 Gen_Area represents the squared distance between two test points of the nearest units

These properties are automatically generated by the GenSU component using the provided set of points. They serve as the fundamental basis for any further evaluations.

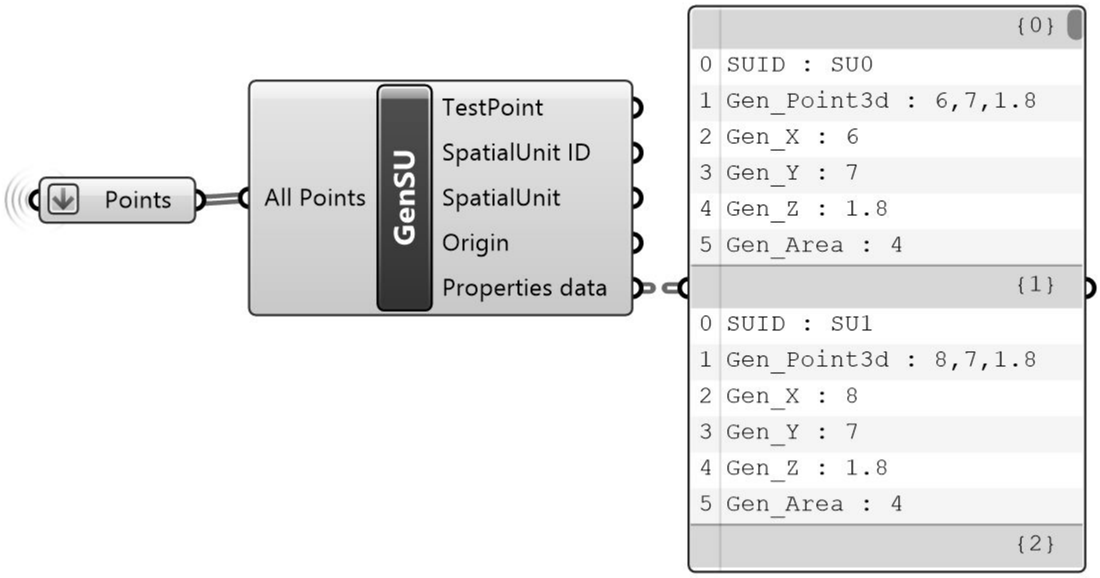


Figure 10. "Generate Spatial Units" component interface.

The Origin output refers to the point from the provided set, which is closest to w 0,0,0.

2.3.2 Model properties

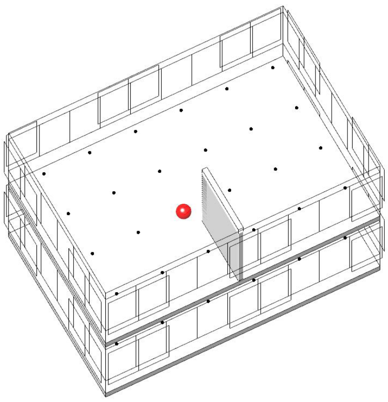


Figure 11. Location of the individual TestPoint.

Model properties are the metrics describing the unit in the context of the building.

Model_Height
Model_FloorHeight
Model_DistanceToStructure
Model_DistancetToEnvelope

2.3.2.1 Height : The height is defined as the distance from the Test Point to the floor or the nearest structural element below.

2.3.2.2 FloorHeight: This metric represents the distance from the first element underneath the testPont to the first element above the testPoint. Depending on the input can measure a slab-to-slab height or a floor to ceiling height. The ceiling height is one of the most significant factors in buildings, but it is also important in human cognitive functions. According to a recent study, open spaces featuring higher ceilings tend to stimulate abstract thinking, whereas smaller rooms with lower ceilings tend to encourage concrete thinking. ”Rooms with higher ceilings were more likely to be judged as beautiful, and activated structures involved in visuospatial exploration and attention in the dorsal stream” [13]. The high ceiling can significantly contribute to the cathedral effect in a building, potentially positively influencing people's creativity.

2.3.2.3 DistanceToStructure shows the distance from the testPoint to the nearest structural element. It serves to verify if the particular Spatial unit contains a structural element in its area.

2.3.2.4 Distance Envelope shows the distance from the testPoint to the nearest envelope element, ignoring other obstacles.

The model metrics are calculated with the Model Structure component.

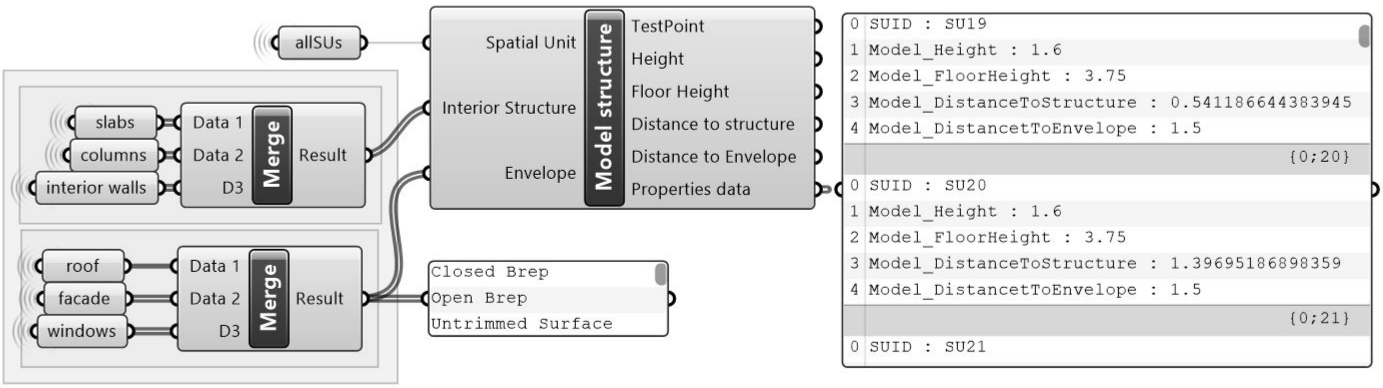


Figure 12. “Model Structure” component interface.

2.3.3 Visibility metrics

The Visibility metrics are used to verify the visibility of a particular object (landmark) from a specific location. This metric is represented by a property called "Visibility Percentage".

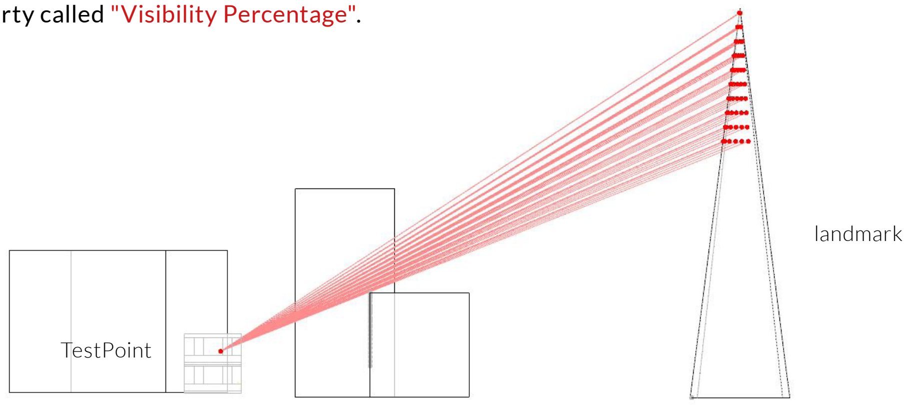


Figure 13. Visibility metric: percent of Visible sensors.

2.3.3.1 Visibility Percentage is a metric which quantifies the percentage of the landmark that is visible from the tested unit. Some objects play a significant role in organising our mental representations of space. They are often referred to as landmarks. Landmarks are easily recognizable objects that contribute to our sense of place and identity by structuring our environment. They serve as cognitive anchors, markers, or reference points, aiding us in orientation, wayfinding, and communication [14]. The visibility of these objects can provide psychological comfort and a sense of security. This effect is particularly pronounced when it comes to indoor landmarks, as they play a crucial role in navigation within buildings [15]. When people navigate, they construct a cognitive map using a reference frame. This process distinguishes between egocentric and allocentric reference frames. An allocentric frame relies on external reference points, such as cardinal directions, while an egocentric frame centres around the body. Navigation often involves the use of landmarks, where decisions like 'turn left after the entrance' exemplify egocentric navigation. Functional elements like doors and stairs naturally attract attention and are commonly referred to as landmarks. Among these elements, stairs, in particular, stand out as easily memorable and practical navigational reference points [16]. Furthermore, the visibility of entrances plays a critical role in assessing security [17].

Apart from navigation and security issues visibility of some objects can be just more desirable than others thus contributing to the general quality of the view.

To assess the visibility of a specific object, the ray tracing technique is employed. This method involves dividing the 3D surface of the landmark object into individual sensor points. A test point of the spatial unit is then connected to these sensor points of a landmark. In a case if a connection does not meet any visual obstacles, including the landmark itself, the sensor is considered to be visible. This evaluation is done using the "visibility" component of the plugin. The component allows visualisation of the Landmark sensor points. The “Isvisible” output returns true if the Percentage of visible points meets the Threshold.

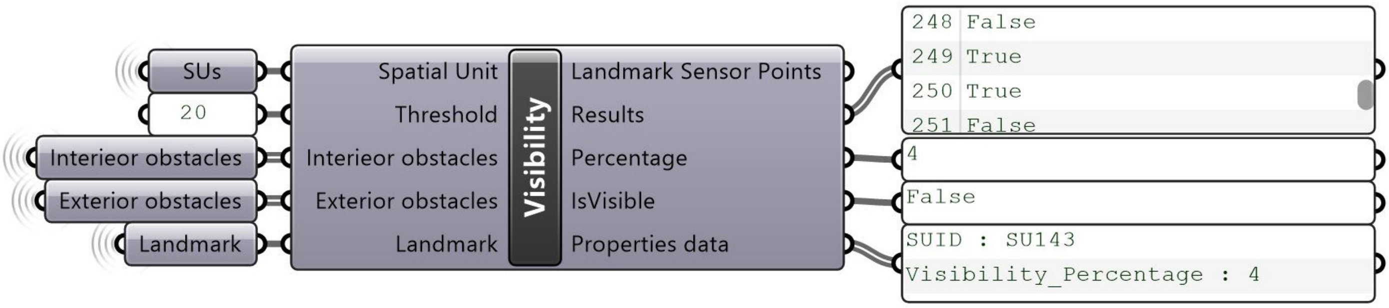


Figure 14. Visibility metric: percent of Visible sensors.

2.3.4 Connectivity metrics

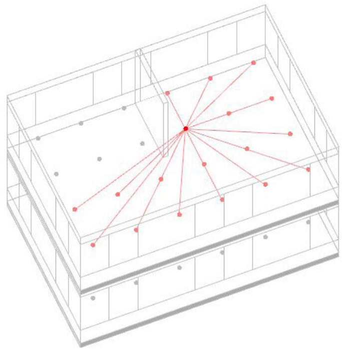


Figure 15. Visual connections.

Internal Visual Connectivity (IVC) introduced by Turan, Irmak and Reinhart, is defined to be the percentage of the interior space that can be seen from a particular position [18]. In this research it refers to the degree in which a single Spatial unit can be viewed from other SUs.

Connectivity_Percentage
Connectivity_NumberOfVisibleSUs
Connectivity_VisibleUnits
Connectivity_FarthestVisibleSUs
Connectivity_Through Vision

2.3.4.1 Percentage: a percentage of visible units from all units
2.3.4.2 NumberOfVisibleSUs: a number of visible units
2.3.4.3 VisibleUnits: a set of visible units SUIDs
2.3.4.4 FarthestVisibleSUs: a SUID of of the furthest visible unit

Visual connectivity of a space is intimately linked to social interaction, surveillance, privacy, security, and control. Individuals who are aware of being watched may conform to societal norms, shaping social behaviour. The notion of visual connectivity lies behind the concept of Panopticon, a metaphor introduced by Jeremy Bentham [19], representing a type of institutional building design where a central watchtower enables a single observer to see all inmates without the inmates knowing if they're being observed at any given moment. This design was used to induce self-discipline and control.

Low visual connectivity is important in areas where confidentiality is essential, such as meeting rooms, medical facilities, or private offices. It helps ensure that sensitive discussions or interactions remain private. This also can foster a more relaxed environment where people feel free to be themselves without feeling exposed. High Visual connectivity can enhance security by allowing continuous monitoring and rapid response to potential incidents in a way that allows for clear lines of sight and observation, which can be complemented by the strategic placement of CCTV cameras to cover blind spots. Visual connection, a key principle of Crime Prevention Through Environmental Design (CPTED) [20].

The properties related to visual connectivity are calculated by component "visual connectivity" The component represents a simplified version of Visual Graph Analysis (VGA) for a 3d network of units. The algorithm builds the direct lines from the test point of the tested unit to test points of all units. The lines that do not meet obstacles are considered as direct visual connections. In addition to the previously mentioned metrics (Percentage, Number of Visible SUs, and the set of Visible USs), the component's output for each unit also provides information about the points where lines of sight intersect with obstacles, the test points of visible units, the farthest visible units and a metric known as "Through Vision."

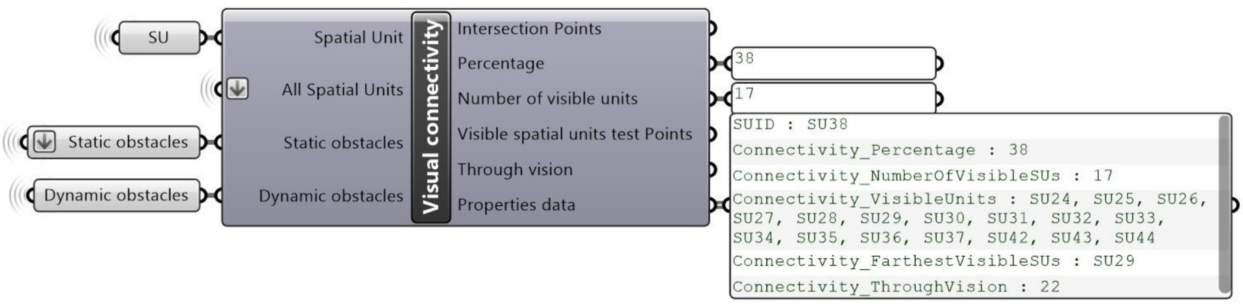


Figure 15. "Visual Connectivity" component interface.

2.3.4.5 Connectivity_Through Vision:

Through Vision ia a metric that quantifies the number of lines of visibility that pass through a particular location within a space. Introduced in 2007 by Turner [21] in a more formal context, “for each cell in the grid, it is the number of times it is crossed by lines drawn between the centroids of all other inter-visible cells”.

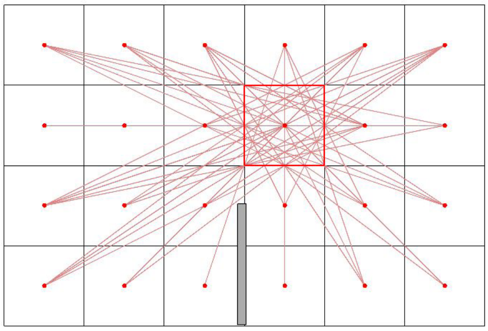


Figure 16. All unobstructed lines of vision crossing the unit .

This metric helps identify frequently travelled locations because they lie on the path between two positions. It is primarily associated with movement in areas featuring extended, straight pathways [10].

Even though it seems close to the connectivity metric, unlike the last one, through vision shows not only how visible a particular place is but also how often it comes in the way of the viewer. To be more specific Visual connectivity focuses on individual sightlines, while Through Vision looks at the broader picture by considering interconnectedness of a location within the entire layout. Areas with high through vision are likely to receive more attention due to their perceived importance in spatial navigation. High Through Vision areas often indicate pathways that are the shortest routes between two points. People tend to perceive these areas as efficient paths for movement, influencing their choices about how to traverse the space.

96 %	96 %	100 %	100 %	96 %	96 %
88 %	92 %	96 %	96 %	92 %	88 %
75 %	75 %	75 %	75 %	75 %	75 %
71 %	67 %	55 %	55 %	67 %	71 %

Figure 17. Connectivity_Percentage

0	11	15	15	11	0
5	31	49	49	31	5
5	27	22	22	27	5
0	3	0	0	3	0

Figure 18. Connectivity_Through vision

It is noteworthy that Through vision = 0 indicates angle position.

To calculate the metric, each unit is represented as a 3D sphere. Whenever a line between two visible units intersects with a sphere, the ThroughVision count increases by 1. Note that lines originating from or leading to a tested unit are not included in this count.

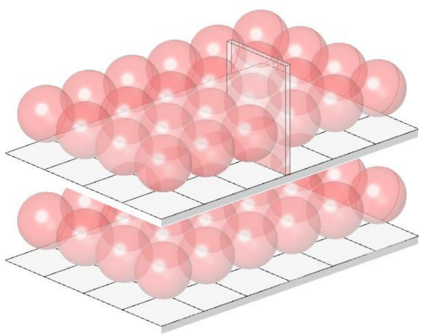


Figure 19. Spatial Unit as a sphere geometry

2.3.5 Isovist metrics

Isovist is a field of view or visibility polygon that represents the region that can be seen from a particular vantage point. The researcch methodology separates the field of view that only include interior space (Interior Isovist) and the field of view that include both interior and exterior spaces (Exterior Isovist).

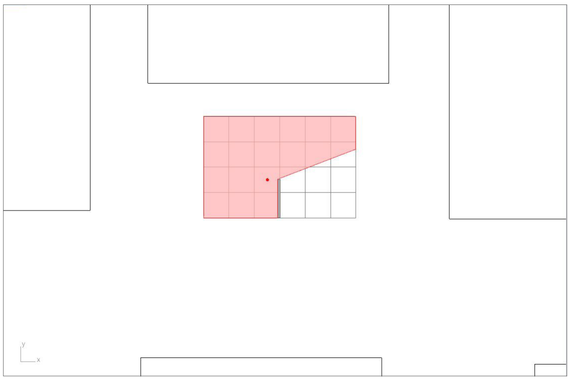


Figure 20. Interior isovist, top view.

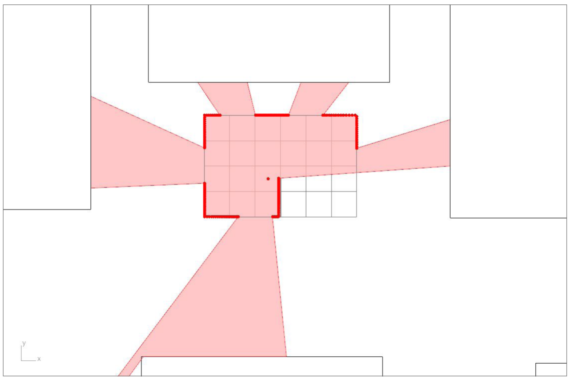


Figure 21. Exterior isovist, top view.

An interior isovist represents the visibility polygon from a specific point within a defined interior space.

An exterior isovist includes the exterior environment that is sible through windows, doors, or other openings.

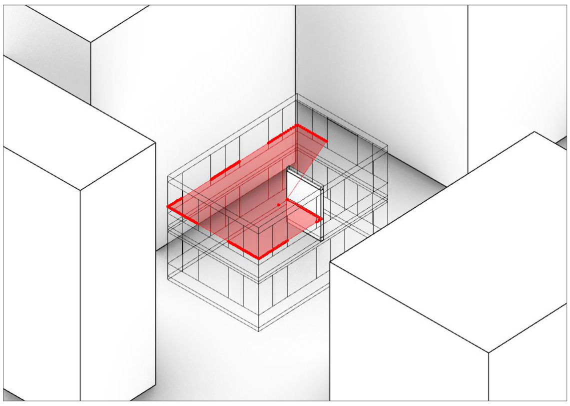


Figure 22. Interior isovist, axonometric view.

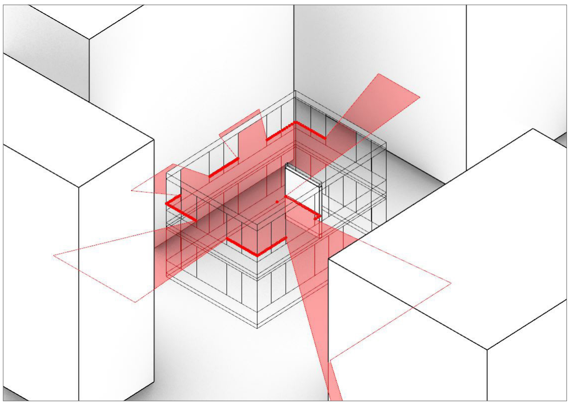


Figure 23. Exterior isovist, axonometric view.

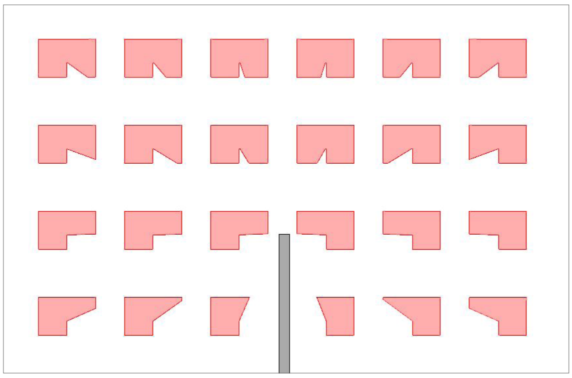


Figure 24. A map of interior isovists within a space.

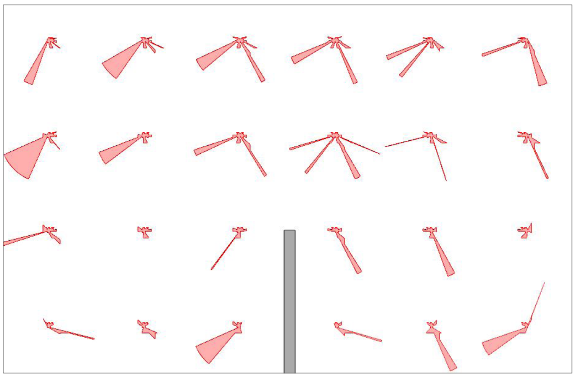


Figure 25. A map of exterior isovists within a space.

Isovist metrics remain a common tool for space analysis. They are often associated with Prospect, Refuge, Mystery and Complexity [21].

There is a direct correlation between Isovist and Visual Connectivity metrics. A network of visible units for an observation point can be referred to as a discrete version of Isovist .

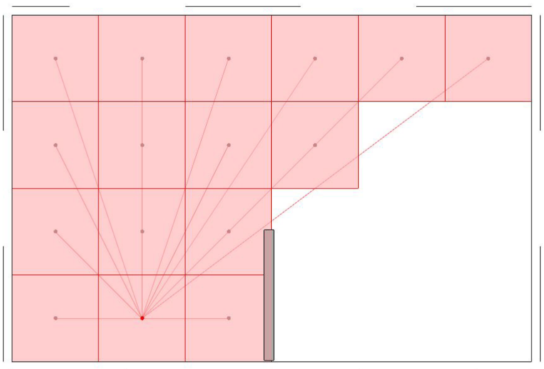


Figure 26. Visible units from a given testPoint. Top view.

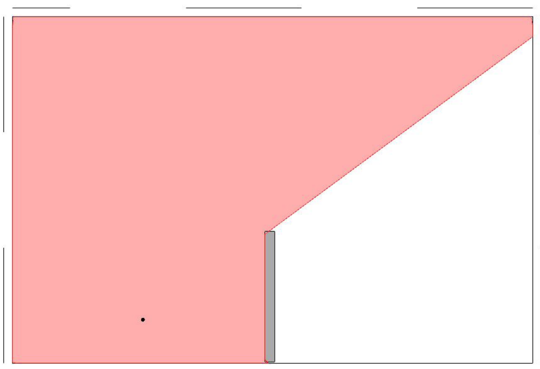


Figure 27. A 2D isovist generated from the given testPoint. Top view.

Despite the similarities the isovists contain more detailed information about the shape of visible polygone.

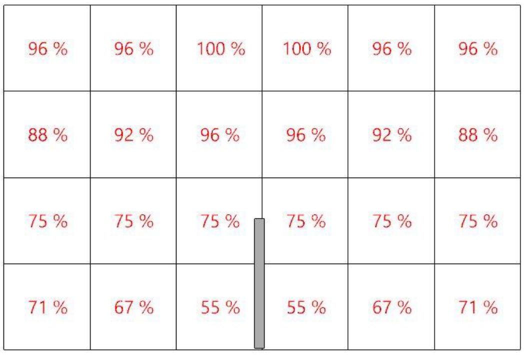


Figure 17. Connectivity_Percentage

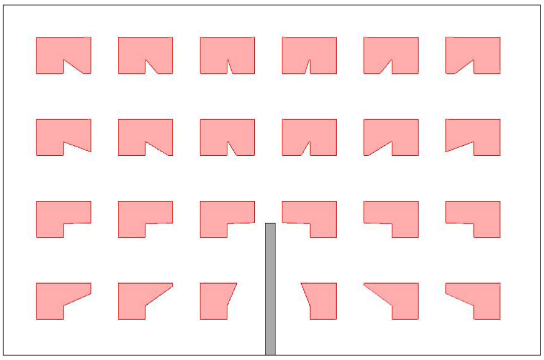


Figure 24. A map of interior isovists within a space.

However, in a scenario where we consider both vertical and horizontal fields of view, or a 3D isovist, the graph representation enables us to retain information about spatial relationships between points and demands significantly less computational power. With more units per space, it approximates the shape of the 3D isovist. In fact, both approaches involve integration: one calculates it based on points per cubic metre, while the other relies on the number of vistas (rays).

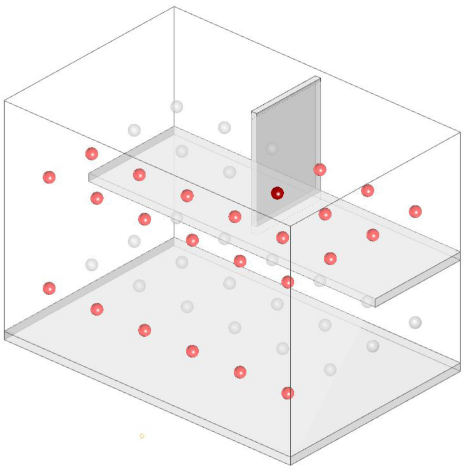


Figure 26. Visible units from a given testPoint.
Axonometric view.

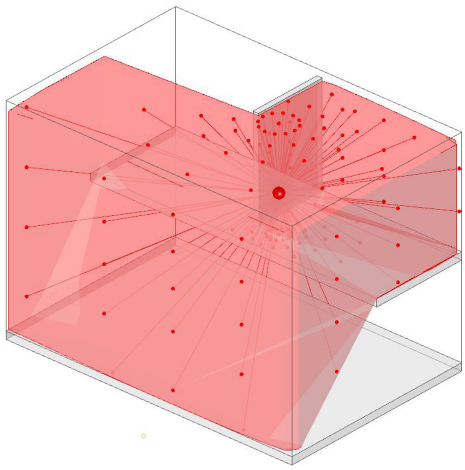
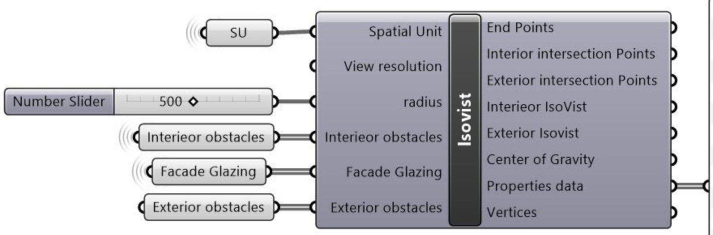


Figure 27. An 3D isovist generated from the given testPoint.
Axonometric view.

The Isovists and Isovist metrics are calculated with the help of an Isovist component. All metrics consider 2d isovists.



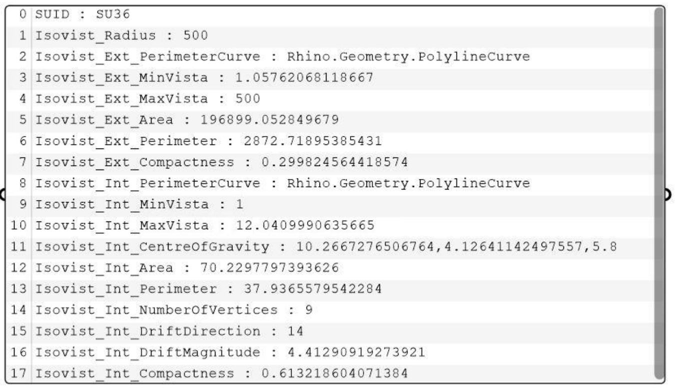


Figure 28. “Isovist” component interface

Isovist component allows for collection of following properties:

Isovist_Radius
Isovist_Ext_PerimeterCurve
Isovist_Ext_MinVista
Isovist_Ext_MaxVista
Isovist_Ext_Area
Isovist_Ext_Perimeter
Isovist_Ext_Compactness
Isovist_Int_PerimeterCurve
Isovist_Int_MinVista
Isovist_Int_MaxVista
Isovist_Int_CentreOfGravity
Isovist_Int_Area
Isovist_Int_Perimeter
Isovist_Int_NumberOfVertices
Isovist_Int_DriftDirection
Isovist_Int_DriftMagnitude

While some of these properties are not directly tied to perception, they can, when combined with other metrics, help to discriminate between different space configuration types.

2.3.5.1 Radius: The length of a vista (a ray)

2.3.5.2 Isovist_Area (Exterior / Interior) : According to the research held by Dzebic and Verdab involving the participants, the Isovist area is significantly positively correlated with ratings of spaciousness and clarity, pleasantness and beauty [23]. However the metric is relative and doesn't give the idea of the shape of the space.

2.3.5.3 Isovist_Perimeter (Exterior / Interior): The perimeter metric is of particular interest due to its relationship with other metrics. It is calculated as the sum of the lengths of the segments connecting the endpoints of the vistas.

2.3.5.4 Isovist_Number of vertices (Interior) : The "Isovist Number of Vertices" simply counts the total number of the corner points within the isovist polygon. It provides information about the complexity and shape of the visible area.

2.3.5.6 Isovist_CenterOf Gravity(Interior) : The Center of Gravity point of the isovist Polygon. The resulting point may be outside the polygon, which indicates that the shape is concave.

$$C_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i + x_{i+1})(x_i\, y_{i+1} - x_{i+1}\, y_i),$$

$$C_y = \frac{1}{6A} \sum_{i=0}^{n-1} (y_i + y_{i+1})(x_i\, y_{i+1} - x_{i+1}\, y_i),$$

Centroid formula for 2d polygons

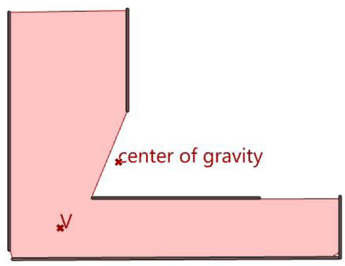


Figure 28. Isovist’s center of gravity lies ouside the isovist polygon.

2.3.5.7 Isovist_Drift magnitude and Drift Direction (Interior)

A Drift is a vector from the observation point to a centre of mass of isovist polygone (G). The metric proposed by Conroy (2001)." Drift Magnitude is a length of the vector in metres and Drift Angle is the direction (in degrees).

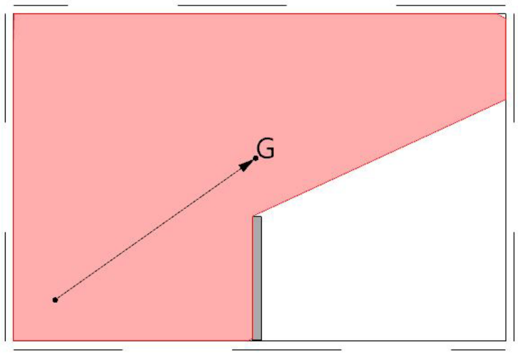


Figure 29. Isovist_Int_DriftDirection : 35
Isovist_Int_DriftMagnitude : 6

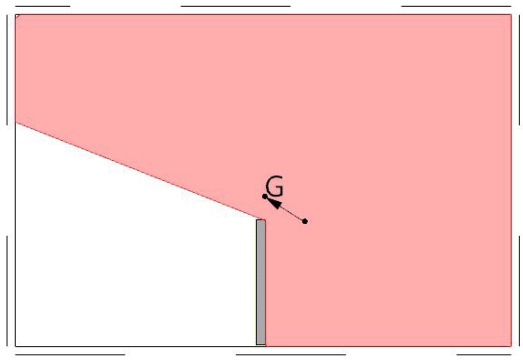


Figure 30. Isovist_Int_DriftDirection : 147
Isovist_Int_DriftMagnitude : 1.15

In relation to the Prospect and Refuge theory, the analysis of drift can provide insights into how a space offers opportunities for both prospect and refuge: Prospect (Openness): Areas with low drift, where the visual experience remains relatively consistent and open, can represent locations that provide a sense of prospect. These areas offer unobstructed views, potentially allowing individuals to facilitate orientation and exploration. Refuge (Enclosure): On the other hand, areas with higher drift, can indicate zones that offer a sense of refuge. These areas could provide a feeling of shelter, safety, or privacy due to their distinct visual boundaries or enclosures. "Drift Magnitude will tend to a minimum value in the centres of spaces and along the centre-lines of roads"[24].

2.3.5.8 Isovist_Compactness (Interior)

Compactness is a measure that compares the area of an object to the area of a circle with the same perimeter.

$$\text{Compactness} = \frac{4\pi * A}{p^2}$$

The measure takes a maximum value of 1 for a circle because its area is equal to that of a circle with the same perimeter. A square compactness is π/4. Objects with irregular boundaries will decrease the measure.

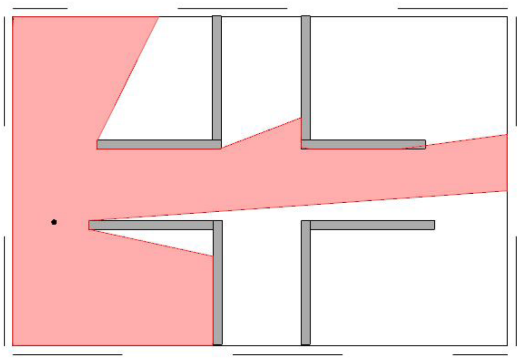


Figure 31. Isovist_Compactness : 0.22

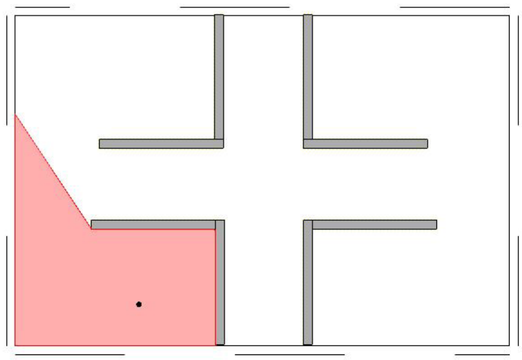


Figure 32. Isovist_Compactness : 0.53

The compactness of an isovist can provide information about the shape and complexity of the visible area from a particular location. A high compactness value (closer to 1) suggests a more regular or circular shape, which may indicate a simpler or more organised view. A low compactness value (closer to 0) indicates an irregular or complex shape, which may suggest a view with diverse features and spatial complexities. Applied to a rectangular layout it indicates the width/length ratio. According to some research Compactness impacts navigation [25],[26].

2.3.6 View access

View Access (the measure of how much of the view can be seen through the window from the occupant's position) [27]; View Access metrics identify how much each part of the exterior environment is observed by associating the Exterior Isovist's geometry with cardinal directions.

View Access_Ext_EastScore	View Access_Ext_WestScore
View Access_Ext_NordEastScore	View Access_Ext_SouthWestScore
View Access_Ext_NordScore	View Access_Ext_SouthScore
View Access_Ext_NordWestScore	View Access_Ext_SouthEastScore

Directly correlated with Windows orientation, View Access can determine which areas of the space are more visually prominent or accessible from a specific viewpoint.

The metric is calculated from the Isovist analysis by the View Access component. The exterior Isovist area is divided into eight segments, corresponding to the cardinal directions of the compass rose. The component calculated the area of the isovist for each direction.

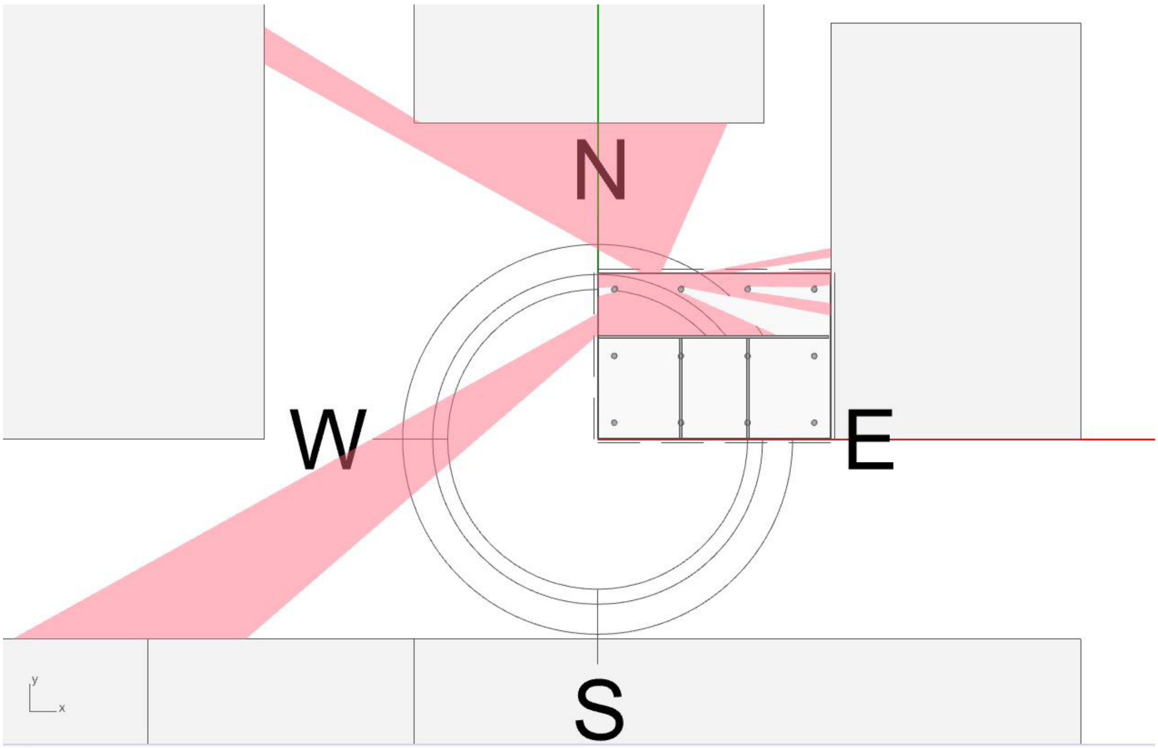


Figure 32. The "View Rose" of an isovist.

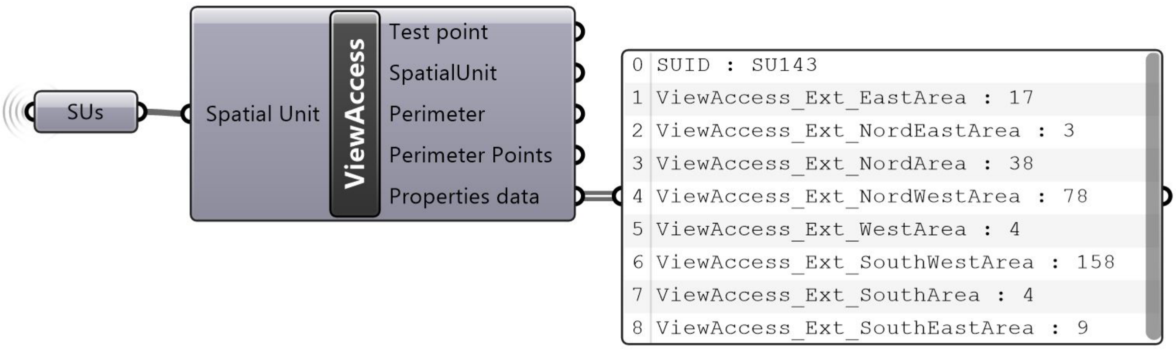


Figure 33. The "View Access" component interface.

2.3.6 View content

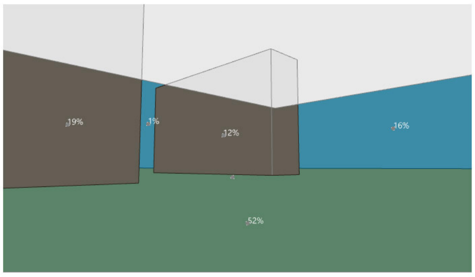


Figure 34. Simplified view from a window.

View content is defined as the sum of the visual features seenin the window view, for example, natural or urban features or the sky. (Berman et al., 2008; Grinde and Patil, 2009; Ulrich, 1981)).

ViewContent_SkyPercentage
ViewContent_GroundPercentage
ViewContent_BuiltPercentage

The view from a window, or the environment a person is in, can have an impact on cognitive state and well-being. The natural views have been shown to have positive effects on occupants' mental state, well-being and overall productivity [28]. The idea that humans have an innate and instinctive tendency to seek connections with nature and other forms of life is popularised by The Biophilia Hypothesis, proposed by biologist Edward O. Wilson in his book "Biophilia"(1984) [29]. Having windows that provide views of the natural environment can play a substantial role in fulfilling this desire and fostering mental, emotional, and physical well-being. The latest environmental labels like BREEAM and LEED as well as European norms include the window view content as the criteria for indoor visual comfort.

To compute this metric, the algorithm initially locates the nearest visible window to the given point, determining its centre. Subsequently, it traces rays from the test point through the identified window, calculating intersections with both the ground and adjacent buildings. Rays that do not intersect are then interpreted as indicating an unobstructed view of the sky. The calculations are made with the View Content Component.

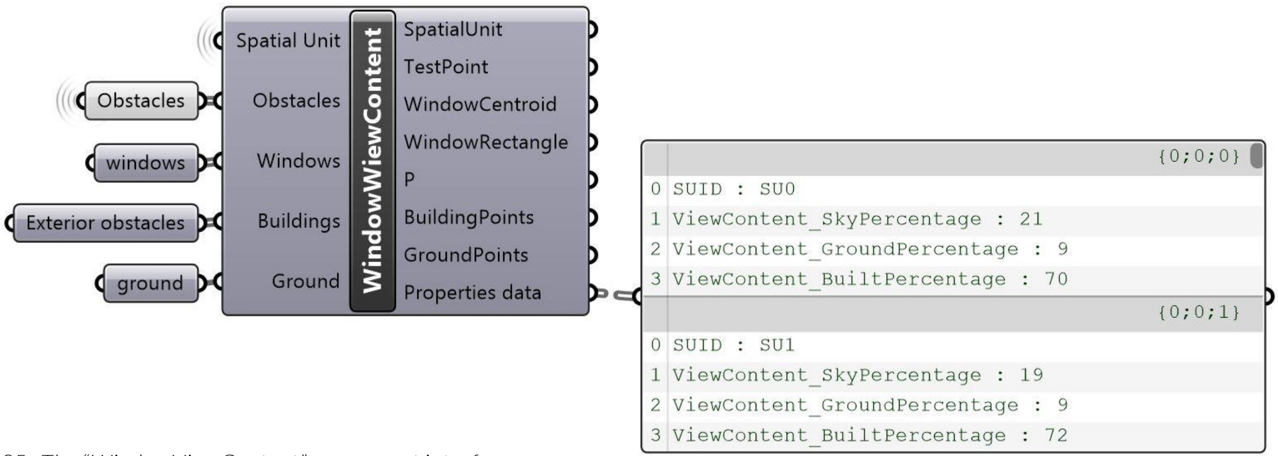


Figure 35. The "WindowViewContent" component interface.

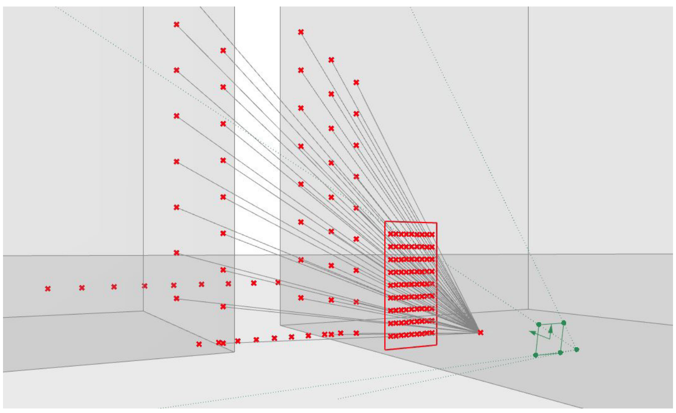


Figure 36. The view direction from the testPoint to the closest window aligned with the frustrum direction.

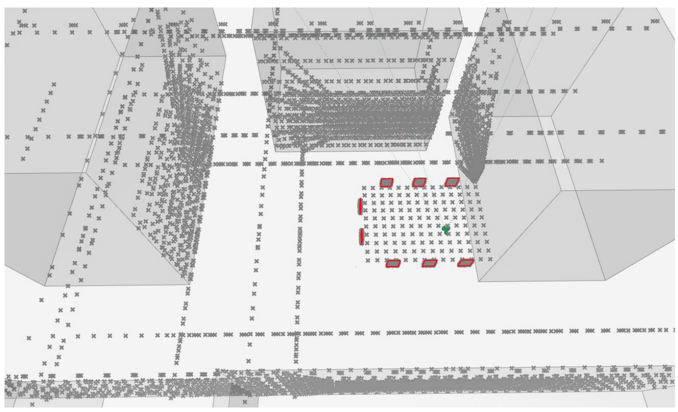


Figure 37. The "BuildingPoints" and "GroundPoints" outputs identify the most viewed parts of the surrounding context from the given units.

3. Case study

3.1 Case study Presentation

To illustrate the logic of the proposed methodology and test the tool, this paper employs a generic model as a case study. The model represents a 5-storey building surrounded by simplified context.

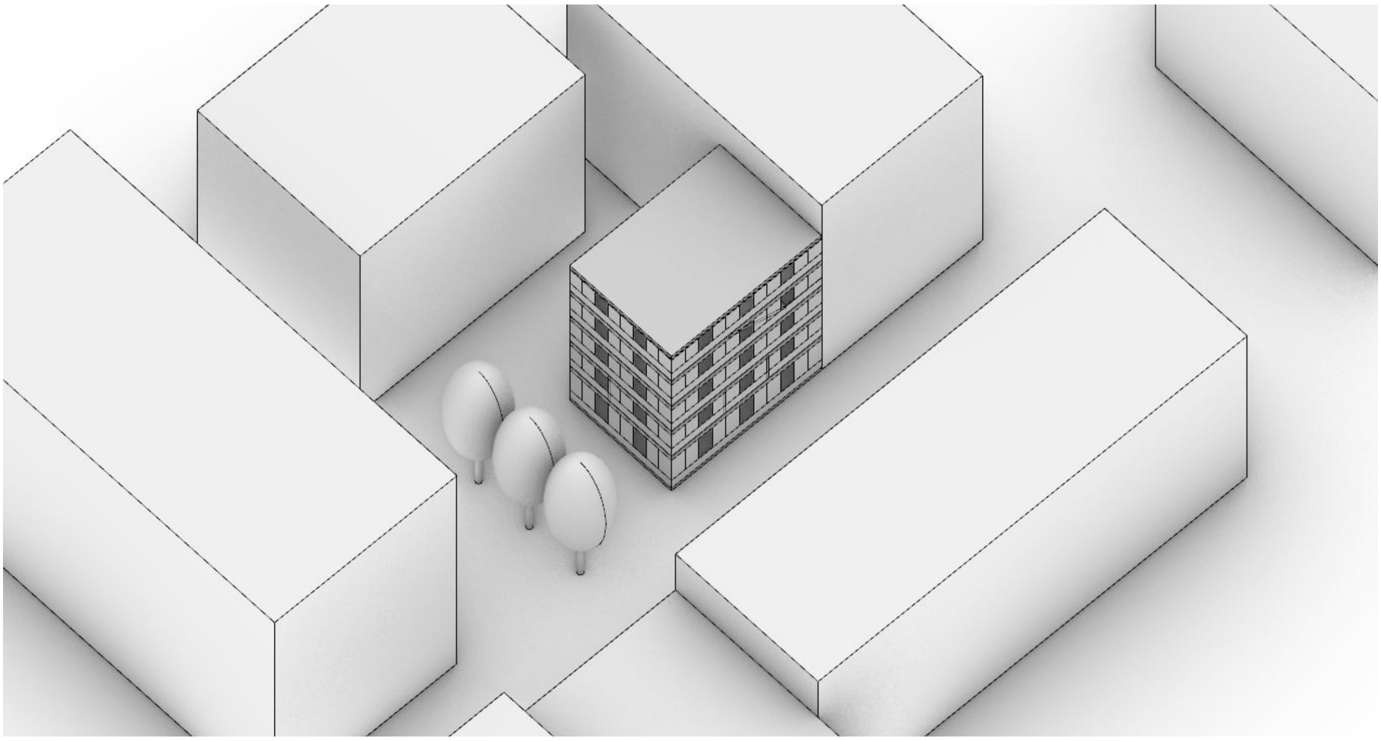


Figure 38. The case study scene wth a context.

The building geometry is represented by the structural elements and partitions and is divided into the following groups: building façade (opaque parts), windows, a roof, slabs, columns and interior walls (partitions).

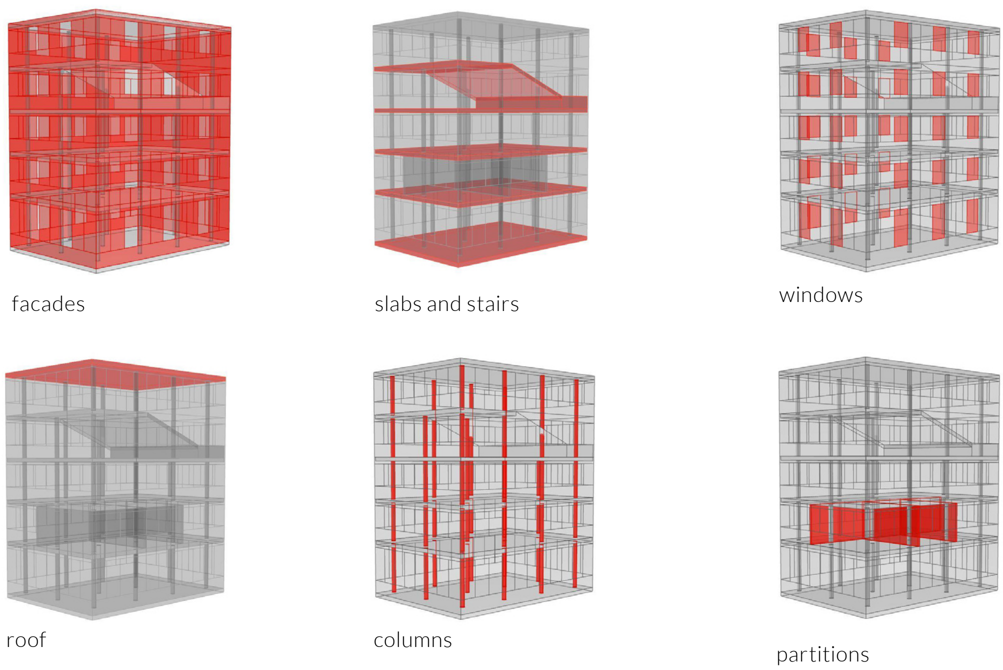


Figure 38. Building geometries grouped by type.

To divide the space into units, the first step involved applying a square 1x1 metre grid to each level. The centre points of the cells were then elevated to a height of 1.6 m above the floor to align with the eye level of a standing person. (700 points in total). These points were then converted into Spatial Units. Care was taken to exclude the units lying below the human height during this process.

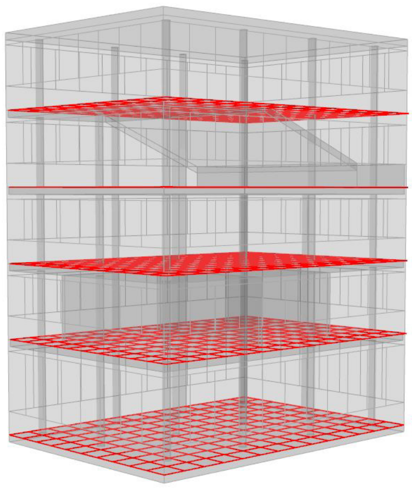


Figure 39. 2D grid applied by level.

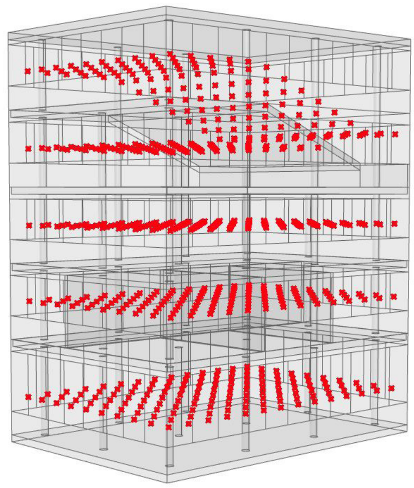


Figure 40. The testPoints of the walkable units.

3.2 Data collection

Firstly Model properties were calculated. The filter component was employed to select the walkable units (650 Spatial units)

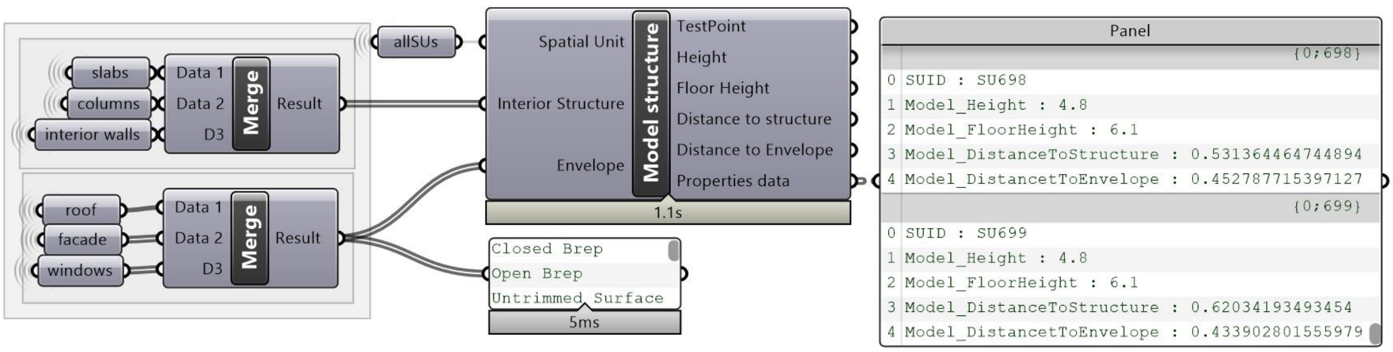


Figure 40. Case study: collection of the Model-related properties.

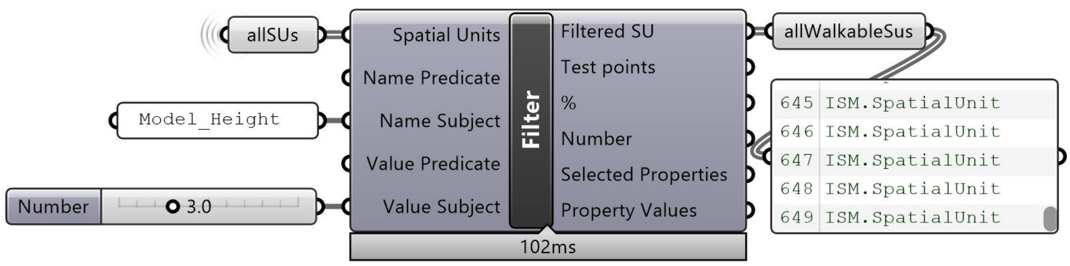


Figure 41. Case stydy: filtering walkable Spatial units.

To calculate Visibility properties the trees were chosen as a landmark geometry.

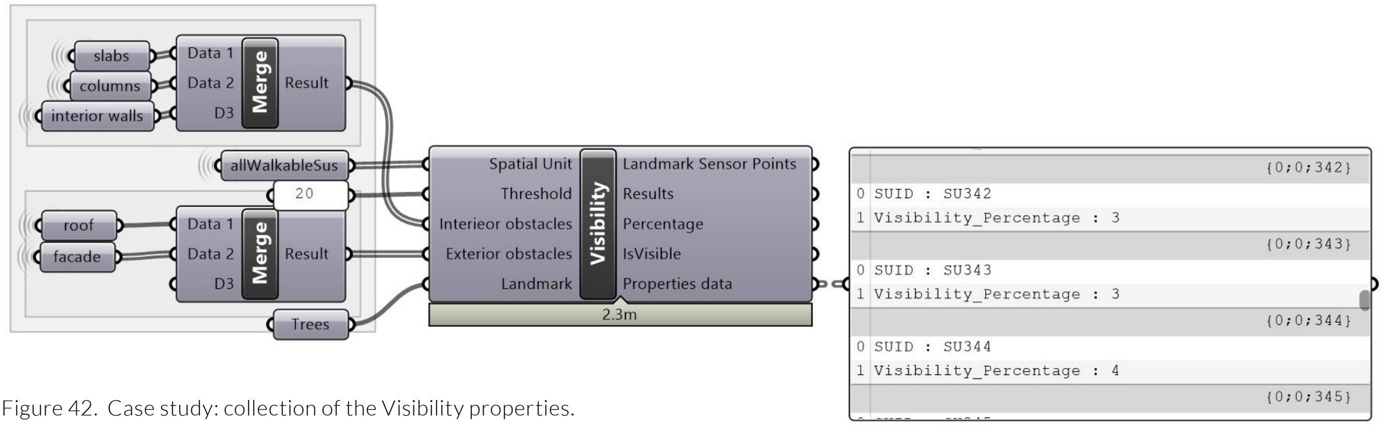


Figure 42. Case study: collection of the Visibility properties.

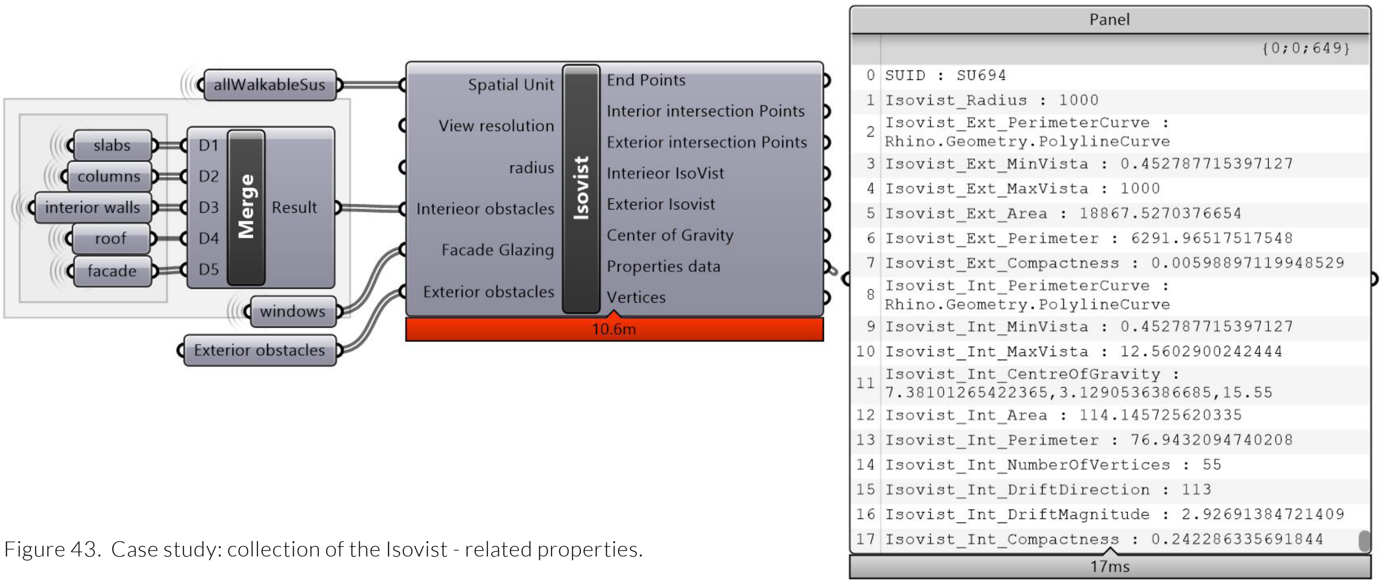


Figure 43. Case study: collection of the Isovist - related properties.

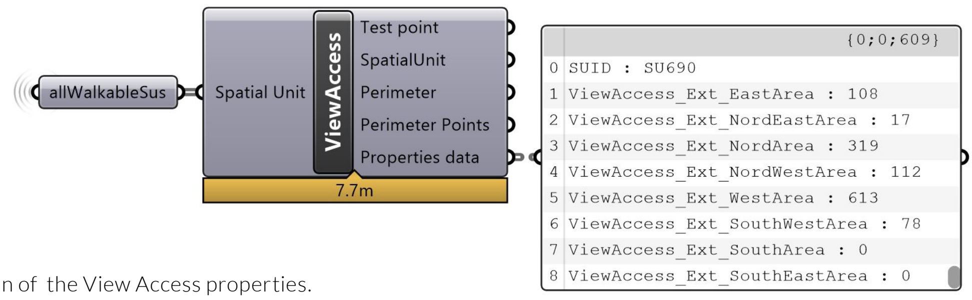


Figure 44. Case study: collection of the View Access properties.

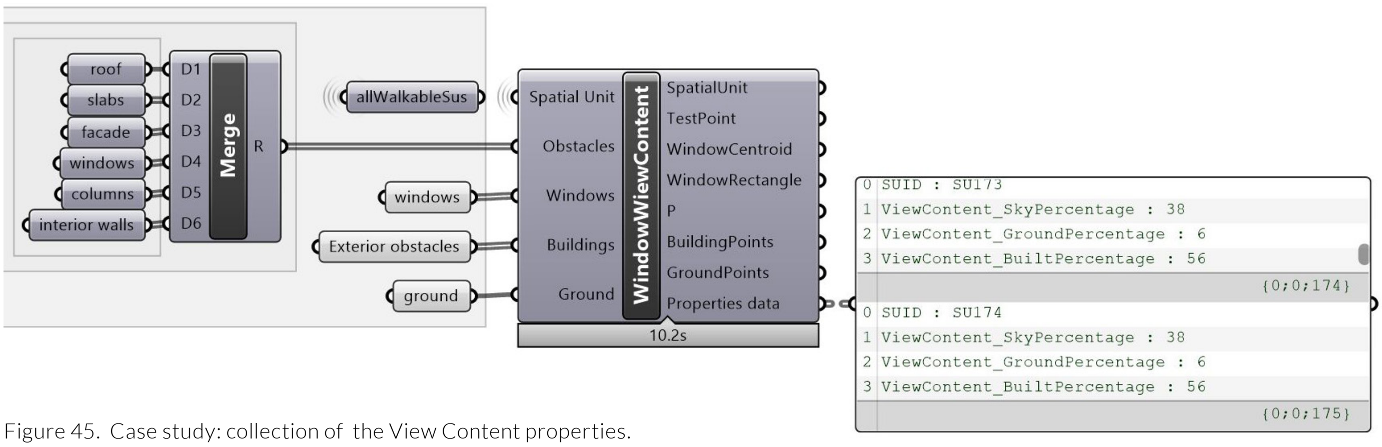


Figure 45. Case study: collection of the View Content properties.

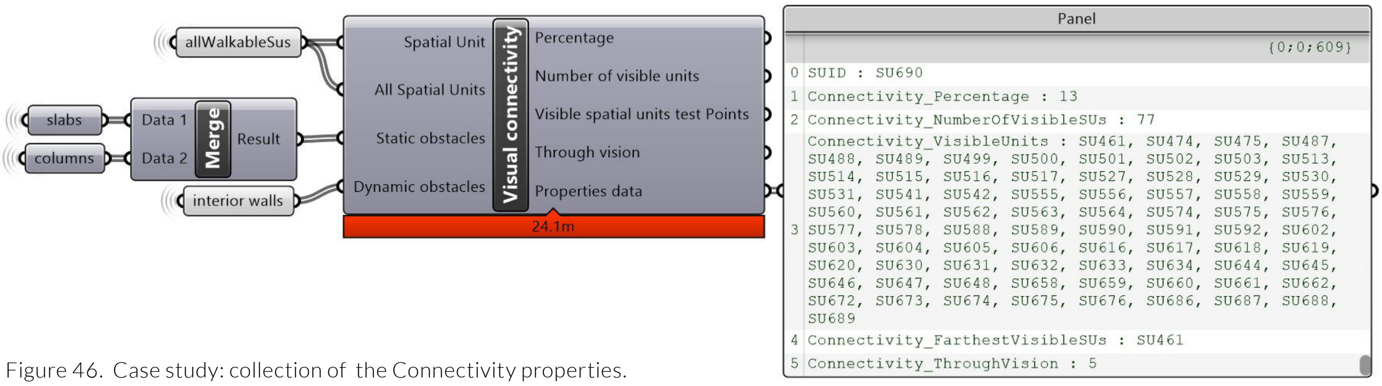


Figure 46. Case study: collection of the Connectivity properties.

3.3 Results

In total 44 Properties were collected for each of 650 units.

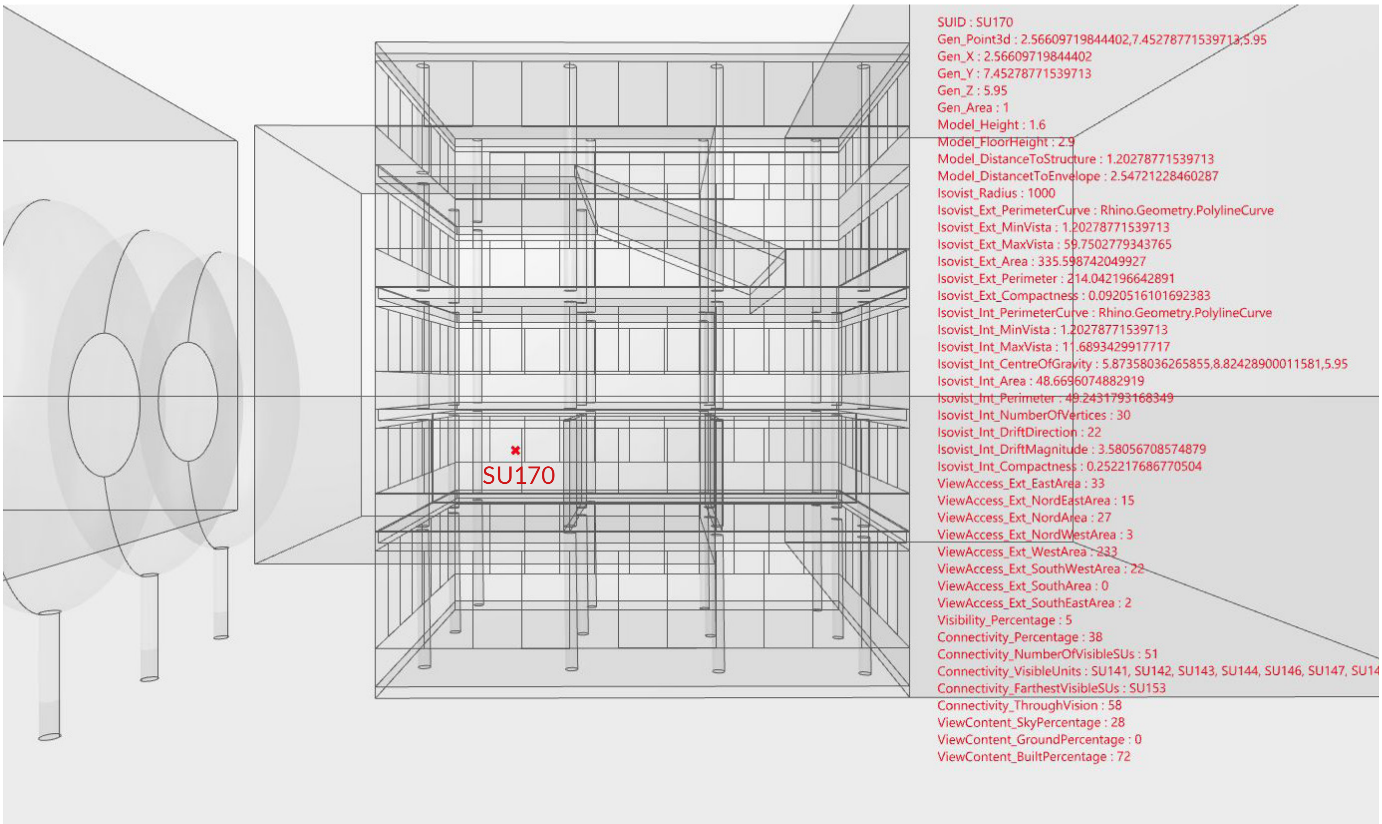
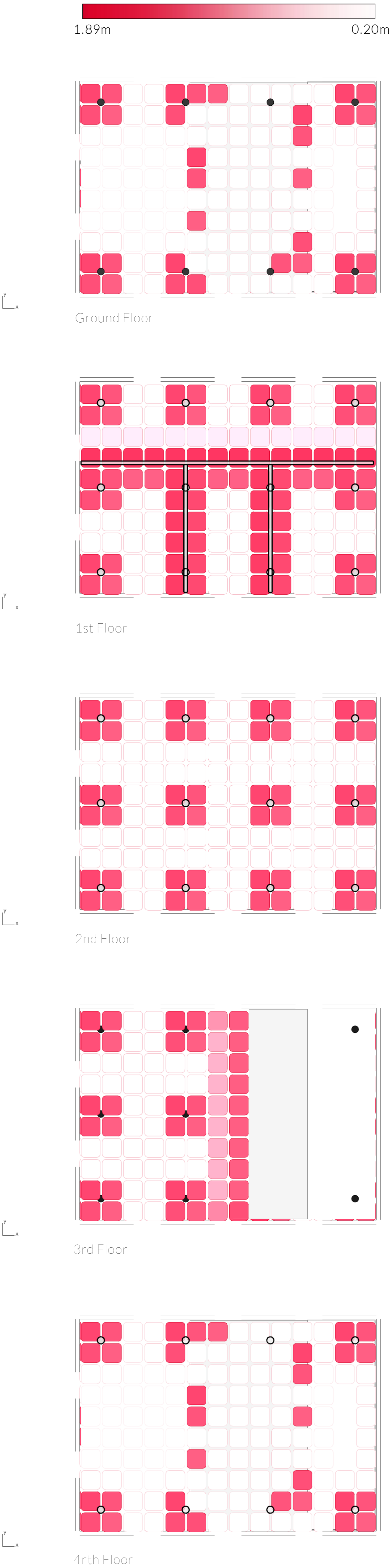


Figure 47. Case study: list of properties collected for a singe unit od space.

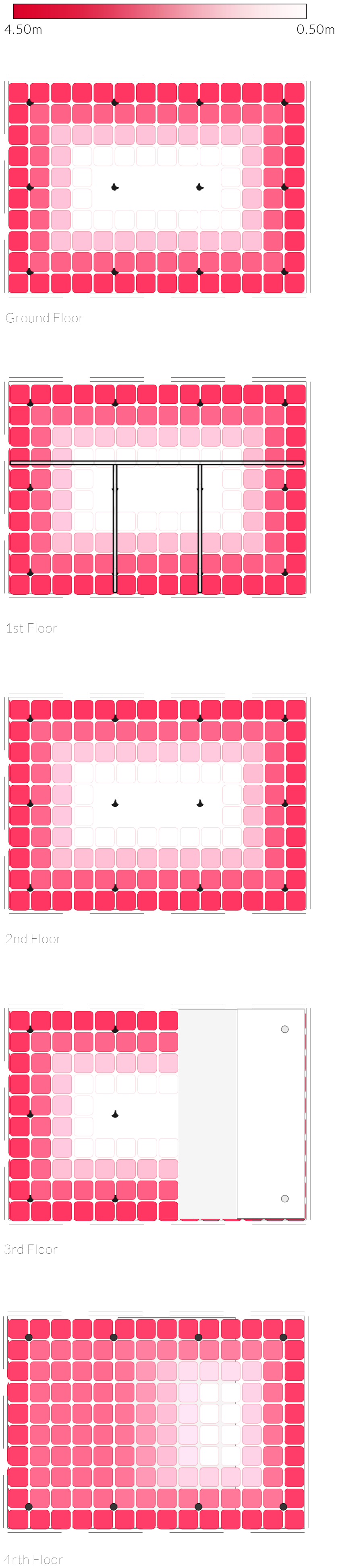
3.4 Data visualisation.

The following chapter presents the resulting values of the calculation through heatmaps applied to the floor plans. Here, the color intensity corresponds to the numerical value of the properties. The heatmaps are grouped by properties

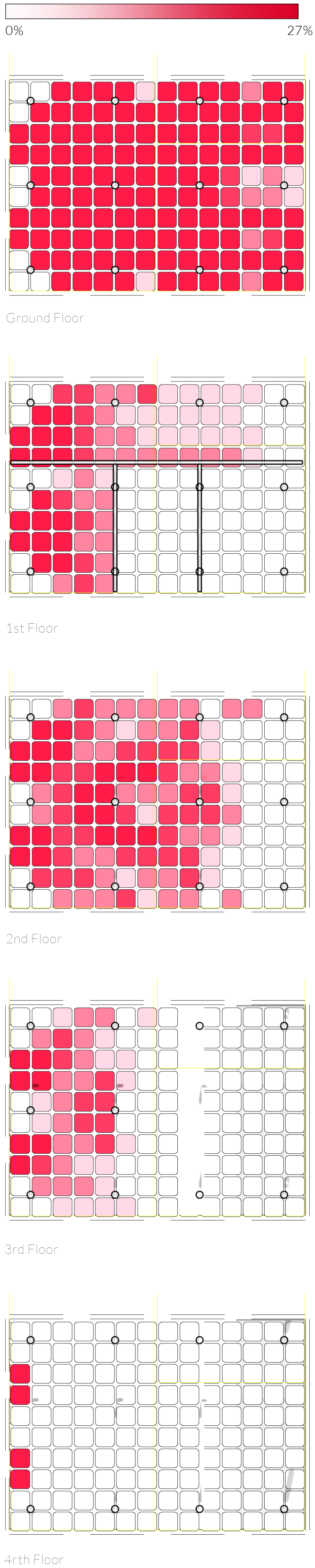
Distance to structure



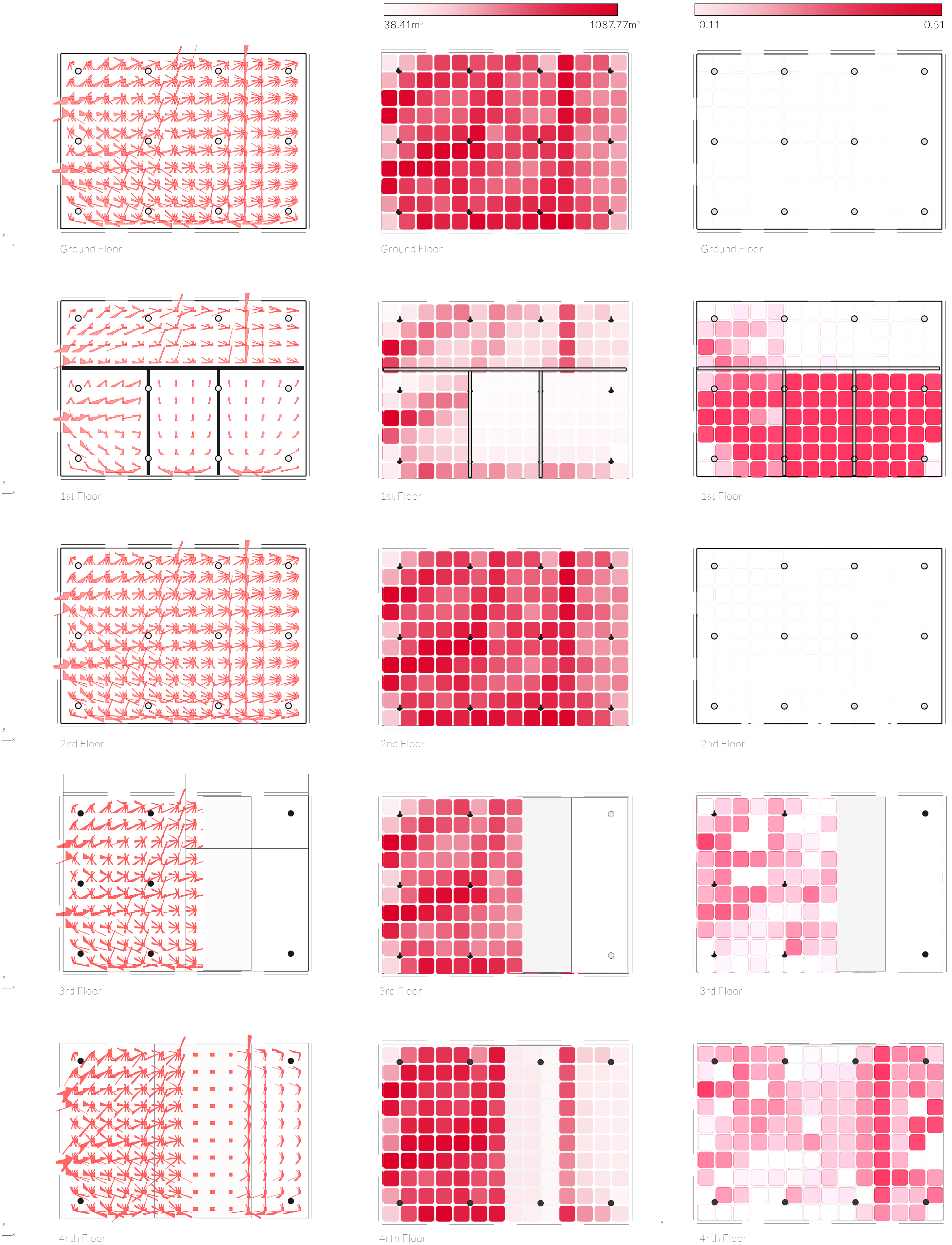
Distance to envelope



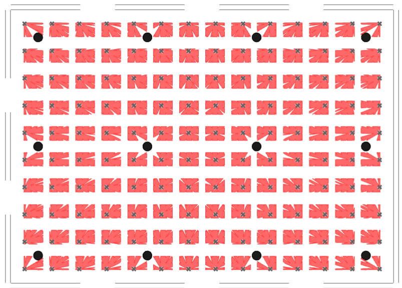
Visibility percentage (of trees)



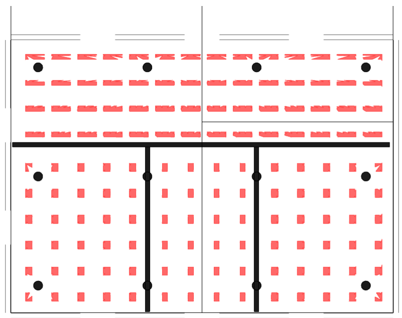
Exterior Isovist | Exterior Isovist_Area | Exterior Isovist_Compactness



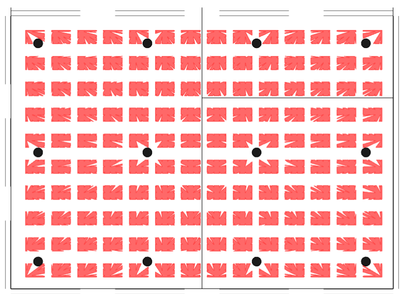
Interior Isovist



Ground Floor



1st Floor



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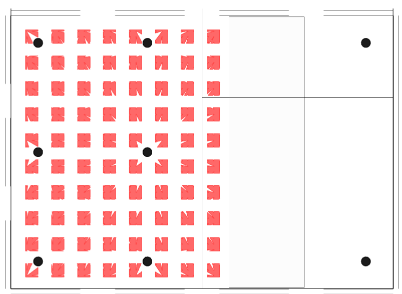

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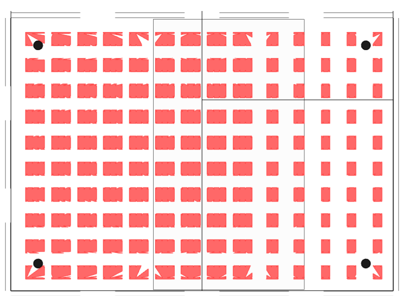
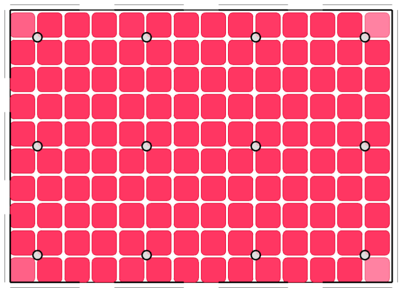


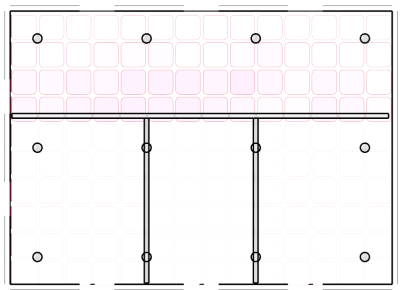
4rth Floor

Interior Isovist _Area

16..71m² 136.37m²



Ground Floor



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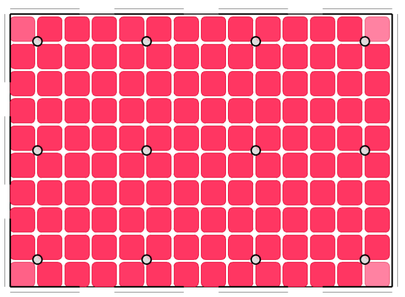

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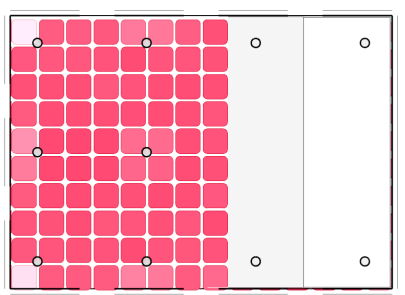

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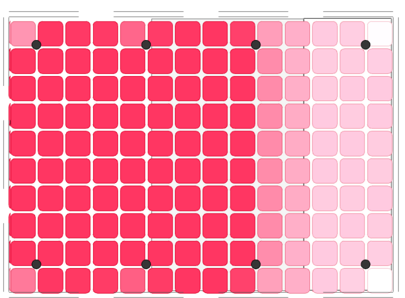
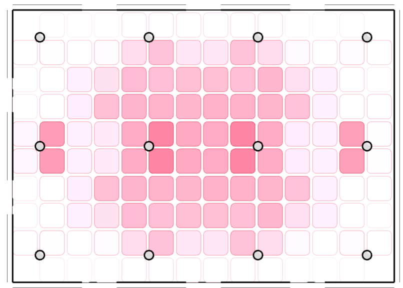


4rth Floor

Interior Isovist_Compactness

0.08 0.74



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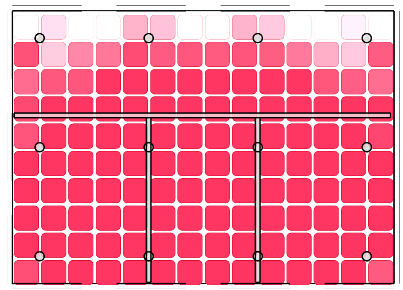

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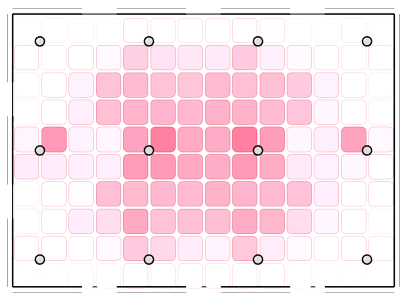

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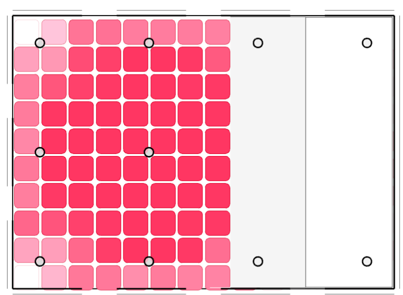

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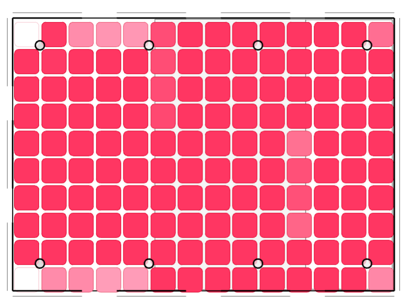
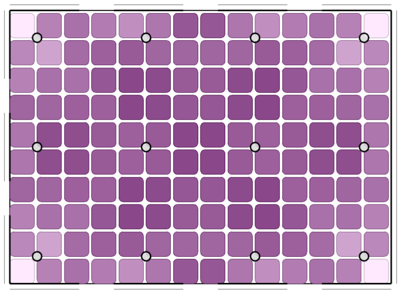


4rth Floor

Interior Isovist_Number of vertices

Interior Isovist_Drift Magnitude

Interior Isovost_Centre of gravity



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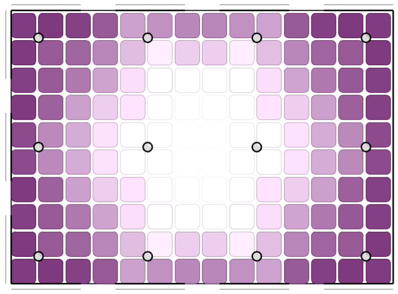

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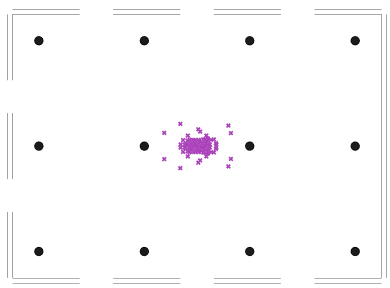

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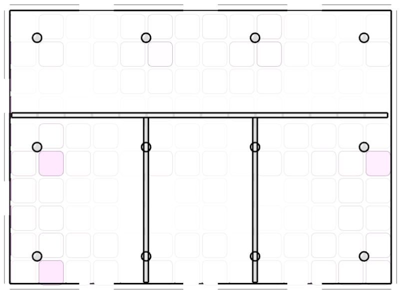

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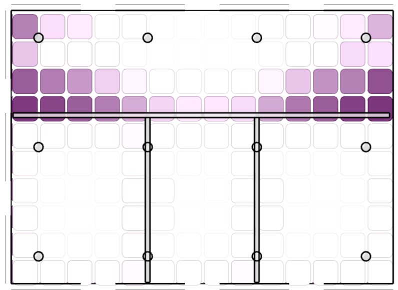

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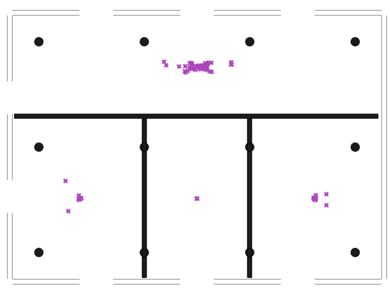

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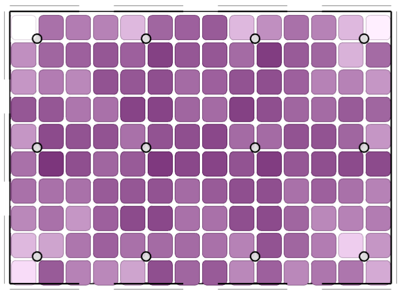

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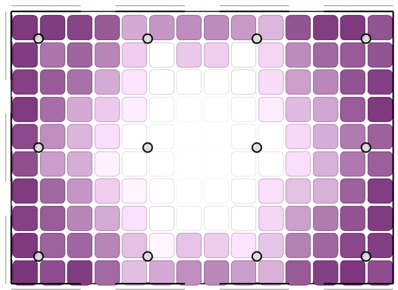

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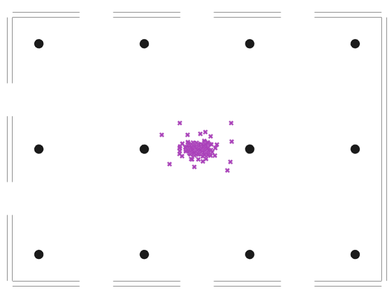

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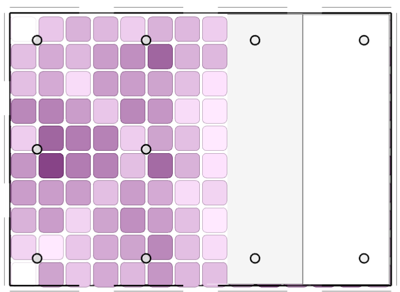

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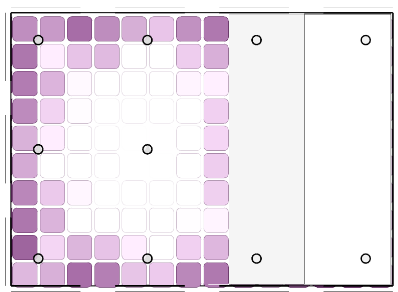

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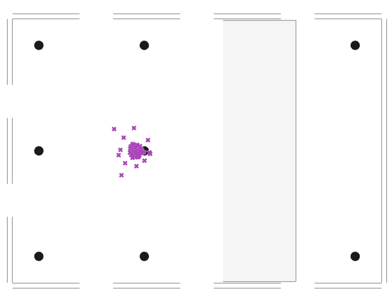

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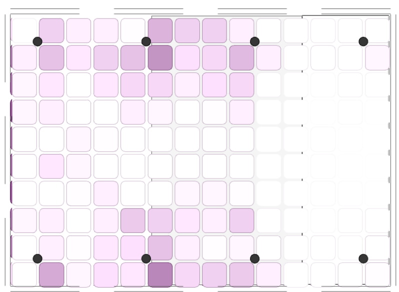
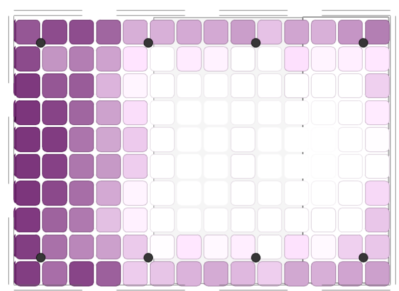


4rth Floor



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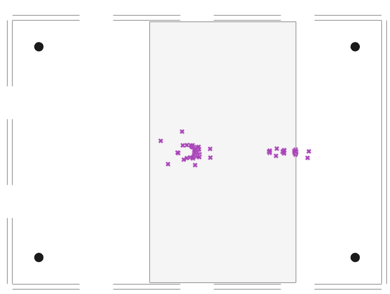
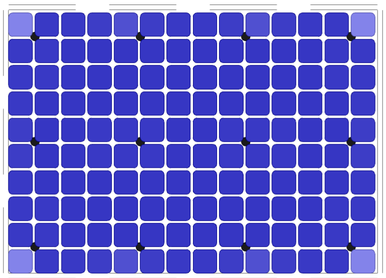


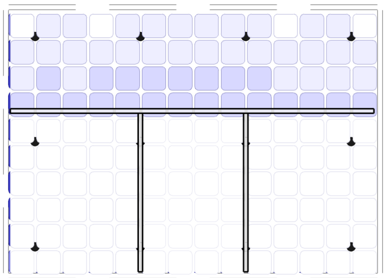
4rth Floor

VisualConnectivity_Percentage

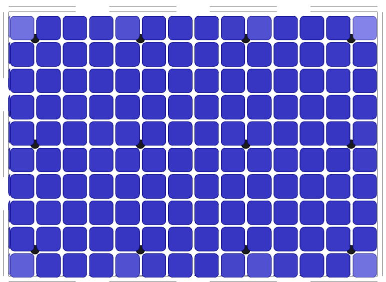
0 %   20 %



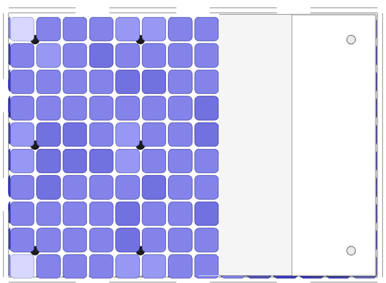
Ground Floor



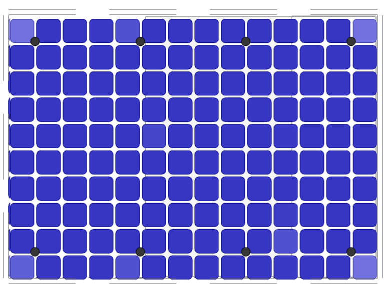
1st Floor



2nd Floor



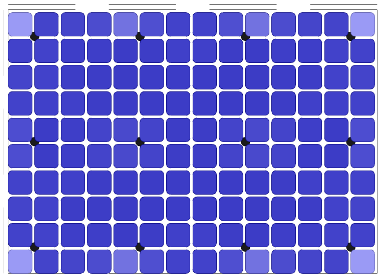
3rd Floor



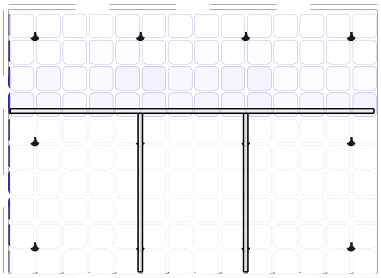
4rth Floor

VisualConnectivity_ Number of visible points

0   140



Ground Floor



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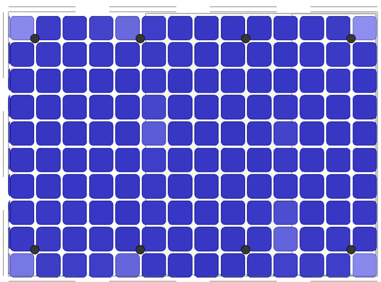

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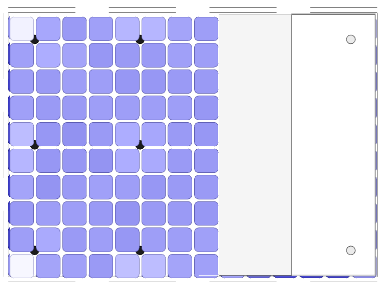

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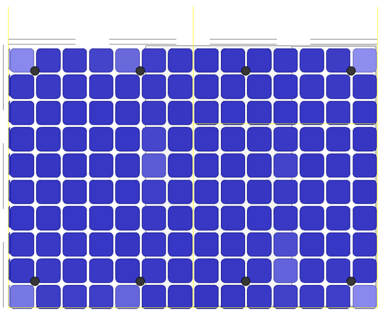
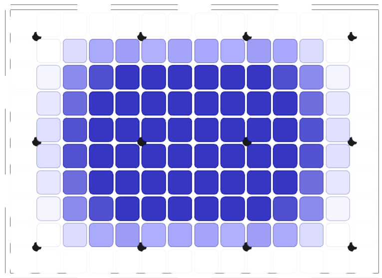


4rth Floor

VisualConnectivity_Through vision

0   366



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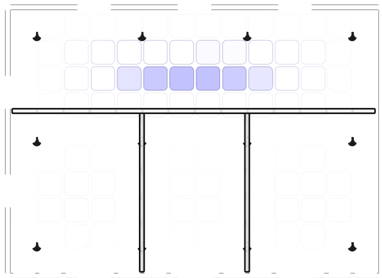

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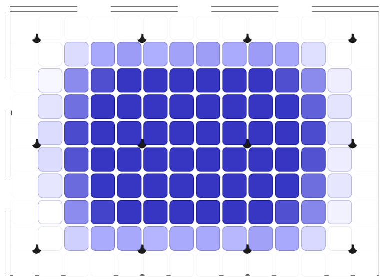

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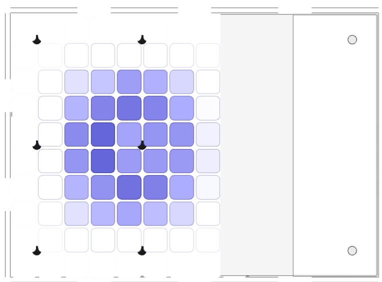

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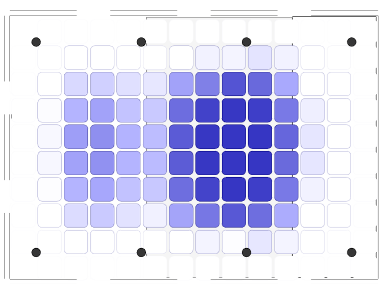
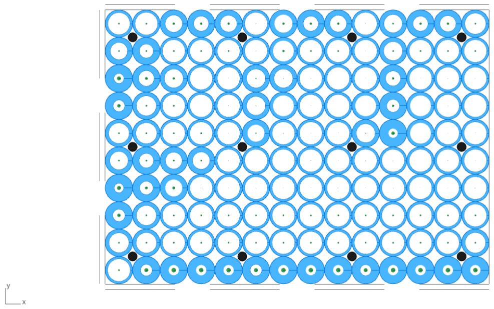
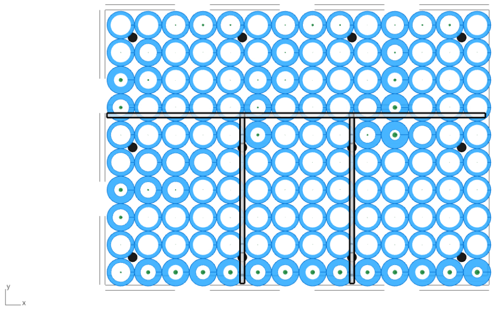


4rth Floor

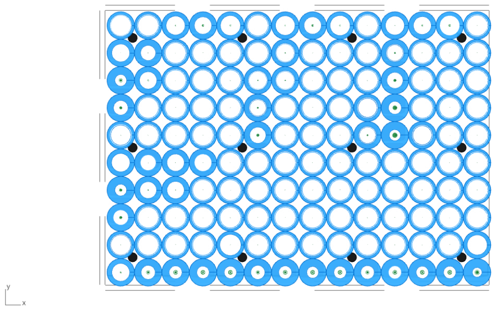
View Content



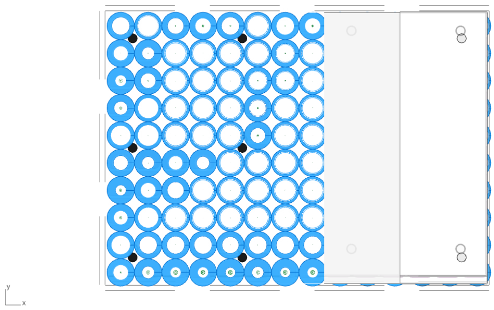
Ground Floor



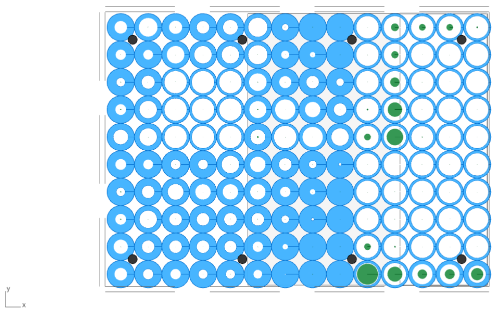
1st Floor



2nd Floor

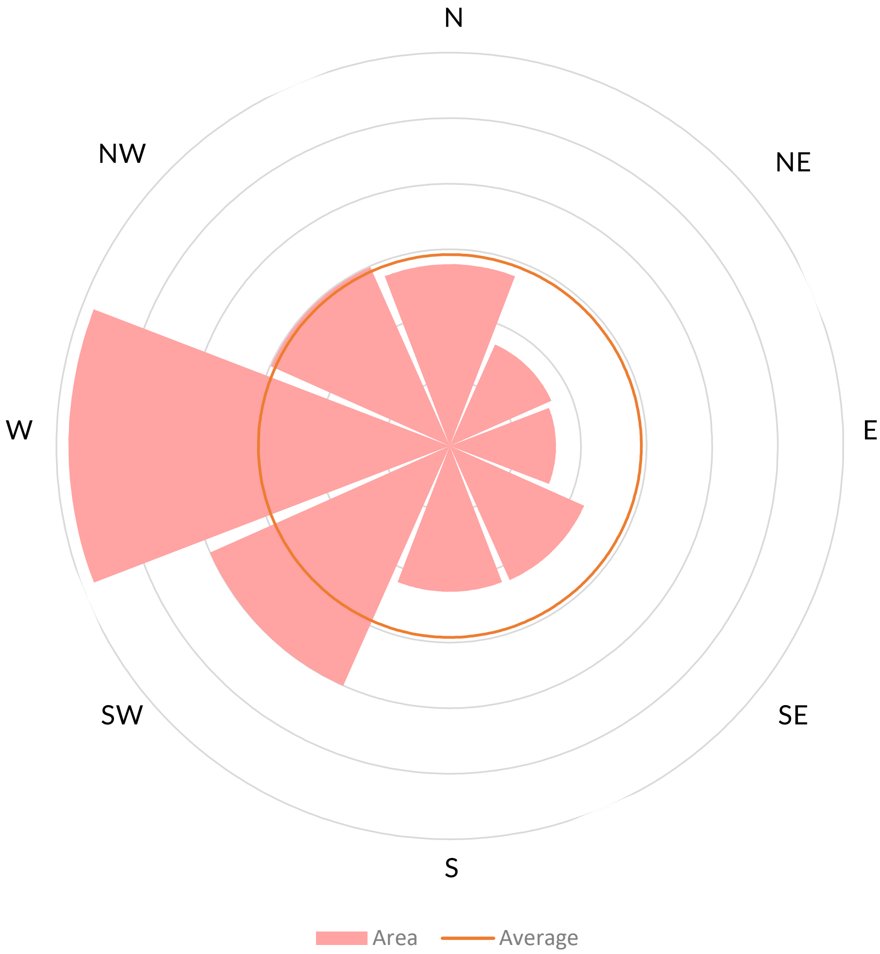


3rd Floor



4rd Floor

View Access



4 Discussion.

4.1 Summary

The proposed framework allows both assessment for local properties of the indoor spaces and for global building properties. Through the combination of filter conditions, this framework enables the identification of specific features at various locations.

Example:

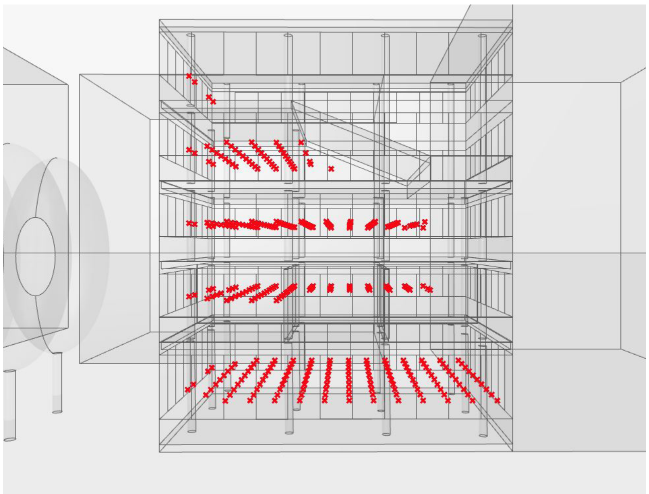


Figure 48. Case study: All units that have a visibility of more than 2% of the trees.

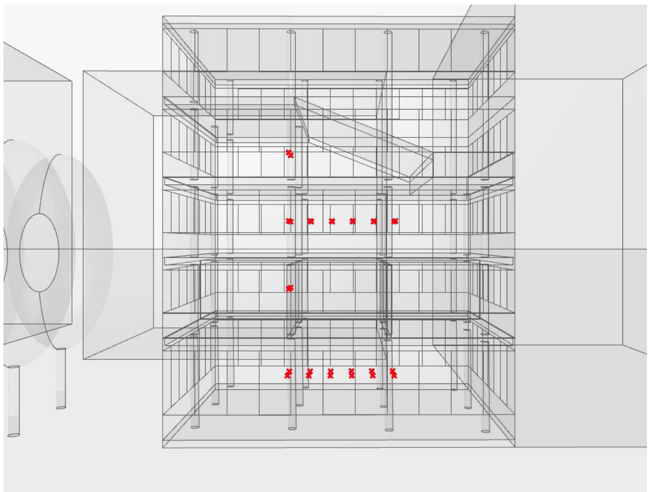


Figure 49. Case study: All units that have a visibility of more than 2% of the trees and are located at a distance of no less than 4 metres from the facade.

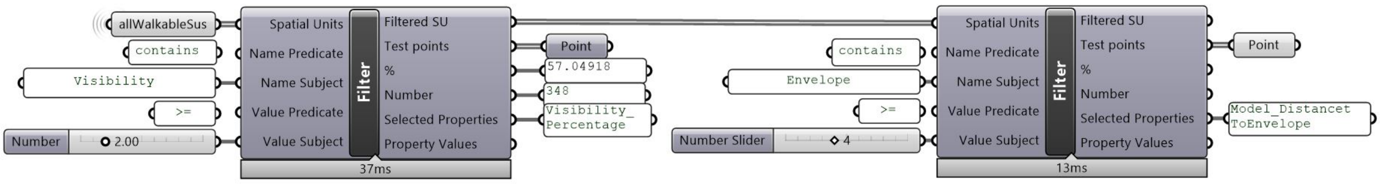


Figure 50. Case study: applied combination of filters

4.3 Implications.

4.3.1 Baseline for space quality

The proposed methodology offers a standardised set of analytical units, providing a common framework for studying human perception in the built environment. With more data collected from the different spaces it is possible to identify key space properties contributing to wellbeing of occupants.

4.3.2 Feasibilities and refurbishment .

The framework, when applied in feasibility studies for existing buildings, can help to find areas for various occupancy scenarios, giving the insight on how spaces can be adapted or repurposed, aligning with the principle of reversibility.

4.3.3 Property management and property evaluation.

For Stakeholders, such as management and property evaluators, the methodology can provide valuable insights into optimising space design for employee well-being and productivity. Property evaluators can leverage the methodology to assess and enhance the value of a property by considering human perception and well-being factors, contributing to more informed decision-making in real estate.

4.4 Limitations.

4.4.1 Absence of reference.

While the described metrics offer insights about architectural space, it is yet to be explored how their combinations work together. Given the quantitative nature of the obtained data, interpretation requires a values baseline. However, determining clear criterias for evaluating perception across diverse space types may be challenging, especially considering the relative nature of some values. Further data analysis is needed to understand how different metrics interplay and impact overall human interpretations.

4.4.2 The framework itself also raises several questions:

4.4.2.1 Size and dimensions.

Is the grid size required to be uniformly dimensioned, or should it be based on human size? Some building standards such as EN 12464-1 stipulate specific requirements, each specifying the range of accepted grid sizes for daylight analysis. These regulations also provide a designated height for the test point, taking into consideration factors such as the sitting position of occupants in office spaces. However, when discussing spaces without specific usage considerations, the unit may have multiple test points, each evaluating different properties.

For instance, the handling of unit size and dimensions in spaces with significant height remains unclear. Should we divide it by floor grid, treating each unit as walkable, or should we stack "potential" units on top of each other?

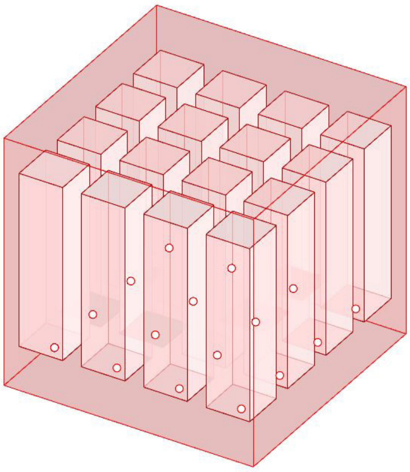


Figure 50. Spatial units are dimensioned according to the height of the space.

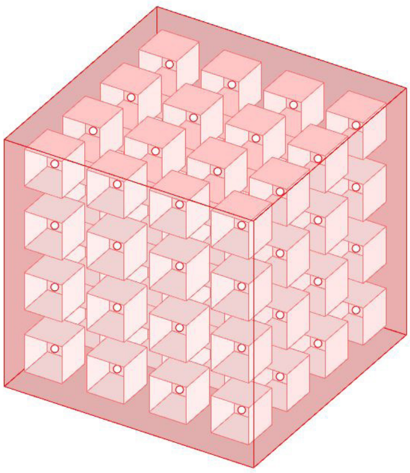


Figure 51. Spatial units are uniformly dimensioned and stacked on top of each other.

4.4.2.2 The grid type

Exploring grid geometry is another aspect to consider. In spaces like amphitheatres or stadiums, a circular grid may be more useful to align with the seating arrangement of the audience.

4.4.2.3 The model

The calculated metric is done on a model and doesn't consider real-world details like furniture or interior plants and decorations, which could act as obstacles. The same applies to features like frosted glass, stores, and louvres that may obstruct the view.

4.4.2.3 Calculations

The time complexity of certain applied algorithms is not linear (O(n)); instead, it seems to lean towards $O(n^2)$ or another higher-order complexity.

4.5 Avenues for further studies

4.5.1 Additional metrics

This paper concentrated on only one Category of metrics: spatio-visual. It would be imperative to complete the tool with Daylight metrics and metrics related to other senses, evaluating Acoustics and Air quality.

4.5.2 Sensors and occupancy patterns

Deploying sensors in buildings will allow for a more comprehensive study of human behaviour and occupancy patterns in the built environment.

4.5.3 Interoperability between tools - Universal framework?

How can the data be exchanged between different tools - can it become a part of a BIM model? Is there a way to convert the data from the units of different sizes?

5 Conclusion

Considering the psychological value of physical space, introducing tools to assess data related to mental health and comfort in indoor spaces would complement existing building energy management practices. The smart use of indoor spaces has the potential to provide numerous benefits for the well-being of occupants. By assessing data from various factors such as view quality, space proportions, daylight availability and other relevant metrics, it is potentially possible to enhance the overall comfort of the individuals occupying the space. While the proposed methodology provides a framework for measuring interior space attributes, further studies are imperative for a more profound understanding of the connections between these identified features.

6 Acknowledgments

This endeavour would not have been possible without the support of numerous individuals. I would like to express my sincere gratitude to: Icaopo Neri, Laélia Vaulot, Romain Duballet, Anton Malmygin, Bonny Nichol, Léo Demont, Tristan Gobin and all those who, in various capacities, contributed to the research — whether through intellectual insights, technical assistance, or consistent encouragement.

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