Visual Connectivity Index (VCI)

Performance Metrics to Evaluate the Ability of Indoor Space and Facade Systems to Connect to Outdoors

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DOI
10.5755/j01.sace.38.2.40998

Publication date
2025

Document Version
Final published version

Published in
Journal of Sustainable Architecture and Civil Engineering

Citation (APA)
Vásquez, C., de la Barra, P., D'alençon, R., & Da Rocha, C. (2025). Visual Connectivity Index (VCI): Performance Metrics to Evaluate the Ability of Indoor Space and Facade Systems to Connect to Outdoors. *Journal of Sustainable Architecture and Civil Engineering*, *38*(2), 19-36. https://doi.org/10.5755/j01.sace.38.2.40998

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JSACE 2/38

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Received 2025/03/24

Accepted after revision 2025/06/16

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https://doi.org/10.5755/j01.sace.38.2.40998

Abstract

Indoor-outdoor visual connectivity studies focus on analyzing view vectors and their spatial distribution, considering the three-dimensional nature of visual perception. Typically, these studies use the observer's position as a focal point from which view vectors radiate outward. However, they often overlook the multiple positions an observer can occupy in space and the various relationships these positions create with the façade system, leading to differing visual connections to the outside environment. Specialized studies that analyze multiple observer positions provide valuable insights by mapping visual connections for each location. However, they tend to lack a singular metric to assess indoor-outdoor visual connectivity as a factor influencing visual performance in relation to the space and façade system.

This article introduces the Visual Connectivity Index (VCI)—a metric designed to evaluate indoor-outdoor visual connectivity. VCI measures the relationship between a façade system and the indoor space it encloses, assessing how uniformly and seamlessly the interior connects to the exterior through the façade system while considering multiple observer positions. VCI contributes to three key areas: (1) It enables the evaluation of a façade system's impact on visual connectivity and its interaction with enclosed space; (2) It provides a performance-based measure of visual connectivity (3) It facilitates the comparison of alternative design solutions within the framework of architectural design.

By synthesizing the complex phenomenon of indoor-outdoor visual connectivity with the role of the façade in shaping this relationship, Visual Connectivity Index (VCI) presents a novel and valuable approach that has not been previously explored. To demonstrate its application, this study systematically compares the performance of 20 design alternatives across three different façade systems, resulting in a total of 60 iterations. The results indicate that VCI is sensitive to various design options, enabling a thorough evaluation of different architectural design choices.

Keywords: visual performance; visual connectivity; façade systems.

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Journal of Sustainable Architecture and Civil Engineering
Vol. 2 / No. 38 / 2025
pp. 19-36
DOI 10.5755/j01.sace.38.2.40998

Introduction

Indoor Environmental Quality (IEQ) encompasses several key factors: air quality, thermal comfort, visual comfort, acoustic quality, and user control parameters (Parkinson et al., 2019; Pedersen et al., 2021; Zuhaib et al., 2018). Together, these factors describe and quantify indoor environmental conditions. Among these, visual comfort significantly depends on occupant position and the cone of vision. Carlucci et al. (Carlucci et al., 2015) define visual comfort as the alignment of human visual needs with environmental lighting characteristics such as illuminance levels, uniformity, color rendering quality, and glare risk. Visual comfort is dynamic, changing constantly with the viewer's relative position to façade openings, affecting eye strain based on lighting conditions and viewing distance (Schiffman et al., 2010). This complexity results in visual comfort being inherently subjective, varying between individuals.

The design of indoor enclosures and façade systems critically influences visual comfort. Their optical and geometric features enable occupants to view outdoors, perceive the passage of time, observe natural lighting, colors, weather dynamics, and other changes, collectively shaping subjective IEQ perceptions. Additionally, subjective factors such as interior layouts, biophilia, views, interior aesthetics, location, and amenities significantly influence occupant well-being, though these are challenging to quantify and standardize (Al Horr et al., 2016). Efforts to measure these factors or establish standards, such as the European Standard EN17037, remain in early development stages. Evaluation using computer modeling and occupant surveys reveals discrepancies between standardized rules and actual occupant preferences, suggesting the need for refined approaches (Waczynska et al., 2021).

Research on visual comfort evaluation methodologies has significantly advanced over the past two decades, focusing primarily on view quality, visual perception, and occupant satisfaction. Existing studies broadly fall into three categories: occupant view perception, visual connectivity through vector analysis, and multivariable approaches.

Occupant view perception studies. Occupant view perception studies primarily use surveys to explore occupant perceptions related to view quality and lighting conditions. They often neglect spatial configuration, instead focusing exclusively on occupants' visual satisfaction. Examples include evaluating textile-based shading systems for view clarity (Konstantzos et al., 2015; Konstantzos & Tzempelikos, 2015), assessing lighting and views in educational settings (Vásquez et al., 2019). Additionally, research demonstrates the positive impact of distant natural views on occupant satisfaction (Kent & Schiavon, 2020), providing essential insights into holistic comfort perception independent of spatial specifics.

Visual connectivity through vector analysis. Visual connectivity research utilizes vector analyses to quantify quality and visual relationships. Visual connectivity is defined as the connection between a given viewpoint and the surrounding environment via unobstructed sightlines (Benedikt, 1979). It is calculated by determining a point p, from which you sample N evenly spaced unit directions u_i. You assign x_i =1 if the ray from p along u_i is clear, and 0 if it is blocked. Then, visual connectivity is calculated as:

$$VC(p) = \sum_{i=1}^{N} x_i u_i \quad (1)$$

At the urban scale, visual connectivity involves tracing visual vectors from fixed observer points toward external reference points. This methodology identifies visual obstructions and evaluates viewing distances and qualities within larger environments such as cityscapes or neighborhoods (Bartie et al., 2010; Sundborg et al., 2019). These analyses typically support urban planning decisions, offering insights into the perceptual relationship between urban features and their visual accessibility.

At the building scale, visual connectivity studies focus on indoor-to-outdoor relationships through the façade, employing parametric geometric modeling and vector-based techniques. This approach evaluates how occupants visually connect with outdoor environments based on window design, façade geometry, and internal spatial configurations. For example, Hwang and Lee (Hwang & Lee, 2018) propose a parametric window design informed by prospect-refuge theory, systematically analyzing occupant visual vectors through various façade designs. Similarly, Turan and Reinhart (Turan et al., 2019) introduced metrics like *Internal Visual Connectivity (IVC)*, using three-dimensional vectors to quantify visible interior spaces from given points, and extended their method to map visual connectivity between indoor spaces and external environments. These studies classify outdoor views based on type (e.g., sky, landscape), diversity, and depth, creating detailed spatial mappings. Despite this analytical strength, current vector-based methods generally emphasize precise geometrical analysis rather than comparative or iterative façade design processes, limiting their direct application in iterative architectural design scenarios.

Another method is *Space Syntax*, which analyzes spatial configurations in terms of visibility, movement patterns, and spatial interaction within buildings and urban scales (Yamu et al., 2021). Primarily, it addresses the spatial topology (how spaces interconnect visually and functionally) to influence occupant behavior and social interaction. While Space Syntax applies effectively at both urban and building scales, analyzing spatial relationships and occupant movements, it does not explicitly assess façade-mediated visual connectivity between indoor and outdoor spaces, which is the specific focus of the current study.

Multivariable criteria studies

Recent approaches utilize multivariable frameworks combining occupant perceptions, geometric analyses, and other variables to optimize window systems and façade designs. For example, Pilechiha et al. (Pilechiha et al., 2020) introduced the *Quality of View (QV)* metric, balancing visual comfort with energy performance optimization, though limited to simpler window configurations. Ko et al. (Ko et al., 2022) proposed a comprehensive *View Quality Index* based on view content, access, and clarity, providing a holistic assessment of window view quality on a standardized scale.

However, current methodologies typically evaluate visual connectivity and façade designs independently from one another or primarily as passive filters. They rarely address the façade explicitly as an active design component capable of mediating and enhancing visual connectivity between indoor spaces and the external environment. As a result, there is a lack of comparative analytical tools that effectively assess façade systems' visual connectivity performance to support iterative and informed architectural design decisions.

Research gap and objectives

To address these limitations, this study aims to:

a Integrate façade systems and indoor space into a unified analytical framework, independent of occupant-specific positions.

b Conceptualize visual connectivity as a performance-related problem, explicitly highlighting façade functionality.

c Develop a synthetic analytical instrument enabling iterative comparative analyses in façade design processes.

These objectives are addressed by introducing a novel Visual Connectivity Index (VCI), a metric designed to quantify how effectively a façade system, whether a simple opening or a complex assembly, connects interior occupants to the exterior environment.

Problem statement

Our objective is to characterize the visual relationship between any given façade system and the inner space, accounting for randomly distributed points of view. In other words, occupant location must not influence the metric: every possible point of view should contribute to the overall measure of connectivity.

For example, two façades might share the same window-to-wall ratio (20 %) yet offer very different viewing experiences. A wide, shallow (horizontal) window provides more interior vantage points for panoramic views than a tall, narrow (vertical) window (**Fig. 1**). Similarly, if identical louvers (same depth and spacing) are applied, horizontal louvers maintain broad fields of view from any interior location, whereas vertical louvers block more of the visual field depending on the observer's position (**Fig. 2**).

Fig. 1

View out comparison between vertical span and horizontal span windows, from four points of view

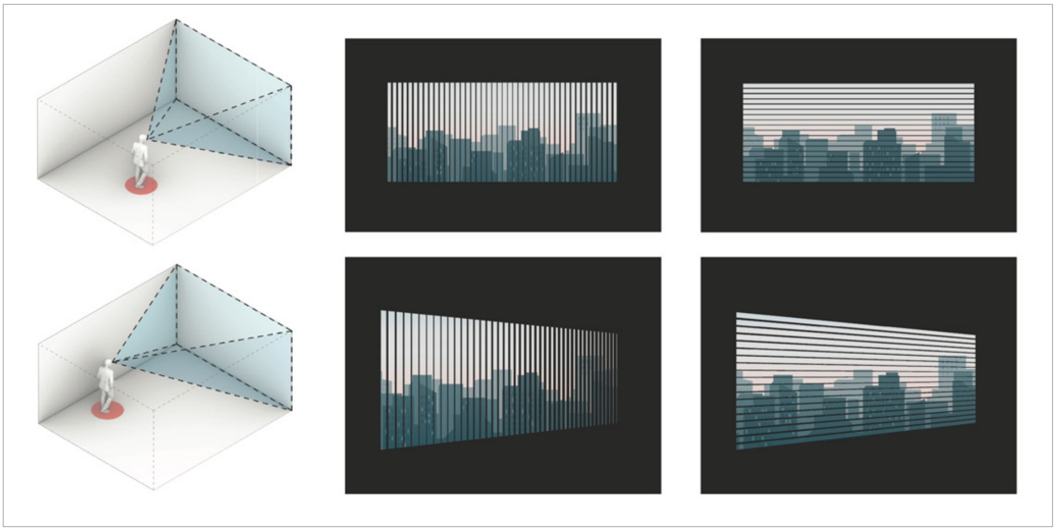
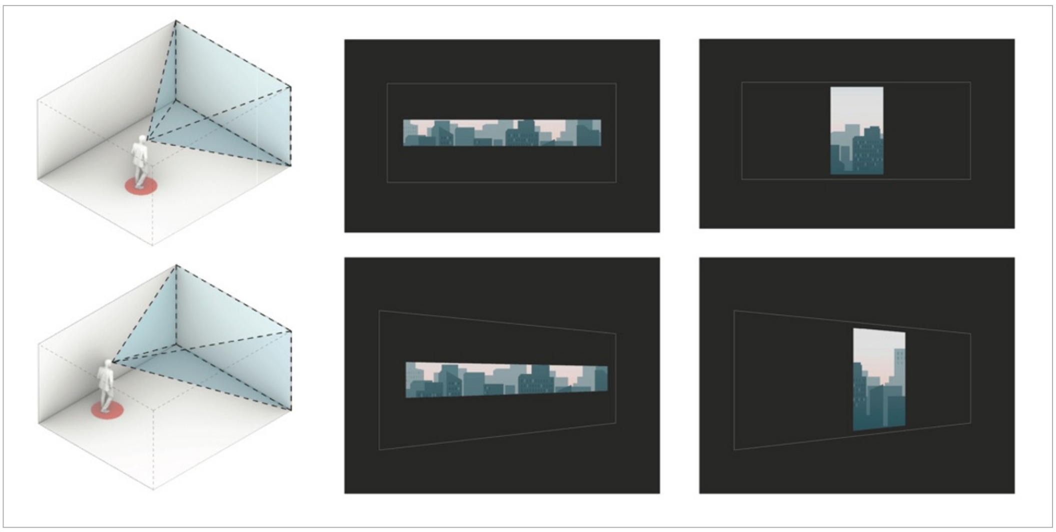


Fig. 2

Comparison between windows with vertical louvers and horizontal louvers, from four points of view



The main challenge is to condense all variations in view quality, caused by both point of view position and facade system configuration, into one meaningful number. Thus, the problem has the following aspects to consider:

- Every single point in space has a single visual connectivity to outside because internal partitions and façade system have a particular relation whit it. It is not the same to stand on front or back of space, near to, or far from internal partitions.

- Different façade systems can have the same geometrical properties, such as window to wall ratio or transparency, but not necessarily the same ability to connect inside to outside. Openings ratios and depth of elements can be relevant to inside - outside visual connectivity.
- What is expected as a good relation between façade system and inner space is to yield the highest connectivity to outside from highest number of possible internal viewpoints. On the other hand, visual connectivity must be distributed in space as uniform as possible.

Procedure to calculate the visual connectivity ondex (VCI)

VCI aims to define average visual connectivity for multiple user positions in inside space. Different façade systems can have equal visual connectivity, so complementary criterion is needed. High visual connectivity performance means good connectivity, uniformly distributed on space, and so an additional distribution criterion is needed. This complement must express how uniform visual connectivity values are, considering multiple user positions. VCI contains this value and is used as a bonus added to average visual connectivity. The result is an index that represents visual connectivity and its uniformity in space, so it represents the relation between space and façade system.

VCI is calculated through the following expression:

$$VCI = WCI + VCB \quad (2)$$

where: *VCI* = Visual Connectivity Index; *WCI* = Weighted Connectivity Index; *VCB* = Visual Connectivity Bonus

Figure 3, represents in a synthetic way the calculation sequence that allows obtaining VCI. In the following, we will explain the calculation of each of these terms.

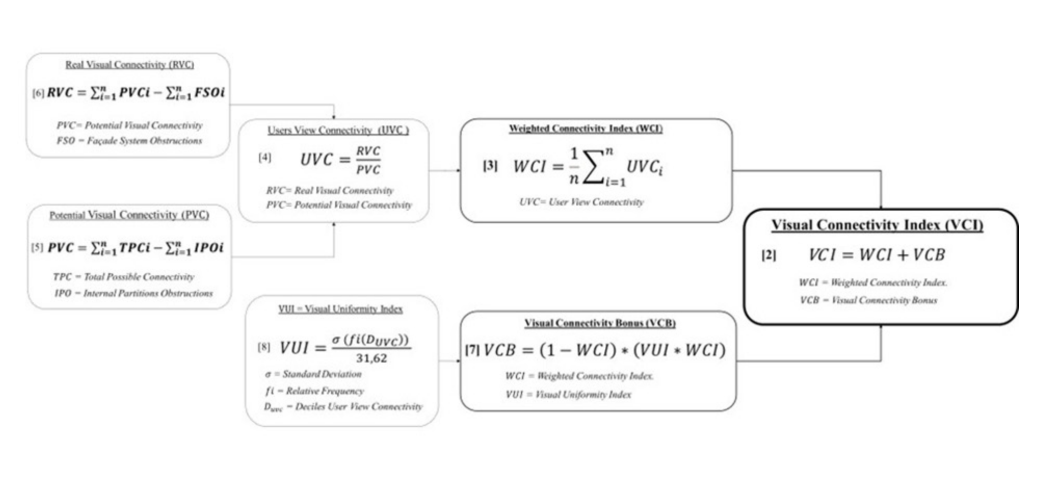


Fig. 3
Sequence of formulas that allow calculating the VCI index, numbered according to their appearance in the text

Weighted connectivity index (WCI)

WCI is the average visual connectivity of all users position inside the space or *Users View Connectivity* (UVC), representing any user position. Its calculation is summarized in the following expression:

$$WCI = \frac{1}{n}\sum_{i=1}^{n} UVC_i \quad (3)$$

where: *WCI* = Weighted Connectivity Index; *UVC* = Users View Connectivity.

User view connectivity (UVC)

UVC is the ratio between the potential connectivity that the enclosing parament could obtain, provided the façade system is completely transparent, and the connectivity allowed by the façade system and internal partitions. It expresses the visual connectivity performance that is particular for every user position and is calculated for every one of them.

UVC is defined as the ratio of the *Real Visual Connectivity* (RVC) (**FIG. 3b**) to *Potential Visual Connectivity* (PVC) (**FIG. 3a**), which would be achieved if the enclosure were completely transparent. Its calculation is summarized in the following expression:

$$UVC = \frac{RVC}{PVC} \tag{4}$$

where: *UVC* = User View Connectivity; *RVC* = Real Visual Connectivity; *PVC* = Potential Visual Connectivity.

Potential visual connectivity (PVC)

Figure 4a shows graphically PVC. It is the maximum amount of visual connection that could be possible if the façade system should be completely transparent. It is obtained by subtracting *Internal Partitions Obstructions* (IPO), which is internal space geometry depending, to *Total Possible Connectivity* (TPC), which is façade parament geometry dependent. Its calculation is summarized in the following expression:

$$PVC = \sum_{i=1}^{n} TPCi - \sum_{i=1}^{n} IPOi \tag{5}$$

where: *PVC* = Potential Visual Connectivity; *TPC* = Total Possible Connectivity; *IPO* = Internal Partitions Obstructions.

Real visual connectivity (RVC)

Figure 4b shows graphically RVC. It is the number of PVC vectors that are effectively crossing to outside, considering that the façade system functions as *Façade System Obstructions* (FSO), according to their design and components. Its calculation is summarized in the following expression:

$$RVC = \sum_{i=1}^{n} PVCi - \sum_{i=1}^{n} FSOi \tag{6}$$

where: *RVC* = Real Visual Connectivity; *PVC* = Potential Visual Connectivity; *FSO* = Façade System Obstructions.

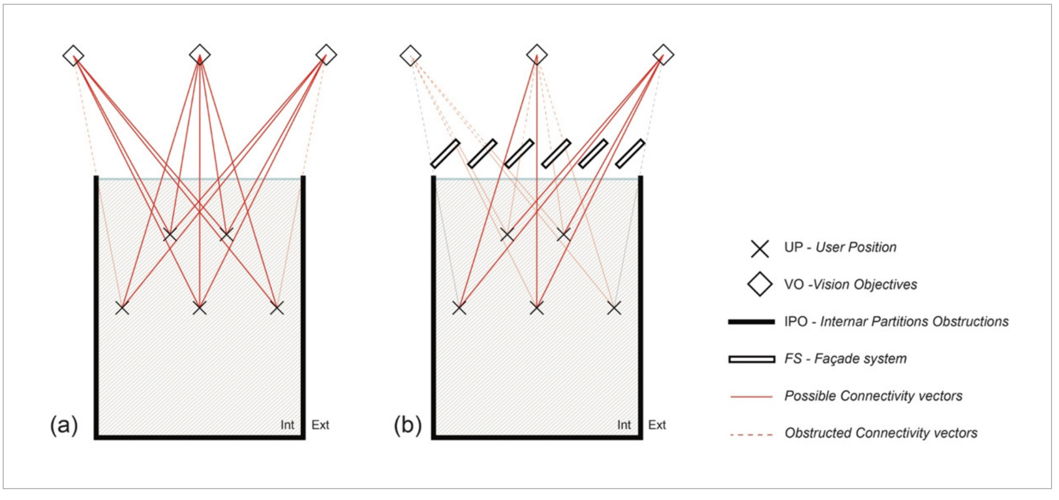


Fig. 4

(a) Potential Visual Connectivity (PVC) (b) Real Visual Connectivity (RVC)

Visual connectivity bonus (VCB)

VCB is the way to evaluate the visual connectivity on space, considering that it must be uniform as possible. It is calculated over the unconnected vectors proportion, to add a bonus to the connected ones, as established by WCI. VCB is calculated through the following expression:

$$VCB = (1 - WCI) * (VUI * WCI) \quad (7)$$

where: *VCB* = Visual Connectivity Bonus; *WCI* = Weighted Connectivity Index; *VUI* = Visual Uniformity Index

The difference (1 - WCI) establishes the ratio of visual obstructions of the façade system; *Visual Uniformity Index* (VUI), that will be explained next, assesses the distribution of visual connectivity in space, considering the range of positions evaluated; the product (*VUI*WCI*) is the bonus factor itself, determined by VUI. This bonus is applied to the ratio of obstructed connections by façade system which, when added to WCI, assesses VCI.

Visual uniformity index (VUI)

VUI evaluates UVC distribution, providing information on the level of dispersion of visual connectivity resulting from the relation between space and façade system. For its calculation, UVC is established for each considered position in space, grouping them in deciles. VUI is obtained from the quotient between the Standard Deviation (*σ*) of the Relative Frequency (*fi*) of each one of the UVC deciles (D_{UVC}) and the maximum standard deviation (*σ max*) which, for the case of 10 intervals is equivalent to 31.62.

$$VUI = \frac{\sigma\,(fi(D_{UVC}))}{31{,}62} \quad (8)$$

where: *σ* = Standard Deviation; *fi* = Relative Frequency; D_{uvc} = Deciles User View Connectivity

VUI describes how uniform the visual connectivity is between the interior and the exterior, without distinguishing if it is high or low. For instance, a shaded façade can describe the same WCI as a semi-opaque façade (**Fig. 5**), but they will be differentiated by VUI. This is why in the VCI calculation it is used as bonus index and not as an indicator by itself.

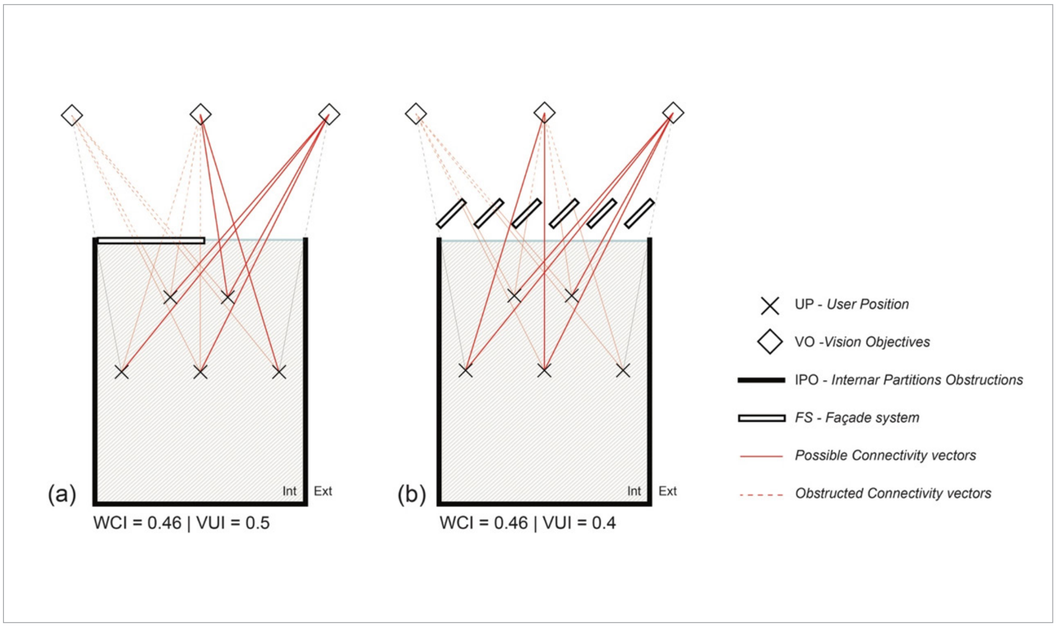


Fig. 5

Comparison between two façade solutions with equal Visual Connectivity.
(i) Semi-opaque façade
(ii) Shaded façade

Method of verification

The method to evaluate VCI is based on exploring its ability to be used as comparative index in façade design processes. To do this, twenty iterations for three types of façade systems are analysed. The evaluation was made through a programming routine in Grasshopper (Version 1.0.0007 - 2019), a plug-in of Rhinoceros 3D software (version 6 SR13 - 2019). **Figure 6** presents the model used to calculate it.

VCI relates two phenomena: interior-exterior visual connectivity and its distribution in space. Its calculation depends on three elements: The *Interior Space Geometry* (SG) (**Fig. 6d**); *Outer Space* (OS) (**Fig. 6h**); and *Façade System* (FS) (**Fig. 6i**). All three are modeled in Rhino and referenced in Grasshopper as input geometries. SG includes the enclosure interior surfaces and partitions; OS is represented as a semi-spherical surface that defines the theoretical field of view; and FS consists of planar or volumetric façade systems to be evaluated.

Within Grasshopper, a Virtual Plane of Vision (VP) (**Fig. 6f**) is defined at eye level inside the SG. A cloud of User Position (UP) (**Fig. 5e**) points is randomly generated on the VP surface, and a corresponding random cloud of Vision Objectives (VO) (Fig. 6g) is generated over the OS surface, these represent potential visual targets and simulate a full visual cone from each UP.

From every UP, straight view vectors are cast toward all VO points. The total number of vectors defines the Total Possible Connectivity (TPC). These vectors are first tested against internal obstructions (IPO) which are derived from specific obstructive elements within the SG, such as the boundary walls. Boolean intersection operations are used to identify which rays are blocked. The remaining vectors represent the Potential Visual Connectivity (PVC).

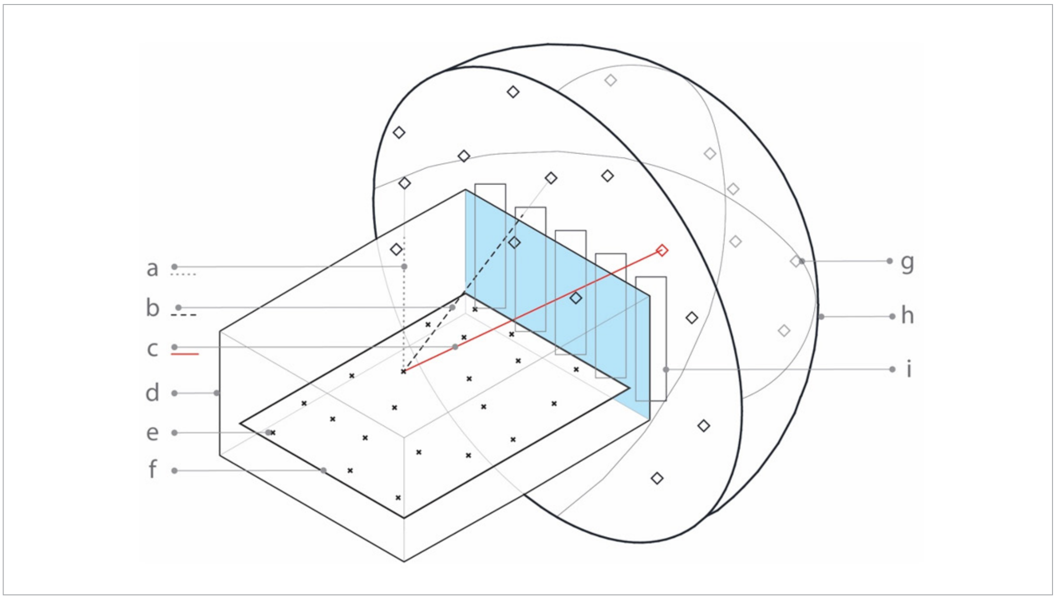


Fig. 6

Model for the calculation of VCI are: (a) Internal Partitions Obstructions (IPO); (b) Potential Visual Connectivity (PVC); (c) Users View Connectivity (UVC); (d) Interior Space Geometry (SG); (e) User Position (UP); (f) Virtual plane of vision (VP); (g) Vision Objectives (VO); (h) Outer Space (OS); (i) Façade System (FS)

To calculate the Real Visual Connectivity (RVC), the same process is repeated, now including the façade system (FS) as a second layer of obstruction. Elements such as louvers and shading devices are evaluated based on their ability to block view vectors. RVC is defined by the number of vectors that reach VO points without intersecting any geometry.

User View Connectivity (UVC) (**Fig. 6c**) is computed at each UP as the ratio between RVC and PVC. These UVC values are then averaged across all UPs to obtain the Weighted Connectivity Index (WCI), representing the global visual connectivity performance. The spatial distribution of UVC is analyzed by grouping values into deciles and calculating the standard deviation of their relative frequencies, resulting in the Visual Uniformity Index (VUI).

Finally, the Visual Connectivity Bonus (VCB) is derived by combining VUl with the obstruction factor (1 - WCI) and added to WCI to produce the Visual Connectivity Index (VCI). This final index synthesizes both the magnitude and spatial consistency of visual connectivity within the evaluated enclosure. VCI is expressed as a single value between 0.0 and 1.0, representing the overall visual connectivity performance of the analyzed façade system.

The analysis that will be presented considers an SG 6m wide, 8m deep and 3.5m high. The VP in SG has 100 UP, which means two possible observer positions for each square meter of the space and OS has 350 points as VO.

Three types of façade systems are iterated: openings (Fig. 7), horizontal louvers, and vertical louvers. In the analysis, VCI, WCI and VUI, will be presented for twenty alternatives configurations of each façade systems: *Window to Wall Ratio* (WWR) for the openings; and rotations for the horizontal and vertical louvers. The sequence will allow us to observe the relation between WCI and VUI, in addition to its effect on VCI. We will present each façade system separately.

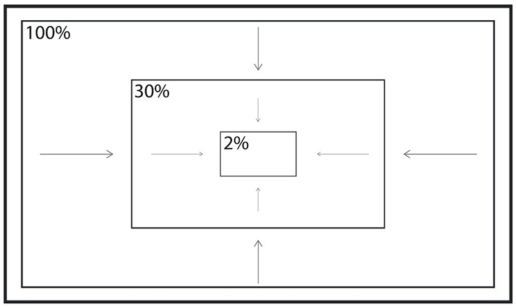


Fig. 7

Selected openings by WWR

Open façade analysis

The graph (Fig. 8) shows the performance of the three indexes (VCI, WCI, VUI) for twenty alternatives of openings, that goes from 0% to 100% of WWR. It can be observed that WCI increases correlatively with the size of the opening. However, VUI has a U-shaped performance, passes from 1 to 1, as WWR increases or decreases.

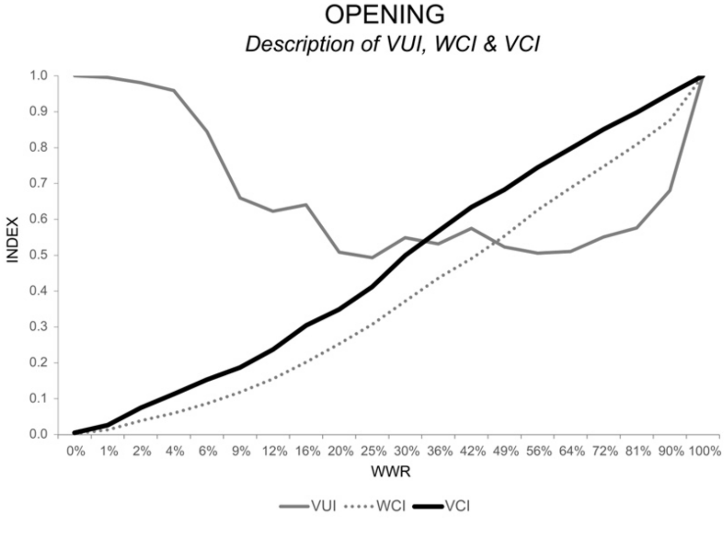


Fig. 8

Comparison of VUI, WCI, and VCI by twenty WWR alternatives

By plotting this performance on a grid, the spatial distribution of the average visual connectivity of all users position inside the space (WCI) can be observed in plan (**Fig. 9**). Three cases are selected: 2%, 30% and 100% of WWR. The distribution is represented with isolines every 0.1 of WCI in red and every 0.02 of WCI in gray. The WCI curves represent how uniform the view (VUI) is for each analyzed case: the higher slopes represent a lower uniformity of view (VUI) because average visual connectivity (WCI) is more variable; and the lower slopes represent a higher uniformity of view (VUI), because WCI varies less. Highest uniformity of view (VUI), mean that more user will be exposed to the same view conditions, whether those conditions are well or poorly connected to outside.

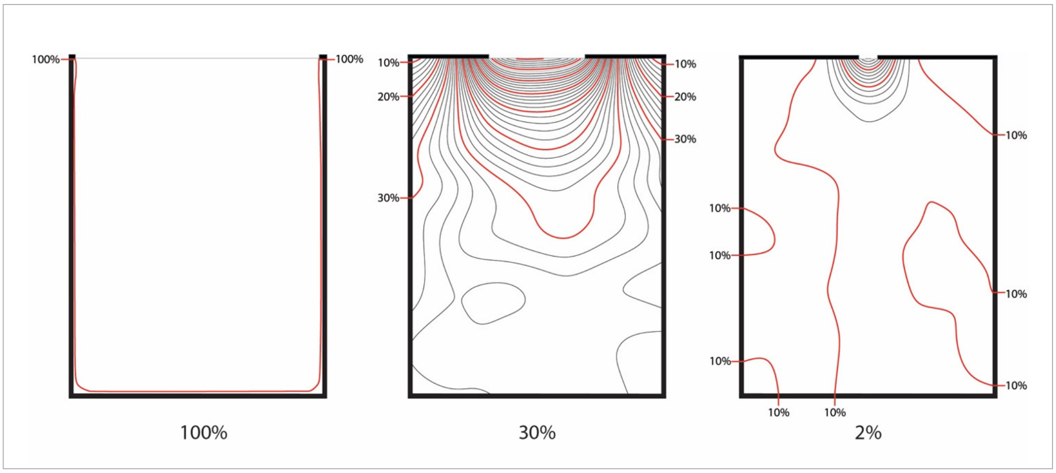


Fig. 9

Comparison of WCI isoline plans for selected WWR (100%, 30% and 2%)

In **Figure 9**, for WWR=2%, the plot presents only the isoline WCI=0.1, which represents a null slope distributed in space, that is, visual connectivity is uniformly distributed, even when obstructed, except in a small area immediately to the span where the slope is bigger. In this case, users will have uniform, albeit low, visibility in the space, except near the window where the possibility of seeing outside increases. On the contrary, for WWR=100%, the plot presents only the WCI=1.0 isoline that runs along the edge of space, without slope, which accounts for a uniformly open connectivity. In this case, users will have uniform and high visibility, that's mean better visual condition, also evenly distributed in space.

In the case of WWR=30%, the isolines are distributed showing high slopes for average visual connectivity (WCI) between 0.1 and 0.5, near the window, decreasing towards the back. This means that users located towards the back of the plan will have greater and uniform visibility between them than those who are closer to the opening, where the conditions will be the opposite.

The set of plans (**Fig. 9**) shows that visual uniformity (VUI) is equal if the façade is completely opaque (WWR=0%) or completely transparent (WWR=100%). That explains why the proposed Visual Connectivity Index (VCI) considers a bonus (VCB) to compensate this contradictory behavior.

Horizontal louvers analysis

The graph (**Fig. 11**) shows the performance of the three indexes (VCI, WCI, VUI) for twenty alternatives of lattice rotations: from 0° (open) to 90° (closed) (**Fig. 10**). We observe that WCI decreases correlatively relative to the inclination of the lattices, expressing its highest value (WCI=0.62) in the 0° position, while in 90° position its lowest value (WCI=0.0). On the other hand, VUI increases irregularly from rotation angles 0° to 90°, in a range of 0.48 to 1.0. Even though the 0° lattice position presents the lowest VUI value, with the highest WCI, the greatest VCI is obtained. That is because in closed lattice rotations positions (90°) VUI is high, but VCI works compensating this contradiction.

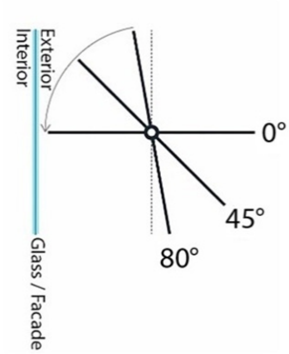


Fig. 10

Positions of horizontal louvers selected

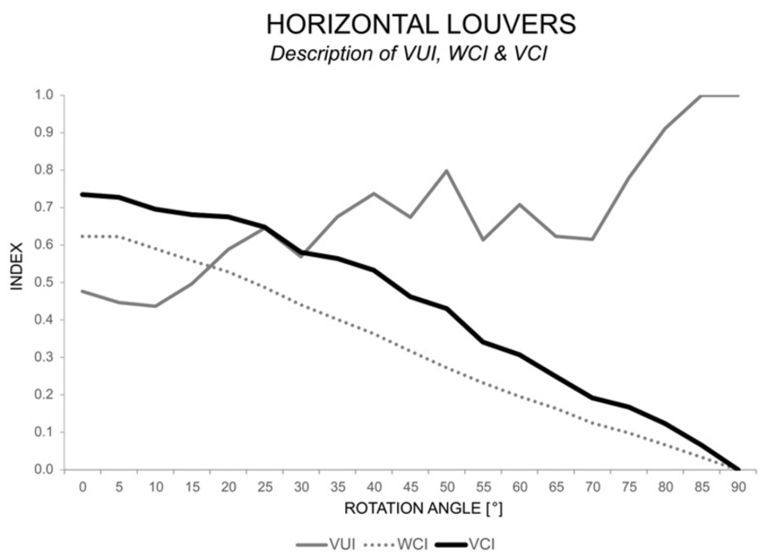


Fig. 11

VUI, WCI, and VCI for twenty horizontal louvers lattice positions, from 0° to 90°

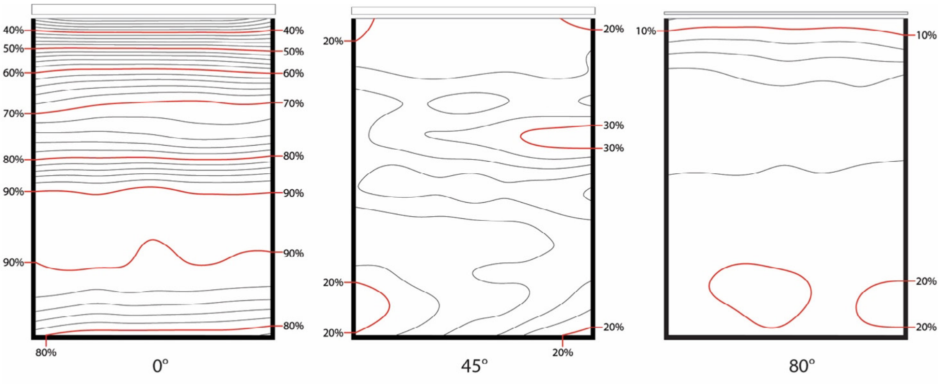
By plotting this performance on the grid, the spatial distribution of the average visual connectivity of all users position inside the space (WCI) can be observed (Fig. 12). Three cases are represented: 0°, 45° and 80° of lattice rotation (Fig. 10). We observe that in the 0° position (open) there is an extensive variation of average visual connectivity (WCI), between 0.40 and 0.90, from the front to the back of the plan, with the lowest values and highest slopes in the areas near the window and maximum values and lower slopes in the background. This means that users closer to the window will experience more variable visibility conditions and less visual connectivity than those in the background. This is explained by the effect of the visual cone, that makes horizontal elements permeable, and the highest connectivity is obtained in the deepest third of the plan.

For the 45° and 80° positions, the plot only shows a few isolines of low WCI values and low slopes because inner space is gradually closing. This shows that the visual connectivity of the lattices decreases as they are closed, however, users will be in increasingly similar conditions.

The set of plans (Fig. 12) allows us to understand that the highest connectivity works whit lowest uniformity. This situation is compensated by the Visual Connectivity Index (VCI), where the bonus (VCB) increase as the variation of average visual connectivity (WCI) increases and decreases as it decreases, which shows VCI ability to reflect the performance of visual connectivity in space.

Fig. 12

WCI isoline plans of WCI for selected horizontal louvers rotation (0°, 45°,80°)



Vertical louvers analysis

The graph (**Fig. 14**) shows the performance of the three indexes (VCI, WCI, VUI) for vertical louver rotations from 0° (open) to 90° (closed) (**Fig. 13**). In the graph, we observe that WCI progressively decreases as the louvers rotate from the open position to the closed position. The maximum WCI is 0.52, because this type of louvers obstructs laterally even in its most open position. Regarding VUI, its performance is opposite to WCI, comprising values between 0.25 and 1.0. The increase in VUI occurs from 45° to 90° (closed) since between 0° and 45° (open) VUI is almost constant. This causes VCI to obtain a constant VCB on WCI as shown in **Figure 14**.

Fig. 13

Positions of vertical louvers selected

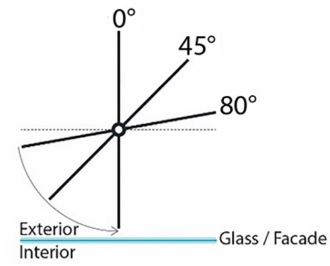
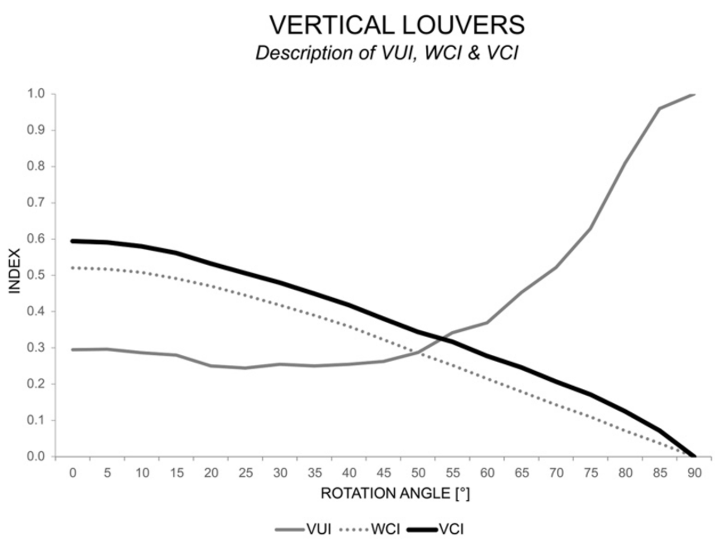


Fig. 14

VUI, WCI, and VCI for vertical louvers lattice positions, from 0° to 90°



By plotting this performance on the grid, the spatial distribution of average visual connectivity of all users position inside the space (WCI) in the plan can be observed (Fig. 15). Three cases are represented: 0°, 45° and 80° of lattice rotation (Fig. 13). We observe in all cases that the average visual connectivity of all users (WCI) distribution varies correlatively with the direction of the louvers and with greater slopes than the previous cases.

In the 0° (open) position, average visual connectivity of all users (WCI) grows head-on with constant and high slopes; at the 45° position, WCI increment is diagonal with respect to the position of the louvers, also with constant and high slopes; and in position 80° WCI is distributed in lower values and low and constant slopes.

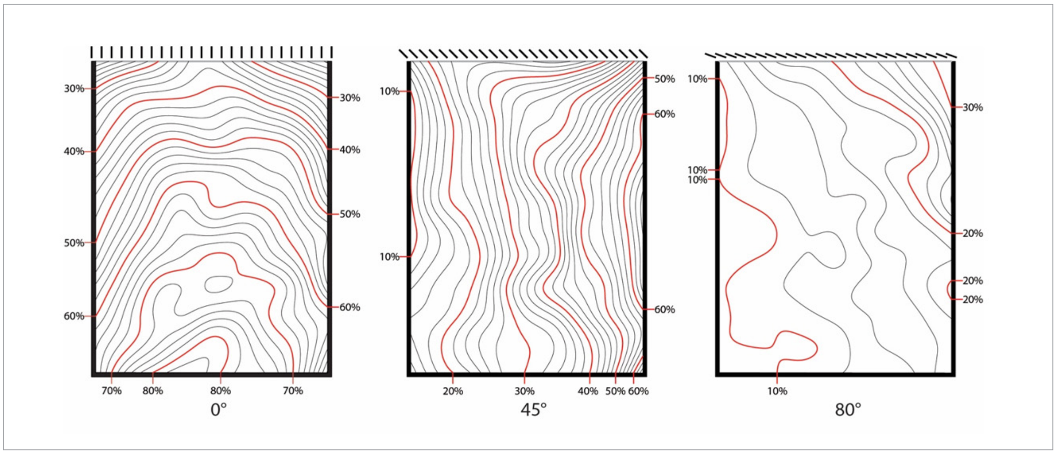


Fig. 15

WCI isoline plans for selected vertical louvers rotations (0°, 45°,80°)

The high slopes of average visual connectivity of all users (WCI) account for the lowest uniformity (VUI), varying constantly in space. For users, it means that their visual connectivity to exterior will be associate to their position in space. This behaviour is consistent up to 60° of rotation, as visual uniformity (VUI) increases, even when it does so by obstructing connectivity to the outside. In this case, VCI works compensating constantly because the VUI goes constantly and proportionally changing.

Results

As global results summary, we present in the following three analyses: VCI, WCI and VCB comparisons. The first two represent average connectivity itself and the second show the effect, while VCB is considered to express the relation between space and façade system.

Figure 15 shows the variation of WCI for the different configurations of the analysed façade systems: WWR and angles or positions for the louvers, graphed in "X" axis, progressively from the most closed position to the most open. WCI represents the average visual connectivity of the one hundred points of the inner space grid and is considered for twenty positions by every façade system type. The iterations shows how each one of them works.

As expected, openings type is the most permeable and with a constant progression since it functions as a diaphragm. The permeability of the horizontal and vertical louvers is similar, even though their maximums do not differ by more than 0.1 of WCI. They work similarly in the first quarter of closed positions, decoupling them self when permeability increases.

The ability of VCI to represent how the different types of façade work in space can be seen in Figure 17. By including VCB of each type of façade system as a bonus factor, the spatial qualities of each appear. Due to their characteristics, the openings maintain a progression between WCI (Fig. 16) and VCI (Fig. 17); however, the horizontal louvers are decoupled starting in the first quarter of opening positions, maintaining a constant difference of 0.1 to 0.15 VCI points.

Fig. 16

WCI Comparison for different configurations of openings, horizontal louvers, and vertical louvers

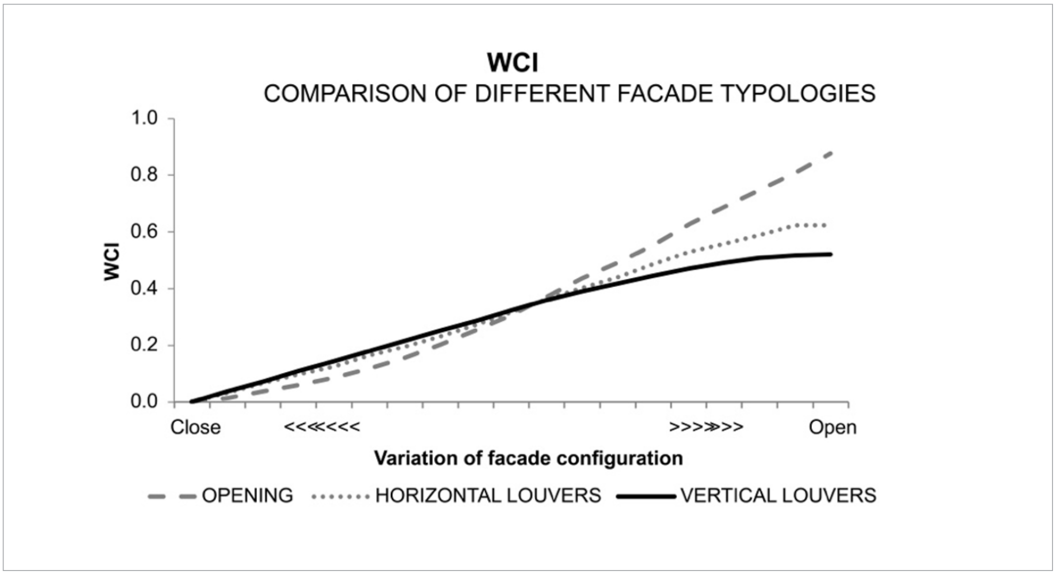
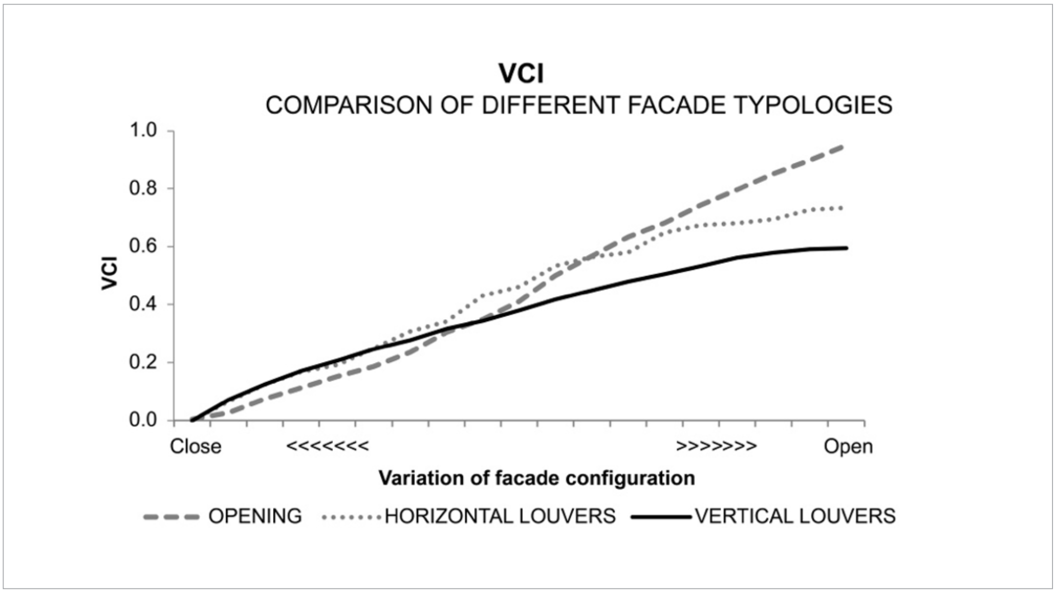


Fig. 17

VCI Comparison for different configurations of openings, vertical louvers, horizontal louvers and openings



The ability of VCI to express the relation between space and façade is evaluated by the VCB, that is a proportional relation of WCI respect VIU. The best bonus is for highest WCI and highest VIU situations. To understand it, let's back to Figure 1 and 2. The best visual perception is obtained by horizontal window and horizontal louvres, because they expand horizontally improving view out and uniformity. This phenomenon is reflected by VCI adding the VCB to WCI, that represent connectivity itself.

Figure 18 shows that horizontal louvres receive the highest VCB because they have the highest WCI and VIU of the analysed cases. The highest bonus is given to central positions when slats are parallel to visual connectivity vectors and VCB values are between 0.13 and 0.17. On the other hand, vertical louvres score around 0,6 uniformly in every open position because they do not work uniformly: opening view to half of the space and obstructing the other half. Openings work as horizontal louvres, but they have a lowest VIU bonus because the increase of WWR is always leaving an obstructed contour proportion.

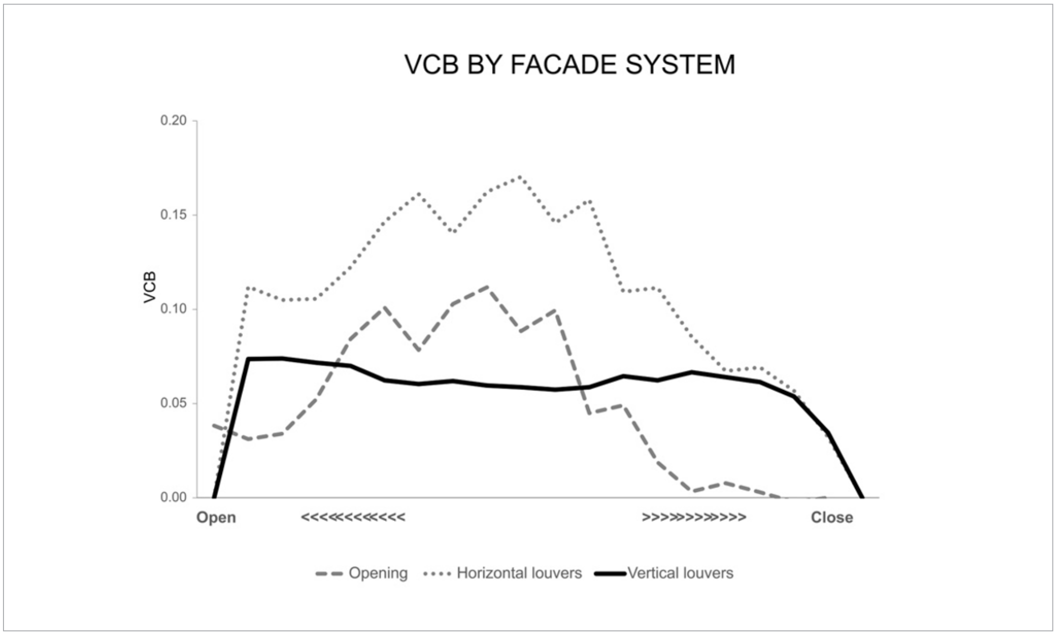


Fig. 18

VUI Bonus comparison for different configurations of openings, vertical louvers, horizontal louvers and openings

Isolines plans of WCI for three studies cases (**Fig. 9, 12 and 15**) show graphically VIU behaviour in space. Therefore, it is possible to understand why horizontal louvres (**Fig. 12**) have the best VCB compensation (**Fig. 18**). The isolines go parallel from the front to the back of the space, always parallel to the façade system. This constance and order are recognized by VCB improving final VCI.

Discussion

VCI is a new metric contributing in three lines: it allows the evaluation of the façade system and its associativity with the space, it encloses and its visual connectivity to the outside; it provides a performance measure of that connectivity; and it allows to compare alternative solutions under the logic of architectural design.

By adding WCI and VCB, VCI compensates for visual connectivity based on its behaviour in space with values between 0 and 1, functioning as an applicable performance coefficient for any type of façade and interior space geometry. Through WCI, VCI allows mapping visual connectivity, as other previous studies do, providing in addition this unique performance value. The performance obtained makes it possible to compare solutions and alternatives because their calculation always maintains the proportionality of the space and the façade facing analysed. This characteristic has not been studied in previous works.

By selection of vision targets, VCI would also allow the efficiency of visual connectivity to be assessed against precisely defined outdoor targets. Reciprocally, it would also allow us to evaluate the visual efficiency of specific areas of the plan. Other works have already presented ways of classifying what is seen from the inside through the façade. However, they do not allow synthetic performance evaluation.

The methodology developed to validate VCI allows us to compare iterations. In this case, 20 alternatives of 3 types of façade systems were compared; that is, 60 alternatives were synthetically summarized in graphs such as those in **figures 8, 11, 14, 16, 17, and 18**. This ability to synthesize a complex phenomenon, as is the relation of the façade system with the space from the point of view of visual connectivity, it is an advantage that until now had not been developed.

For future development and integration into applied tools such as those in certification systems, a multi-domain comfort approach should be addressed. Indoor Environmental Quality (IEQ) Plugins, such as DeCodingSpaces Toolbox for Grasshopper are limited to the evaluation of specific

Interior / Exterior Points. The additional value of the method proposed here is that it considers three-dimensional space as the basis of the analysis with multiple, simultaneous positions accounting for it.

Visual Confort integration should be proposed or integrated in certification schemes, thus encompassing other indicators: Daylight Factor / Glare Control / Outdoor Visual Access.

Conclusions

VCI is a tool for the design of façade systems applicable under specific conditions in any project and can be incorporated into the type of studies that analyze visual connectivity with a focus on the interior exterior connection in buildings. One of the future challenges for the development of VCI, is to link it with visual perception studies. For this, it is necessary to incorporate into its formulation aspects related to the perception of light by means of luminance and illuminance mapping to detect the probability of glare, the availability of natural light or ways to qualify the vision objectives outside. For this, there are other models already developed whose incorporation requires work to be developed in the future.

VCI emphasizes a unique aspect of the façade system, which is its ability to connect interior and exterior from a geometric point of view. This in partlimits its ability to evaluate façade systems. However, in its current state, it is possible to relate it to other known evaluation coefficients, such as solar and light transmission, to complement it and have more complete evaluations.

At the same time, VCI does not account for particular protections, such as perforated sheets and textile materials, due to its geometries or grid densities. It also does not consider all the complexity associated with vision, especially aspects of composed perception or lighting comfort, and is currently limited to a quantification of the geometry of visual connectivity. So far, only three types of façades were tested, and more complex geometries would need to be researched for further development in the future, to gain a broader understandinf of the ptentials and limitations of the indicator.

One of the characteristics of VCI is that it allows for iterative studies, so it is possible to associate it in algorithms of control of responsive façades to limit movement with a visual criterion. VCI can also become a regulatory analysis instrument as it is a performance index applicable to any type of building. Its ability to relate the interior space and the façade system would make it possible to specify the objectives that some existing certifications and standards have today.

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Simbology

VCI = Visual Connectivity Index

WCI = Weighted Connectivity Index

VCB = Visual Connectivity Bonus

UVC = Users View Connectivity.

UVC = User View Connectivity.

RVC = Real Visual Connectivity.

PVC = Potential Visual Connectivity.

TPC = Total Possible Connectivity

IPO = Internal Partitions Obstructions

FSO = Façade System Obstructions

VCB = Visual Connectivity Bonus

WCI = Weighted Connectivity Index

VUI = Visual Uniformity Index

σ = Standard Deviation

fi = Relative Frequency

D_{uvc} = Deciles User View Connectivity

SG = Space Geometry

OS = Outer Space

FS = Façade System

VO = Vision Objectives

UP = User Position

VP = Virtual Plane of Vision

WWR = Window to Wall Ratio

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