Doctoral Dissertation

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Indoor daylight performance and outdoor daylight parameters:

characterizing different cities as a basis for urban design.

Iara Gonçalves dos Santos

Technische Universität München

TUM School of Engineering and Design

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1. Prof. Dipl. -Ing. Thomas Auer

2. Prof. Dr. Eleonora Sad de Assis

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+49 89 289-22475
Deutschland (Germany)

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Erklärung

Ich versichere hiermit, dass ich die von mir eingereichte Abschlussarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Ort, Datum, Unterschrift

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List of abbreviations and acronyms

aa - Ambient accuracy

ab - Ambient bounces

ABG - ABG Statistical Consultants

ABNT - Associação Brasileira de Normas Técnicas

ar - Ambient resolution

ad - Ambient divisions

AMS - American Meteorological Society

as - Ambient sampling

BA - Buenos Aires

BIS - Bureau of Indian Standards

BO – Bogotá

CIE - Commission Internationale de l´Eclairage

DA - Daylight Autonomy

DGNB - Deutsche Gesellschaft für Nachhaltiges Bauen

DIN - Deutsches Institut für Normung

DK – Dhaka

DS - Dar es Salaam

e.g. - exempli gratia (for example)

FAR - Floor area ratio

GH – Grasshopper

GHI - Global horizontal irradiation

GIS - Geographic Information System

H/W - Aspect ratio

i.e. - id est (that is; namely)

IES - Illuminating Engineering Society

IESNA - Illuminating Engineering Society of North America

IF - Image-forming system

IAUC - International Association for Urban Climate

IBPSA - International Building Performance Simulation Association

KA – Karachi

KGC - Köppen-Geiger climate classification

LB/HB - Ladybug/ Honeybee

LBNL - Lawrence Berkeley National Laboratory

LCZ - Local Climate Zones

LI – Lima

LM - Lighting Measurements

LO – London

msDA - Monthly spatial Daylight Autonomy

NIBS - National Institute of Building Sciences (U.S.A.)

NIF - Non-image-forming system

RJ - Rio de Janeiro

sDA* - Spatial Daylight Autonomy

SH – Shanghai

SVF - Sky view factor

UN - United Nations

WBG - The World Bank Group

WFR - Window-to-floor-ratio

WMO - World Meteorological Organization

WWR - Window-to-wall-ratio

Note: non-exhaustive list. Here, the ones that relevant for the comprehension of the research.
** Because aspects of sDA diverge in literature, sDA' is used for the approach in this study.*

List of symbols

α– Alpha, significance level (statistics)

Λ – Wavelength (radiometry)

λ_v – Wavelength (photometry)

ϕ - Radiant flux

ϕ_v - Luminous flux

º – degree

cd/m^2 – candela per square meter

E - Irradiance

E_t - total illuminance on a horizontal surface

E_v - Illuminance

I - Luminous intensity

I_v - Luminous intensity

I_t : Total irradiance*

J/m^2 – Joule per squared meter

L - Radiance

lm – lumens

L_v – Luminance

N/S/E/W – North/South/East/West

nm – Nanometer

pm- post meridiem

Q - Radiant energy

Q_v - Luminous energy

s – second

sr – steradian or square radian

vs. – versus (compared with)

W – Watt

(w x d x h, m) - Width x depth x height, measured in meters

3D - Three-dimensional

* Depending upon the reference, the symbol for irradiance is E or I.

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Affiliation(s):

Technical University of Munich (TUM), Germany: 6, 7, 9, 13, 14, 18b, 19a, 19b, 21a, 21b, 23, 26b, 31, 33, 35, 36a, 37.

The Federal University of Minas Gerais (UFMG), Brazil: 2, 25, 36a, 36b.

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"my city…
I am that lover
of your narrow, short, undecided streets (...)
Singing your past. Singing your future (...)
I am these leaning houses, whispering to each other."
(Cora Coralina, own translation)

"When I am in the city I have the impression that
I am in the living room with its crystal chandeliers,
its velvet rugs, satin pillows.
And when I am in the slum, I have the impression that
I am a disused object,
worthy of being in a dumping room."
(Carolina Maria de Jesus, own translation)

"What is a livable city? (…) economic prosperity, social stability, sound social order, rich culture, convenient life and beautiful environment (…), pleasant climate, sufficient areas of Greenland, adequate hours of sunshine (…) we share the same concern for the constant improvement of the urban lives."

(Expo in the Shanghai Urban Planning Exhibition Center, China).

Abstract

Studies that group cities or regions by similar characteristics related to climate can be useful for supporting design decisions that enhance livability in the built environment. Recent examples of such studies are present in Oke et al. (2017), Hausladen et al. (2012), Reinhart (2014).

In the field of daylight, cities are being grouped by similarity in terms of (a) daylight climate (i.e., Andersson et al., 1986, Fonseca et al., 2017), or by similarity in terms of (b) indoor daylight performance (i.e., Reinhart, 2002). Both approaches have advantages. Results from the comparison of cities by the first, based on mathematical operations done using weather databases, are easier and faster to obtain than those by the second, which relies on computer simulation process. However, results from indoor performance are of utmost significance for urban design, and it is a vital step for providing detailed, assertive design solutions case-by-case.

This research investigated the combination of both approaches (a) and (b), using quantitative cluster and ranking techniques. A sample of cities was selected for comparison among the most populated in the world by 2030. Parameters related to daylight were selected and obtained for each city to conduct the comparison approach (a'). The indoor daylight performance to conduct (b') was obtained from a series of urban models for each city using computer simulation. In the end, the similarity of groups of cities formed considering (a') was contrasted to (b'), and the level of correspondence between them was identified.

This correspondence could indicate that the processing of data that is easier to obtain could serve to pre-select cities for further detailed simulation based on the aimed potential of (dis)similarity among them. This could save human-economical-temporal resources in the search for design solutions for common challenges of cities.

Detailing some of the methods, the selection of cities was done using Geographic Information System (GIS) to associate three criteria: population, global horizontal radiation and climate variation. Daylight-related parameters to compose (a') first resulted from the combination of climate data (illuminance, sky cover and sky type), and later from organized illuminance data and latitude attributes. Indoor daylight performance (sufficiency) data, based on the concept of spatial daylight autonomy (sDA), were obtained in ground floors of urban models. These were modelled based on the LCZ 1-Compact High Rise classification scheme by Stewart and Oke (2012). Adopted software included DIVA-for-Rhino, Grasshopper Ladybug/Honeybee, APOLUX, ClimateConsultants. For the comparison of (a') *versus* (b'), annually and monthly based, two cluster methods were adopted: Ward d2 visualized in dendrograms and *k-means*.

Other statistical techniques supported the data analysis.

Results indicated that the increase of urban density does not necessarily degenerate the average of indoor performance in the lower floor levels. Rooms with small windows oriented towards tall buildings of low reflectance are problematic to achieve minimum daylight sufficiency. Thus, building guidelines that limit window dimensions without considering the urban context might create poor indoor daylight conditions. From all the selected cities, one differed clearly in terms of indoor daylight performance considering the selected annual metric: London, in part due to its highest latitude among the sample. For the monthly metric, London and other three cities were found similar to each other, confirming that variability of daylight throughout the year matters in this classification. Cluster results are sensitive to the parameters and metric selected: a critical selection of the parameters before conducting the clustering process is recommended. The cluster resulting from the combination of illuminance and latitude presented better correspondence to performance than by using the combination of the three selected climate data. However, in all tested comparisons, a precise correspondence between groups generated by daylight-related parameters and those generated by indoor daylight performance was not found. As a result of this process, considering the methods, conditions, and assumptions of this research, the hypothesis was refuted: the classification of cities according to a few daylight-related parameters is not enough to indicate daylight sufficiency conditions indoors in dense and/or compact urban context.

Keywords: urban daylight climate, indoor daylight performance, climate-responsive urban design, computer simulation of performance, urban morphology, daylighting, energy in buildings, lighting.

1. Introduction

Daylight is essential for human life. It has several benefits that can be associated directly or indirectly with diverse social, environmental and economic impacts.

Indeed, daylight is important to human health, activating a sophisticated mechanism after reaching eyes and skin (Edwards and Torcellini, 2002; Boyce, 2014). Eyes are a part of two connected systems stimulated by light: the image-forming (IF) system and the non-image-forming (NIF) system. The former is responsible for visual perception and, as a consequence, for the human relation to the outside world. The latter contains photoreceptors that activate biological functions in the brain such as cell division and hormone production, including the regulation of the circadian rhythm i.e. the 'sleep-awake' cycle within 24h. In this sense, daylight is central to the proper development of human eyes, the control of biological rhythm that regulates hormones and cognitive performance, as well as to the production of Vitamin D; additionally, it is necessary for enhancing the sustainability of the entire ecosystem, including plants and animals (Aarts, et al., 2017; International Energy Agency – IEA, 2016).

Notwithstanding advances in technology, artificial lighting cannot replace daylight completely. It will still require costs throughout its life-cycle for material production, maintenance, replacement, recycling. Moreover, the general costs associated to electricity are relevant. In this regard, artificial lighting accounts for circa 0.72% of world gross domestic product (Tsao and Waide, 2010) and ca. 19% (ca. 3000 TWh) of global energy consumption. Considering building electricity consumption worldwide, artificial lighting accounts for 20% thereof, and the electricity savings potential in building lighting by 2030 could correspond to all the electric consumption of 2013 in Africa (IEA, 2016).

The use of daylight indoors can alleviate energy challenges, with advantages. In fact, the field of (day)light is being expanded from topics such as energy savings, visibility, aesthetics, comfort, to public health, ethics, livability, well-being, with benefits related to physical, physiological and psychological effects on human body, as it is being stated _ see also Commission Internationale de l´Eclairage (CIE, 2017). Notwithstanding, the knowledge on design for daylight indoors is not widespread. A study across architecture universities in Europe indicated illiteracy in "*daylighting metrics, regulations, assessment tools and software*" (Giuliani et al., 2021). The situation in other regions is probably not very different.

Another critical point refers to daylight deprivation. This can be intensified in dense, compact and verticalized urban agglomerations. Nevertheless, this form of built densification is being promoted as a partial design solution to accommodate the increasing urban population, which is projected to grow by 2.5 billion people until 2050 (United Nations – UN, 2015).

The lack of daylight is already being affiliated with public health issues such as epidemic levels of myopia in urban environments, a problem that can grow since humans currently spend the majority of their time indoors _ an average of 90% is estimated for Americans and Europeans (Aarts, et al., 2017). Not without reason, the expression "*the indoor generation*" is found in non-academic medias[1]. Considering the fact that population is aging and living longer under retirement and/or mobility restrictions, combined with the increase in opportunities for people of all ages to work from home through digital resources, the time spent indoors tends to be longer. This, in spaces sometimes not designed for well-being. The alert that the total daily light exposure of people in industrialized societies is too low for their well-being according to different researches (CIE, 2004)[2], combined to the awareness of the importance of daylight for human development, reinforces the need for solutions to promote indoor daylight.

As energy consumption is expected to increase, changes in markets, policies and practical implementations are necessary (Aktuna, et al., 2016). In the fied of urban design, instruments such as guidelines and standards are relevant tools to avoid energy consumption or the risk of daylight deprivation. However, "*codes are still based on mostly outdated scientific data and need re-examination in the light of more recent research*" Aarts et al. (2017, chapter 4). Existing instruments in design for daylight are mostly based on simplified performance assessment principles, e.g. static condition of the sky, which might be unsuitable for certain locations and have negative implications for occupants. In the field of indoor daylight, results of investigations under more realistic sun and sky conditions in different time frames are being accurately demonstrated since the late 1990's, providing conditions for supporting a transition to guidelines based on climate-based daylight modelling through dynamic metrics (Mardaljevic and Christoffersen, 2013).

At the urban scale, the awareness of the problem of rapid urbanization and the importance of daylight promote the development of such instruments. For that, it is essential to understand how urban morphologies affect indoor daylight. This is a complex task due to the interaction of diverse factors. Examples are the effects of shadowing and inter-reflections in the urban context. About this point, Samuelson et al. (2016) remember that, due to accelerated development, both design teams and policy makers need to work considering unknown surroundings. Urban databases of existing surroundings of an area, such those potentially provided by Geographic Information Systems (GIS) or CityGML, might not serve as useful primary reference in the design for the future of these agglomerations.

[1] Google search, Nov/2018.

[2] Total daily exposure are discussed in terms of lux, considering all sources of light, daylight included.

Studies to support the development of updated, climate-based design strategies and instruments for promoting access to indoor daylight are urgently needed, but are also still rare.

Comparative studies might speed up the process of understanding indoor daylight behavior and thus enhance the development of design solutions that might be used as a reference for multiple cities. This particularly pertains to the cities with similar[3] parameters related to daylight, such as outdoor daylight climate, which might exhibit similar indoor performance conditions. This correspondence between indoor daylight performance and daylight related parameters, concentrating on climate, represents the focus of this study.

The necessary minimum amounts of indoor daylight are being widely discussed with a focus on image-forming and minimum conditions for visibility, for the purpose of safety, execution of tasks (productivity), and/or avoiding to switch artificial lights on. Usually, reference is made to minimum illuminance levels (lux). Indoors, these amounts are being defined with the support of static metrics, a simplified approach that considers given phenomena under a specific position of the sun on a selected day and at a selected time of the year, focusing on a targeted sky condition – usually the overcast sky type. This approach is helpful, but it can underestimate the daylight potential. In response to this, dynamic metrics are being proposed as an alternative in order to widen the knowledge of indoor daylight performance by considering variations in outdoor climate conditions. The variations comprise sky conditions and sun positions within the analyzed time frame. An example of a dynamic metric is the spatial Daylight Autonomy - sDA, considered "*the best descriptor for daylight performance*" in a space in terms of 'daylight sufficiency' after a comparison of metrics (Heschong, 2012).

Studies tackling such minimum levels can benefit from computational advances. Indeed, researches on daylight are being enhanced through new computational tools, hardware and software, as well as the diffusion of programming languages. These tools are becoming indispensable in dealing with the increasing complexity of urban factors, but also with the advances of the topic of daylight itself. Examples thereof are the researches by Cheng et al. (2006a) and Martins (2014), who investigated indoor daylight conditions in urban context using static metrics; by Mardaljevic et al. (2011) and Reinhart (2014), who assessed indoor daylight in test rooms using dynamic metrics; by Reinhart et al. (2013), Saratsis (2015), Santos et al. (2017), and Dogan and Park (2018), who evaluated indoor performance within urban sites also using dynamic metrics. Studies based on the comparison of cities considering variations in aspects such as the climate and urban model, using computer simulation and quantitative techniques, can be useful to understand the dynamics of urban morphologies and their effects in daylight. In this context, this research is proposed.

[3] "Similar" in the context of this research is synonymous with analogous, comparable, related.

1.1. Research proposal

1.1.1. Knowledge gap

In the field of daylight, interesting studies were presented by Reinhart (2002) and by Fonseca et al. (2017). The former compared cities based on results of simulation of indoor daylight performance using a dynamic metric. The latter compared cities based on climate data, which are relatively simpler to obtain.

More specifically, Reinhart (2002) compared and grouped cities located in the USA and in the south of Canada, considering a pre-defined number of five groups. The indoor daylight performance was obtained for a test room using Daylight Autonomy metric. This approach takes into consideration how daylight effectively interacts with the built environment in a temporal interval, and how effective it tends to meet the occupants' needs. The city-by-city simulation is necessary for detailed design proposals, but it is complex: requires several different types of input data, sophisticated knowledge in building dynamics, skills in the application of specific software. Depending upon the level of detail of the model(s), the algorithms in the software, and the capacity of the available hardware, it can be also a time-consuming process. Such study enhances the understanding of daylight performance similarity among cities, being valuable for providing a preliminary comparative panorama of daylight indoor behavior in different locations.

Fonseca et al. (2017) proposed a daylight zoning for Brazil by comparing municipalities, focusing on data for sky cover and global horizontal illuminance. The study resulted in a map with three daylight zones and considerations about the method and parameters adopted. Interestingly, the data of these parameters are easily accessible for several cities worldwide, even free of cost, while algorithms are available to compensate for the absence of data in some regions. The resulting information provided by daylight climate zoning on a macro-scale can be precious for different fields. However, although this zoning aimed to provide useful information for building design, the information can not be directly converted in practical input and orientation for designers, that need to understand the influence of its parameters on indoor daylight conditions considering different urban/architectural configurations or locations. To that end, indoor daylight performance simulation would be the proper approach, which is exactly what the previously mentioned study has done. Alternatively, both approaches could be applied complementarily, and this point is the root of this proposal.

Thus far, no methods have been found that compare and group cities both in terms of daylight climate and by daylight indoor performance simultaneously, aiming to provide information as to favoring daylight in the design of dense, compact, verticalized urban context. Additionally, quantitative information on the similarity between cities and the discussion regarding the relevance of these differences for indoor daylight design were not found.

In summary, this research proposes the development and application of a framework to compare cities both in terms of outdoor daylight-related parameters and indoor daylight performance, extracting information during and upon completion of the process that might be useful for urban morphology design focused on daylight sufficiency. Specifically, it starts from the search for a correspondence of similarity between daylight climate and daylight performance, considering that the easier access to the former could speed up the finding of similarities of the latter.

In the future, these comparative studies could serve as a tool for selecting different cities that could, potentially, use similar strategies for indoor daylight performance based on the similarity of certain parameters, i.e., certain climate conditions. The possibility of versatile application, at least in theory, is aligned with the aim to optimize resources - methodological, human, conceptual and financial - in the search for effective design solutions for cities.

Considering the above-mentioned aspects, the investigation revolves around the following research questions and hypothesis:

1.1.2. Primary Research question

Is the similarity of cities considering a limited number of daylight-related parameters an indicator of their similarity in terms of indoor daylight performance under dense, compact, verticalized urban context?

1.1.3. Secondary Research questions

- Do cities with similar outdoor daylight climate have similar indoor daylight performance in a dense, verticalized urban context?
- How to group cities by similarity in terms of different daylight related parameters and indoor daylight performance?
- Which parameters related to weather data that can influence daylight in a sample exhibit a high degree of correspondence to performance?
- Do different simulation variations alter the results of similarity among cities?
- Do the variation of the time frame of a metric alter the results of similarity among cities?
- Considering a sample of cities, which of them are the most similar to each other in terms of daylight performance? And in terms of daylight climate parameters?
- How increasing urban density (compactness) affect indoor daylight levels?

1.1.4. Hypothesis

Classification of cities according to a few daylight-related parameters is enough to indicate daylight sufficiency conditions indoors in dense, compact urban context.

1.1.5. Objectives

- Analyze the state-of-the-art studies of indoor daylight performance through computer simulation, as well as current guidelines on the topic, related performance metrics and parameters that are relevant for daylight indoors,
- Identify and integrate existing methods and techniques that allows comparison of different outdoor daylight-related parameters and indoor daylight performance for the purpose of this work,
- Find ways to reduce the number of inputs of the models for urban daylight simulation to a number that is sufficient to complete the experiment with coherence, including by testing characteristics of urban models that can favor daylight indoors,
- Check in a sample of simulations how the increase in urban density (compactness) can affect indoor daylight levels in different cities,
- Discuss the potential of applicability of methods and techniques to other studies and generalizability of study results to other cities.

1.2. Structure of the Research

This Chapter 1 (Introduction) provides the context of the research proposal, the hypothesis, research questions, research structure and summary of the research paradigm (Figure 1).

Chapter 2 (Background) provides a literature review with respect to basic concepts linked to the urban daylight climate, metrics for daylight assessment, classification systems for climate-based design, guidelines and other instruments for pomoting indoor daylight, studies of daylight performance using computer simulation, as well as proper statistical techniques for comparisons and data analysis.

Chapter 3 (Methodology) presents the development and implementation of the framework to guide the investigation, which is composed by four main steps:

a) selection of cities for study;

b) climate parameters related to daylight: data collection and analysis;

c) indoor daylight performance: data collection and analysis;

d) comparison of parameters extracted from weather files *versus* daylight performance.

Chapter 4 (Results and Discussion) presents and discusses critically the outcome of this study, focusing particularly on the application of the framework and test of the hypothesis, and commenting on relevant information gathered in the process of parametric simulations, climate data preparation, and tools used for statistical comparison.

Chapter 5 (Conclusion) comprises a panorama of relevant results regarding some of the addressed topics (daylight climate data, performance simulation, urban guidelines), critical evaluation of the chosen methods and overall framework, lessons learned in the process, as well as identified opportunities for future studies.

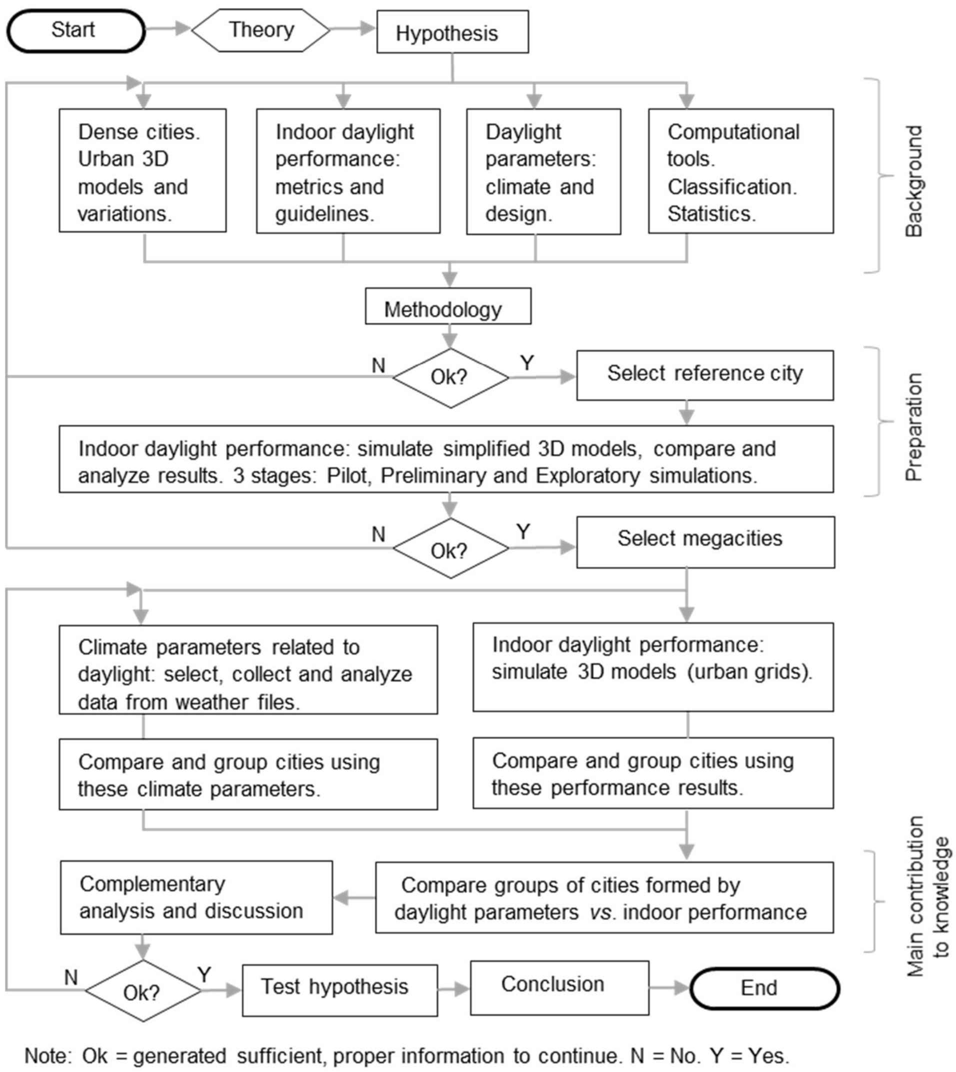


Figure 1: Flowchart of the general structure of this work. Source: own author.

1.3. Summary of the Research Paradigm

Research Paradigm: Positivism

Title: Indoor daylight performance and outdoor daylight parameters: characterizing different cities as a basis for urban design.

Ontology:

Space: Urban morphology/geometry. Elements of design for indoor daylight that are influenced by urban designers/planners. Instruments (design guidelines, etc.) to enhance indoor daylight performance.

Non-space:

Climate. Dynamic daylight. Urban daylight climate. Indoor daylight performance. Daylight-related parameters. Metrics for performance. Simulation model. Classification as a basis for comparison.

Epistemology: Empiricist.

Hypothesis: Classification of cities according to a few daylight-related parameters is enough to indicate daylight sufficiency conditions indoors in dense, compact urban context.

Methodology: Inductive

Literature review, computer simulation, advanced statistics.

Results:

I) Framework for test the hyphotesis was developed, tested and critically evaluated.

II) Upon application of the framework, the hypothesis was refuted.

III) In this process, relevant information was collected, especially regarding daylight simulation, daylight guidelines, weather data gathering, and classification systems.

IV) International cities were compared and grouped by daylight-related parameters and by indoor daylight performance under urban conditions using a dynamic metric.

Highlights:

1) A method for climate and performance comparison was developed and tested using advanced statistics and a sample of ca. 22% of future megacities worldwide.

2) Studies on computer simulation, classification systems, climate and design parameters, metrics, as well as guidelines for design favoring indoor daylight were reviewed.

3) Weather data were obtained using software in which new features were developed for the purposes of this study.

4) Studies on indoor daylight performance using a representative dynamic metric were conducted, considering the effect of design on dense urban sites, including shadowing and inter-reflectances on higher levels than the ones found in literature.

5) Example of guidelines for design based on indoor daylight performance were proposed (to be refined in future studies).

6) Limitations of the proposed approach and opportunities for future works were discussed.

Axiology (Values):

Daylight is essential to livability in cities, especially for human health and sustainable ecosystems. Therefore, access to daylight is a right that should be protected and promoted.

Energy savings indoors profit from minimum illuminance levels during the daylight hours.

Densification through verticalization and compactness is alternative path for pursuing urban sustainability.

Research and solutions for urban design can benefit from the assessment of daylight climate parameters and indoor daylight simulation.

Climate transpose geopolitics. The same can apply to urban design solutions, minding local (in)tangible heritages.

2. Background

This Chapter presents a literature review in the field of daylight with a focus on studies related to computer simulation and urban design, aiming mainly to:

a) clarify basic concepts on which this study relies,

b) set the theoretical basis to develop a framework to test the hypothesis, and

c) choose methods and elements for testing the hypothesis, including main literature references for comparison, suitable software, input data, performance indicators (metrics) and statistical techniques, among others.

The method of Systematic Literature Review (SLR) was applied in order to compile, synthesize, select and analyze information relevant for the study. This method scrutinized by Brereton et al. (2007) and by Kitchenham and Charters (2007) was thus chosen as a reference for digital searches. From the last authors, the SLR was implemented in the sequence below:

[1] Identify the main topics for review,

[2] Define the research question(s) and develop a draft protocol; identify a few relevant studies and conduct a pilot study; specify inclusion/exclusion criteria according to which forms are tested; refine the protocol,

[3] Identify appropriate databases/sources; test search terms according to previous step,

[4] Run searches; find the studies; save all citations (titles/abstracts) in a reference manager,

[5] Get full texts of articles; apply screening criteria twice; save documents that remained after the second screening,

[6] Evaluate and select studies; appraise study quality; collect data; perform a review,

[7] Synthesize the results; explore heterogeneity and publication bias; produce a quantitative (i.e. apply statistics) or a descriptive review,

[8] Interpret and present data; report the results, discuss their applicability, the generalizability of conclusions and limitations of the review; add recommendations when applicable.

Considering step 3, there were initially three selected peer-reviewed databases/sources: Scopus, which claims to be the broadest web-based database of abstracts and citations; ScienceDirect, which has a large database of scientific papers and e-books; and Web of Science, which has recently started collaborating with a search engine of the whole internet, the Google Scholar. It includes publications made available by specific journals, like the ones by the International Building Performance Simulation Association (IBPSA) and the Lighting Research and Technology.

An example of this process is given in Table 1, showing the results of a test in the search of studies dealing with performance assessment within the urban context using computer simulation. The high number of results retrieved in one of the databases made evident the need for reviewing the keywords and addition of more restrictive ones in this case.

Table 1 :

Example of search results in selected databases.

	Database	Search string - Details of input parameters	#Hits
1	Scopus	TITLE-ABS-KEY (((urban OR city OR cities) AND (energy OR environmental OR performance) AND (modelling OR computer OR simulation)) AND NOT ((transport* OR water* OR smart OR health* OR patient OR waste OR transport* OR vehicle* OR biolog* OR psycholog*))) AND PUBYEAR > 1995	11,690
2	Science Direct	pub-date > 1995 and TITLE-ABSTR-KEY ((urban OR city OR cities) AND (energy OR environmental OR performance) AND (modelling OR computer OR simulation)) and not ((transport* OR water* OR smart OR health* OR patient OR waste OR transport* OR vehicle* OR biolog* OR psycholog*))	547
3	Web of Science	Limits: 1996-2017. Index: CDerwent, EDerwent, MDerwent. Topics, from: ((urban OR city OR cities) AND (energy OR environmental OR performance) AND (modelling OR computer OR simulation) NOT (transport* OR water* OR smart OR health* OR patient OR waste OR transport* OR vehicle* OR biolog* OR psycholog*))	391
4	IBPSA	Keyword: “urban”. Initial year: undefined.	794*

Notes: Period of research run: Jan-Feb/2017. The same keywords were used in all databases 1,2,3.
*Number and list of publications retrieved automatically by Google. Souce: own author.

Experts in specific fields were consulted for recommended literature. Also, the ‘References’ sections of available publications were screened in search for other relevant publications.

Within step 4, all citations from the previous step were saved and managed with JabRef manager (v.3.8.2, windows 10, Java 1.8.0-121, 2017). The software was adopted in the compilation, taking advantage of its features such as ranking, grouping, finding duplicate citations and exporting references.

In some cases, the selected publications were grouped into clusters, separated in categories, a method described in Prieto et al. (2017). Then, inside each cluster a screening was executed in order to filter the most suitable publications of the category, later ranking them according to their relevance for this study. This process was important for facilitating the screening and the analysis within step 7.

The next sections present an analysis of the selected publications.

2.1. Urban daylight climate: basic concepts

This section establishes the basic concepts related to daylight, light, climate, daylight climate and urban daylight climate, which are adopted in this research.

2.1.1. Daylight

Daylight is related to the stimulus associated with the optical radiation from the sun. Optical radiation refers to a broader electromagnetic spectrum that includes visible light, ultraviolet and infrared regions (Boyce and Mcibse, 2006). From a human perspective, the Commission Internationale de l'Eclairage - CIE defines daylight in its online vocabulary as the "*part of global solar radiation capable of causing a visual sensation*", which is visible in the range of 360-400 nm up to 760-830 nm of the electromagnetic spectrum, depending on the observer (CIE, 2018b) - a range that the human brain interprets as variations from violet to red (Figure 3). The Illuminating Engineering Society – IES (2018) defines daylight as the "*direct and/or diffuse light from the sun*", which in turn makes it important to define and characterize the term 'light'.

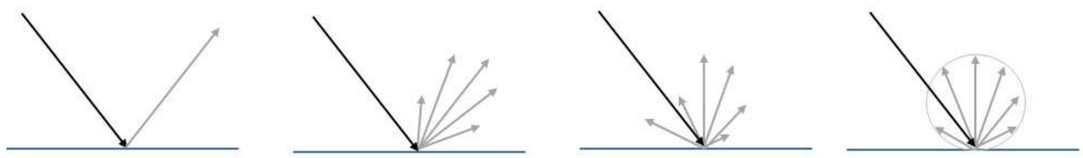
According to the Lighting Research Center –LRC (Taylor, 2000), light is an electromagnetic wave in movement, although it also exhibits the nature of a particle. Considering its properties, a light ray that hits a surface can be both or exclusively:

- Reflected, broadly in three angles named in comparison to the incident one (Figure 2):

- specular angle (equal, common in polished surfaces),
- spread angle (diverse but similar, common in rough surfaces),
- diffuse angle (diverse, common in matte surfaces, and known as Lambertian when the flux is emmited equally in every direction).

- Refracted through the surface to the material beneath, bending and changing its velocity, while being: transmitted, absorbed, and/or scattered.

When filtered, the light is selectively absorbed and/or transmitted according to the wavelengths. Under these properties, sunlight received on the Earth can be reflected, absorbed and scattered both by the atmosphere and by the environment such as ground, buildings, mountains and water bodies.



(a) (b) (c) (c')

Figure 2: Reflected angles named (a) specular, (b) spread and diffuse(c) with its Lambertian (c') version.
Source: adapted from Taylor (2000).

From another perspective, light[4] is any "*radiant energy that is capable of exciting the retina and producing a visual sensation*", and "*the visible portion of the electromagnetic spectrum*" (IES, 2018) (Figure 3). This definition is appropriate if 'energy' is understood as "*the property of matter and radiation which is manifest as a capacity to perform work*", and 'sensation' is assumed from its root in the Latin word 'sensus', meaning "*a faculty by which the body perceives an external stimulus*"[5]. This is due to the fact that light is not only to be 'seen' or 'discerned visually', as it was thought for centuries.

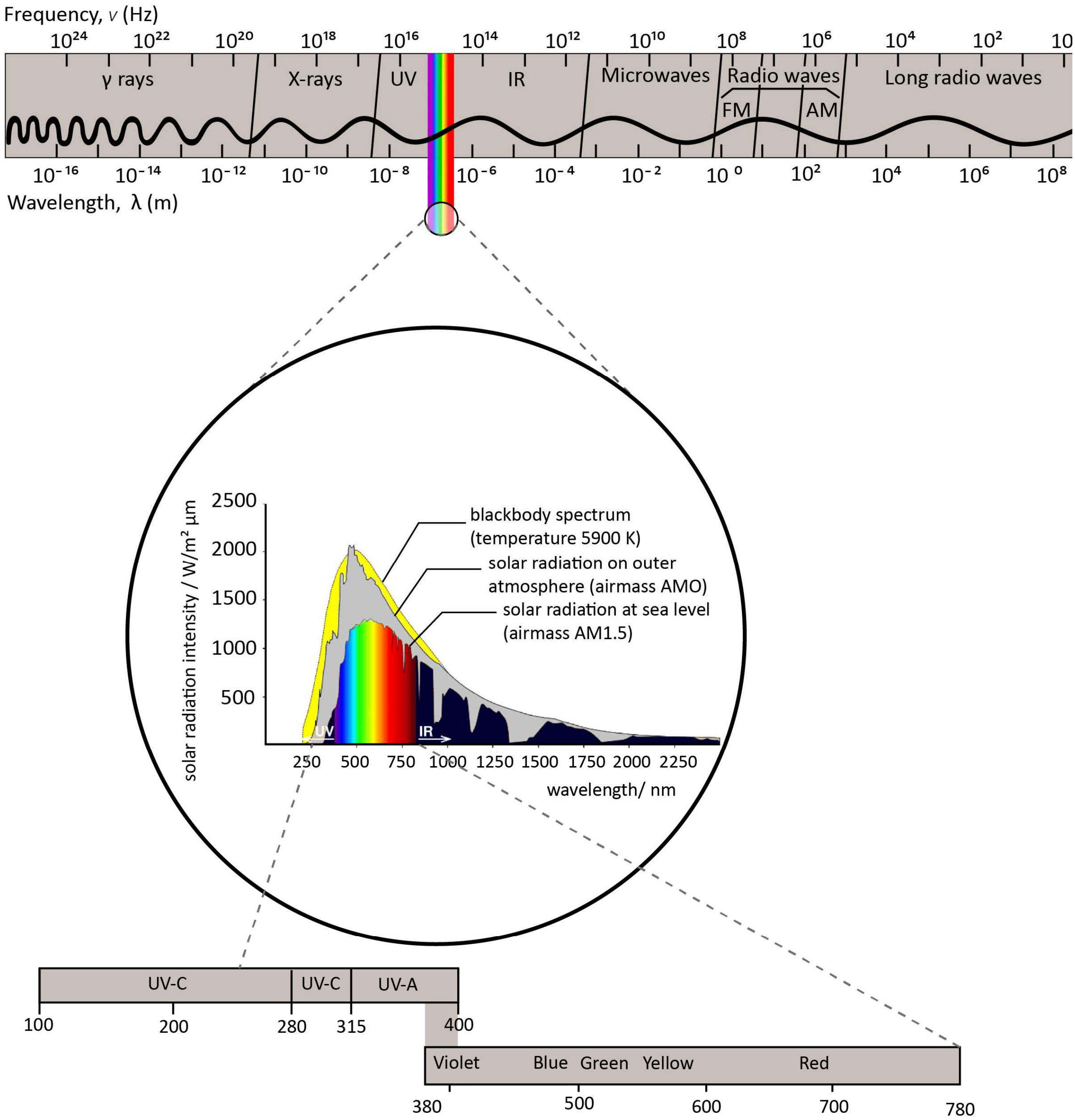


Figure 3: Scheme of electromagnetic spectrum with profile of visible light.
Source: adapted from Taylor (2000), European Commission (2008), and Jagielloński (2017).

[4] <https://www.ies.org/definitions/light/>, accessed May/2018
[5] Oxford dictionary, https://en.oxforddictionaries.com/

Actually, in the International Lighting Vocabulary by CIE (2018b), light has two different meanings: "*1. characteristic of all sensations and perceptions that is specific to vision (the perceived light); or 2. radiation that is considered from the point of view of its ability to excite the human visual system*".

It is known that photoreceptors within the eye, rods and cones, convert radiation within the visual range into signals to the brain. Rods dominate in low luminance levels (scotopic vision<0.001 cd/m^2). Cones dominate in brighter lights (photopic vision >3.0 cd/m^2), with association of wavelengths to colors: shorter (400 nm) as 'blue' and longer (>710 nm) as 'red'. Both rods and cones are activated between these luminances and that is called mesopic vision (Taylor, 2000). Other special photoreceptors that contain "*intrinsically photosensitive retinal ganglion cells*" (ipRGCs) respond to optical radiation and influence human physiology and behavior (Lucas et al., 2014; CIE, 2015). Thus, there are two processes related to the effects of light that activate the visual system. The process of image forming (IF), with its colors and brightness, and the non-image-forming process (NIF). From 1980 to 2000, there was an increasing number of studies to quantify effects of light on human behavioral, circadian, endocrine and therapeutic aspects based on photopic illuminance (lux), while the discovery of the special ipRGCs in the last decade is opening new horizons for the investigation of aspects related to NIF responses (Lucas et al., 2014).

In fact, light is related to human response and its interpretation by the brain within a complex process that is in the process to be understood. Its effects on human health are related to light: 1) treated as optical radiation, associated to thermal and photochemical mechanisms in the skin and eyes; 2) through the visual system, related to visual aspects; and 3) operating through the circadian system (Boyce and Mcibse, 2006). Humans prefer environments illuminated by daylight because of its balanced spectrum of color. Daylight may play a role in the development of the eye in children, which was recently associated with epidemic levels of myopia in Asian urban centers. If combined with a view to the outdoor environment, especially to a natural landscape (water or vegetation), it may reduce stress and anxiety in humans. Overall, daylight is a free resource that stimulates biological functions, such as process of skin reddening, synthesis of Vitamin D, dissociation of bilirubin, regulation of the natural circadian rhythms for the timing of sleep and wakefulness. Circadian rhythms are associated to body temperature, urine composition, cortex activity and levels of the hormone melatonin. Melatonin affects puberty onset, the reproductive system, cancer development, mental agility, mood levels, sleep rates, fatigue decrease. The production of melatonin is followed by cortisol secretion that affects the development of white blood cells; levels of blood pressure; nervous system regulation; breaking down of carbohydrates, protein and fat. Additionally, daylight is necessary for the proper development of the ecosystem that supports human existence. These characteristics and benefits were extracted from perspectives by different authors (Edwards and Torcellini, 2002; Mohamed, 2008; Amundadottir et al., 2016; Aarts et al., 2017).

Overall, daylight is crucial for avoiding physical, psychological and physiological damages in humans, with environmental, social and economic consequences. With urban population spending longer hours of daytime indoors, the role of design responsive to the urban daylight climate is becoming more relevant.

2.1.2. Urban Daylight Climate

Considering the built environment, the potential for indoor daylight availability through design, disregarding occupant behavior, is affected by the interaction of the following (adapted from Santos et al., 2017):

1) the source (mainly the sun, as the main star of the solar system, and in some cases the moon, which is relevant for studies that include dusk and dawn),

2) the external mediators (atmospheric conditions, urban morphology, topography, greenery, landscape),

3) the receptor (architectural components, built indoor characteristics such as layout, finishing, furniture, etc.).

For studies of urban daylight climate, simplifications might be necessary. An interesting reference was found in Mardaljevic (1999), in which components of daylight are set as: (a) direct sun, (b) direct sky, (c) externally reflected, and (d) internally reflected (Figure 4).

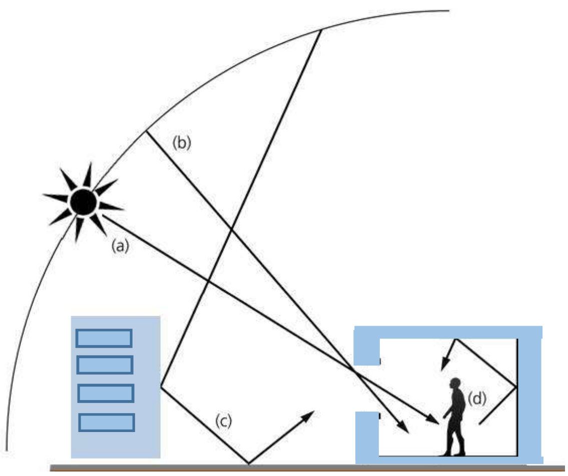


Figure 4: Components of daylight: (a) direct sun, (b) direct sky, (c) externally reflected, and (d) internally reflected.
Source: adapted from Mardaljevic (1999).

Despite necessary simplifications, the concept of 'urban daylight climate' is complex, recent and not well established. The meaning of the above stated expression adopted in this research relies on the concept of climate, urban climate, daylight climate and urban daylight.

Climate represents the "*slowly varying aspects of the atmosphere–hydrosphere–land surface system (…) over periods of a month or more*" (World Meteorological Organization – WMO, 2017). It is related to weather, which is "*the state of the atmosphere, mainly with respect to its effects upon life and human activities*", consisting of the short-term variations in the atmosphere, from minutes to days, and popularly thought of "*in terms of temperature, humidity, precipitation, cloudiness, visibility, and wind*" (American Meteorological Society - AMS, 2000). Commonly, climate is a result of weather parameters which are measured, registered and treated systematically over the period of thirty years (WMO, 2018). However, the reports of some parameters are not standardized worldwide (International Building Performance Simulation Association – IBPSA, 2016). Climate is being perceived in a broader context lately, including in its components: 1) current and historical climate trends; 2) natural climate variability; 3) the urban heat island effect and air pollution; and 4) [future] climate change due to global greenhouse gas emissions (Blake et al., 2011).

Climate is represented under weather data sets which are developed according to different methodologies. One of the most common weather data sets for characterizing a local climate is composed of 12 months of hourly data (8,760 hours) of statistical weighted long-term distribution of measured parameters (Crawley, 1998). These data are usually obtained from meteorological stations located close to the ground level, close or within urban sites. It has been relatively recent that the awareness has been raised to include observations of changes on the measured site over time in the reports, since they could affect the collected data; in this regard, Oke (2004a) states that such collected metadata have equal importance to the gathered meteorological data. There are also situations in which data sets are incomplete, non-existent, unreliable or non-representative. This is sometimes the case for locations where meteorological stations are sparse and data registers are recent. Under certain circumstances, it is possible to use algorithms to gather, visualize and to 'correct' or calculate missing data. This algorithm strategy is helpful in producing more complete databases.

Regarding databases, an example thereof is the Global Solar Atlas (2015), which provides climate data including spatial visualization in a series of world maps. Among the provided parameters is the yearly average of daily totals of global horizontal irradiation (GHI) (kWh/m^2 per year), covering the period from 1994 to 2015, depending on the region. Another example in terms of broad climate database is Meteonorm, a company that claims that their algorithms are also capable of compensating the lack of local data in some conditions and also the deviations in measurements recorded at the meteorological stations located outside the urban areas in order to assist building and urban planners (Remund et al., 2015; Meteonorm, 2016); it openly quantified uncertainty of ground measurements as lying between 2% and 10%, besides the uncertainty related to interpolation and satellite data (Remund and Müller, 2011). The database of Meteonorm brings weather data forecast considering global climate change according to scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC); currently, these forecasted data are not directly applicable for daylight assessment.

When it comes to climate database for daylight assessment, CIE declared the year 1991 as "*International Daylighting Measurement Year*" to establish a set of common guidelines for measurements of daylight-related parameters worldwide through the 'International Daylighting Measurement Program' (IDMP) and later the 'Guide to Recommended Practice of Daylight Measurement' (CIE, 1994). This document established that at least these parameters should be measured: global illuminance and irradiance, diffuse horizontal illuminance and irradiance, sunshine duration, illuminance by sunlight and skylight on vertical surfaces; if possible, zenith luminance, direct solar illuminance and irradiance should also be measured. By 2008, the IDMP registered 48 stations, of which 22 stations were able to measure sky luminance distributions, the majority of them being in the North Hemisphere (Pereira et al., 2008).

The lack of measured data is being compensated by the use of conversion models. The Solar Radiation and Illumination Standard NBS 1148 (Treado and Kusuda, 1981), for instance, established the calculi of illuminance as a function of irradiance as follows:

$$E_t = 110 \times I_t \quad \text{(Eq. 1)}$$

Where:

E_t: total illuminance on a horizontal surface (lux),

110: the value of luminous efficacy related to cloud conditions (lm/W)

I_t: total irradiance (W/m^2).

Climate is subdivided according to variations in time and spatial scale in order to facilitate its understanding. For design purposes, the atmospheric layers near to the ground are subdivided in scales. Oke (2004b) differentiates among micro-, local-, meso- and macro scales. According to this author, microscale ranges from centimeters to hundreds of meters, being related to the influence of elements such as buildings, streets and courtyards on climate. Local scale ranges from one to several kilometers, and it considers the effects of landscape features on climate, but excludes microscale effects; and it is related to neighborhoods with similar conditions of urban development. Mesoscale, extending to tens of kilometers, refers to the influence of urban settlements on weather and climate at the scale of an entire city. Undeniably, in the lower scales, implemented design influences climate.

The second term ‘urban climate’ is related to the interaction between the atmosphere and urban elements, including climate and the urban form. ‘Urban form’ is a combination of tri-dimensional geometric structures, land cover and fabric (Oke et al., 2017).

The term ‘daylight climate’ is a result of the incidence of solar energy in the atmosphere. Kittler and Darula (2002) describe its parameters while explaining that this term is used:

“*1. as a composition of prevailing conditions of solar radiation or sunlight intensity and frequency duration due to turbidity and cloudiness in combination with the usual occurrence of sky types characterized by their radiance or luminance patterns as well as brightness levels influenced by cloud type and cover; and*

2. as the area or region where a certain grouping of relevant natural radiation, sunlight and skylight factors is characteristic and prevails either in typical seasons or throughout the whole year with a long-term occurrence pattern, especially considering the frequency of cloudless, partly cloudy and overcast sky conditions.”

Solar radiation is the electromagnetic radiation from the Sun (CIE, 2018b). Sky cover quantifies the amount of sky covered and/or concealed by clouds or by obscuring phenomena such as haze, dust, smoke, fog, blowing snow, among others; reported in tenths, it ranges from clear (0.0) to a covered sky (1.0 or 10/10) (AMS, 2000). In this sense, sky cover is different from cloud cover, cloudiness, or cloudage, which is the portion of the sky cover that is attributed solely to clouds, often reported in tenths or eighths of sky covered, also as per the AMS. Atmospheric turbidity is a dynamic parameter associated with the amount of solid and liquid particles (aerosol) suspended in the atmosphere; it is useful for assessing local air pollution, and it is the main factor in controlling the attenuation of solar radiation reaching the Earth’s surface under cloudless sky conditions (Lopez and Batlles, 2004), affecting significantly the direct and diffuse components of illuminance (Gueymard, 2005). In fact, in the atmosphere sunlight is attenuated by air molecules, water vapor droplets or clouds, aerosol particles, ozone, carbon dioxide (CO_2), nitrogen, oxygen, dust particles (Kittler et al., 2012; Aarts et al., 2017). Near the horizon multiple scatter dominates, making the sky appear to be gray or white at low elevation angles (Kocifaj, 2009) and filtering more shorter wavelengths rather than longer ones, which turns the color of the sky reddish during sunrise and sunset. An example of this last phenomena is presented in Figure 5 (a1), that shows the interior of a room with white walls and furniture appearing reddish while reached by sunlight under a predominantly cloudy sky during a late sunset in Munich-Germany (spring, April, ca. 20h). Figure 5 (a2) presents the top of a high rise building covered by clouds, to remember that the effects of air stratification outdoors in variations of indoor conditions along the floors are little known in case of superstructures such as supertall and megatall[6] buildings. This specific image reveals part of the megacity of Shanghai-China under an overcast sky (July, ca. 10h, summer).

Figure 5 (b1 and b2) also presents the reddish phenomena, exemplifying the differences in hours of direct sunlight according to latitude and time of year: a late sunset in London-UK (June, summer, ca. 21h), and in Belo Horizonte-Brazil (July, winter, ca. 18h).

Figure 5 (c1) shows an aerial view of the horizon from an airplane demonstrating the presence of different concentrations of gases and particles that compose the different layers of the atmosphere, filtering the solar radiation until it reaches the ground. This picture also demonstrates the shadows on the ground level due to irregularities on topography, since the image was taken close to sunrise (Dec., ca. 10h, summer), approximately 150km away from the megacity of Rio de Janeiro-Brazil. A part of this megacity appears in Figure 5 (c2) taken ca. 15 minutes later, showing the same effect of shadowing due to a small angle of incidence of solar beams, but here over urban structures.

These pictures[7] reinforce the fact that daylight is dynamic, varying in duration, color, intensity, among other aspects, that in long term characterize the daylight climate of a geographic location.

The fourth term, 'urban daylight' was one of the topics of the International Conference on Urban Climatology (ICUC) held in 2003. 'UrbanDaylight' is recently associated with a plugin for software that allows certain daylight assessment in urban context (Dogan et al., 2012).

It is known that buildings modify thermal, humidity, radiative, and aerodynamic (and wind flow) aspects in the surroundings. The most relevant radiative effects "*are a decrease in the solar radiation receipt by areas in shadow, a local increase in solar receipt by reflection from sunlit walls, and the reduction of net long-wave cooling from surfaces near the building due*" to changes in sky view factor and in the surrounding heated buildings (Oke, 1978).

Alteration in these aspects can modify urban daylight. Excessive moisture and pollution alter the level of diffuse sky light and color perception. Higher temperatures may also result in high level emissions of volatile organic compounds (VOCs) and fast photochemistry, increasing air pollution (Cady-Pereira et al., 2017). Wind contributes to dispersion of pollutants, being important in several cities. It is known that some megacities have the worst air quality of the world, considering the levels of methanol, ammonia, formic acid, and ozone - the four major gases related to air pollution (Kornei, 2017). This is partially a consequence of high population density, traffic and economic activities (Dodman, 2009). Concentrated urban air pollution can

[6] Height >300m and 600m, respectively (Council on Tall Buildings and Urban Habitat - CTBUH, 2018).

[7] The pictures of Figure 5 were taken using the same equipment, in the interval of approximately 1 year, and they were not edited (no filters). Distortions in colors might have occurred.

also cause more intense rainfall as fine particles influence clouds (Bai et al., 2018). The level of air pollutants can affect visibility during certain periods of the year, especially during dry season_case of Mexico City (Cady-Pereira et al., 2017). All these phenomena alter sky conditions and daylight characteristics, affecting daylight outdoors (Figure 6) and consequentially the daylighting potential indoors. Daylighting is the *“lighting for which daylight is the light source“*, a word that replaces the antiquated term *“natural lighting*” (CIE, 2018b).

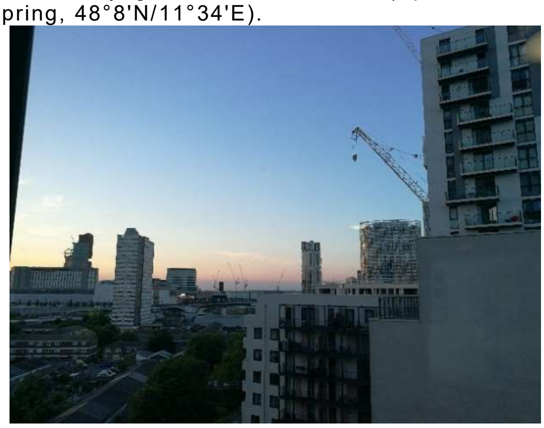
Concerning the complete expression ‘Urban Daylight Climate’, it appears registered as one of the key topics of the International Conference on Urban Climatology of 1999 (http://www.eurasap.org/37/past1.html, accessed on 20/Aug/2018). It can be broadly understood as reciprocal interaction between urban form and climate that connects with aspects of daylight. In this sense, it can be strongly related to aspects of the urban climatology, and could be defined as one of its branches.

In fact, the built environment alters the properties, the perception, and therefore the use of the daylight at the urban canopy level, indoor and outdoor. And because the built environment can also alter other important parameters of local climate which influence daylight, the urban climate affects the urban daylight climate. The publication by Oke et al. (2017), announced as the first full synthesis of modern scientific and applied research on urban climates, and written by experts in the field of urban climatology, addresses briefly the topic of daylight. For instance, the authors mention that street geometry affects the amount of diffuse solar irradiance by limiting the access to the sky vault, which can be quantified by the SVF, and that the portion reflected by surfaces is not sufficient to compensate the loss of light from the sky.

Currently, more studies related to the urban daylight climate are required. In fact, they are essential, especially considering potential inter-relations to other aspects of urban climate. This viewpoint is endorsed by the representatives of the International Association for Urban Climate – IAUC (2018), who repeat Bai et al. (2018) in the demand for more comparative studies of cities in various contexts in order to understand how “*urban morphologies, building materials and human activities affect (…) heat and light radiation,* [and] *urban energy*”, among other aspects. Their mention of studies on heat, [day]light and energy together is justified since these factors are interconnected. And due to such interconnections, design recommendations in one field can affect the performance in another.

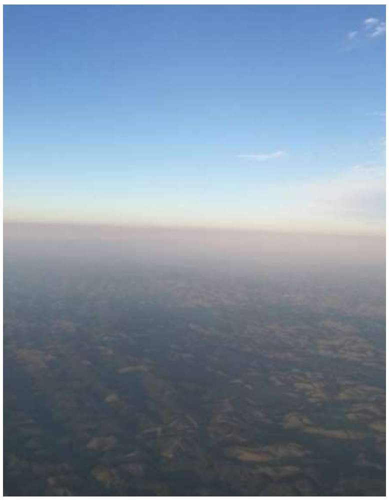
(a1) Indoor white walls and furniture colored by reddish daylight of sunset. Munich (April, ca. 20h, spring, 48°8'N/11°34'E).

(a2) Clouds cover the top of a high-rise building. Shanghai (July, ca. 10h, summer, 31°13'N/121°27'E).

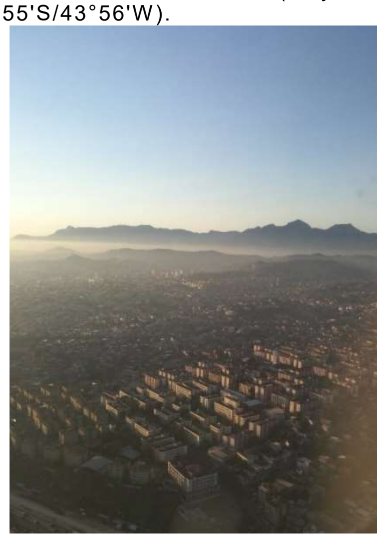


(b1): Sunset in London (June, summer, ca. 21h, 51°30'N/0°7'W).

(b2) Sunset in Belo Horizonte (July, winter, ca. 18h, 19°55'S/43°56'W).



(c1): Aerial view shows different layers of the atmosphere that filters solar radiation until it reaches hills.



(c2): Shadows in urban structures, Rio de Janeiro-Brazil (Dec., ca. 10h, summer, 22°54'S/43°12'W)

Figure 5: Dynamic daylight in micro-, local and mesoscales.
Source: own author.

Figure 6: Example of decreased daylight potential outdoors reinforced by pollution: softened view of buildings in New Delhi. Source: Own author.

This interconnection is also reflected in the correspondence or equivalence of morphological and environmental indicators that influence characteristics of daylight indoors, but which are explored in other fields of knowledge. As an example, Table 2 presents a non-exhaustive list of such indicators, which were extracted from more than 300 publications covering the topics of not only light, but also heat, energy and wind related to design, spreading across diverse fields: urban climatology, urban ecology, urban planning, environmental planning, urban energy planning, and architecture. Those indicators affect daylight indoors through aspects like variations of sky vault and of inter-reflectances in the built environment, spectrum filtering, air pollution concentration, among others.

As it can be inferred from the literature review, Urban Daylight Climate is the result of dynamic interaction between daylight climate and the built environment causing variations in the spectrum, intensity and duration of light, which is experienced visually and/or non-visually by components of ecosystems, including human beings.

The field of urban daylight climate has been profiting from recent scientific discoveries, more accurate data and new computational tools allowing for a variety of promising studies. How urban daylight climate affects animals, greenery, vertical farms, water bodies, and cities' surroundings should be further investigated. Future climate trends, pollution, air stratification, glare are also interesting topics. These items, however, are not included in the scope of this study. Under the concept of urban daylight climate, this work assumes the human-centric perspective for visual image-forming indoor during the day. It focuses on energy savings and performance, based on minimum illuminance levels, in order to potentially avoid on the use of artificial lighting. It also focuses on the interaction between the urban morphology (one of the aspects of urban form) and the historical climate (one of the aspects of urban climate), taking into consideration inter-reflections of daylight between buildings within a dynamic approach.

This decision considers the fact that urban daylight climate is especially important when dealing with urban density, since overshadowing can decrease daylight levels indoor.

Performance is "*how well an activity is done*"[8]. Under the perspective of daylight indoors, it can be understood as "how well daylight is provided", or "how good indoor daylight is". These meanings are discussed in the next section.

Table 2

Morphological and environmental indicators that influence characteristics of daylight in the built environment.

Mass	**Ref.***	**Sky**	**Ref.***
Density	1	Sky view factor (SVF)	11
Building built area or footprint	1	Sky view factor at façade	14
Building Plot ratio (BPR)	2	Sky Exposure Factor (SkyEF)	15
Floor space ratio (FSR)	2	Sky opening	16
Floor Space Index (FSI)	1		
Floor area ratio (FAR)	5	**Reflectance & Other**	**Ref.***
Gross floor area (GFA)	2	Total exposed envelope area	12
Open Space Ratio (OSR)	1	Façade ratio per orientation	12
Spaciousness	1	Mean Surface Irrad (Roof/Façade)	12
Mesh of the grid	1	Envelope Irrad Per Façade	12
Compactness	2	Form factor	12
Urban Plot Ratio	3	WFRatio	12
Surface-to-floor-area ratio	7	Active/Passive Floor Area	17
Building Site coverage	6	Daylight façade to floor area index	18
Ground Space Index (GSI)	1		
Urban Site coverage	3	***References**	
Nearest-neighbour Ratio	3	Berghauser Pont and Haupt (2010)	1
Volume of buildings to area ratio	3	Lehmann (2016)	2
Volume of non-buildings	3	Mohajeri et al. (2016)	3
Surface to volume ratio (S/V)	8	Newman and Kenworthy (1989) cited in Steemers (2003)	4
Height-to-width ratio	11	Lee et al. (2011)	5
Aspect ratio (H/W)	12	Lee et al. (2015)	6
Network lenght (L)	1	Sattrup and Strømann-Andersen (2013)	7
Shape factor	9	Ratti et al. (2003)	8
Verticality	9	Martins et al. (2016)	9
Distance between buildings	9	Kawamoto (2014)	10
Building depth, width, height	9	Stewart and Oke (2012)	11
Buildings' heights distribution	10	Nault (2016)	12
Height of roughness elements	11	Gan and Chen (2016)	13
Mean Height	12	Cheng et al (2016)	14
Length-to-width ratio (L/W)	13	Zhang et. al (2012)	15
Continuity	13	Teller and Azar (2001) cited in Zhang et. al (2012)	16
Porosity (comprehensive, etc.)	13	Mumovic and Santamouris (2013)	17
Rugosity (absolute, relative)	13	Chen and Nordford (2017)	18

Source: own author.

[8] Cambridge dictionary, online version, accessed Oct/2016.

2.2. Defining good indoor daylight: systems and metrics

It is important to define the ‘good indoor daylight’ in order to provide coherent assessment, comparison and design propositions. This discussion requires the clarification of *good lighting*, as well as the definition of systems and metrics for characterizing and quantifying (day)light.

Reinhart et al. (2006) note that the question “*What is good daylighting?*” has received attention of different research carriers, and that the answer is different for experts in architecture, lighting energy and cost savings, building energy consumption, load management. Various professions concentrate on different aspects of daylight and, thus, provide different answers to the question. However, the definition of good (day)lighting is complex, still not consensual and evolves with the proper understanding of the role of this phenomenon.

Focusing on human factors and setting the roots in general lighting, Boyce and Mcibse (2006) states that "*good quality lighting is lighting that allows you to see what you need to see quickly and easily and does not cause visual discomfort, but does raise the human spirit*”. The final words of this statement make evident the complexity of the topic, bringing out the subjective part with the expression ‘raise spirit’; this can be understood as within the field of aesthetics, which is also related to culture, erudition, education, etc. In any case, the statement is interesting because it refers to both ways of assessing daylight performance: by quantity and by quality. Both quantity and quality performance depend upon individuals’ age, gender, adaptation, genetics and physiology, among other factors.

Quantity for image-forming demands refers to the amount of light needed to produce images of sufficient resolution on the retina (Aarts et al., 2017), in a fast way, with minimum effort, and without compromising the eye’s integrity/health. Beyond aesthetics, quality of light includes not only the amount for sufficient resolution of images, but also refers to aspects of visual comfort such as avoiding excessive glare or uniformity, and correct rendering of colors.

This study restricts the concept of ’good daylight’ to its aspect of quantity for image-forming. More specifically, it focuses on a minimum illuminance level (lux) that is being adopted in current researches on daylight for different typologies: from residential spaces to offices, as well as libraries, etc. This level is being related to values considered necessary for executing ‘general’ tasks safely during the day, and without the need to switch on artificial lighting in a certain period of occupation of the space throughout the year. The following sections aim to clarify these points, starting from the distinction between systems for characterizing light.

In India, the national building code states that “*Good lighting is necessary for all buildings and has three primary aims. The first aim is to promote work and other activities carried out within the building; the second aim is to promote the safety of the people using the building; and the* *third aim is to create, in conjunction with the structure and decoration, a pleasing environment conducive to interest of the occupants and a sense of their well-bei*ng" (Bureau of Indian Standards – BIS, 2016).

Given the importance of efforts to characterize good daylight, systems for describing and measuring light are necessary. The next section presents some of them.

2.2.1. Systems for light characterization: radiometry *vs.* photometry

Radiometry is a "*system of language, mathematics, and instrumentation used to describe and measure the propagation of electromagnetic radiation, including the effects on that radiation of reflection, refraction, absorption, transmission, and scattering by material substances in their solid, liquid, and gaseous phases*", while photometry is a branch system with same purpose, but restricted to a smaller part of the spectrum: the part that stimulates the human visual system (McCluney, 2014).

In order to differentiate between the units, the symbols for photometric units are differentiated by subscript v (visual) when necessary, such as Ev (Table 3). In terms of radiometry, the most common unit is Watt (W), which measures radiant flux (power). Radiant exitance (W/m^2) is the radiant (energy) flux per unit area leaving the surface of a source of radiation. Irradiance (also W/m^2), is the radiant flux per unit area received by a surface. Radiance is the emitted flux per unit solid angle per unit projected area ($W/m^2/sr$).

In terms of photometry, lumen (lm) measures luminous flux. Lumen can be converted into Watt under certain conditions, establishing the equivalence to the radiometry. Illuminance (lm/m^2 or lux) measures the photometric (visible) flux per unit area. Luminance ($lm/m^2/sr$ or cd/m^2) is the illuminance per unit solid angle and it is related to the perception of brightness. As per Aarts et al. (2017), luminous efficacy is the ratio of the illuminance to the corresponding irradiance of solar radiation.

Table 3:

Radiometric vs. photometric units.

Quantity	Radiometry		Photometry	
	Symbol	Unit	Symbol	Unit
Wavelength	λ	nm	λ_v	nm
Radiant and luminous flux (power)	ϕ	W	ϕ_v	lm
Radiance and luminance	L	$W/m^2/sr$	L_v	$lm/m^2/sr$
Irradiance and illuminance	E	W/m^2	E_v	lm/m^2; lux
Radiant and luminous energy	Q	W-s	Q_v	lm-s
Radiance and luminous intensity	I	W/sr	I_v	lm/sr; cd

Source: adapted from Taylor et al. (2000).

2.2.2. Metrics for daylight characterization

Another step into the quantification of 'good daylight' is the definition of metrics, which are detailed in this section, with focus on the ones that are related to the human visual system.

A metric is defined as a "*system or standard of measurement*"[9]. Metrics are useful for evaluating, comparing and serve as a reference for optimizing performance of proposed designs. Therefore, the choice of a metric is important for the development of strategies and guidelines for climate-based design.

The definition of metrics, their recommended values/thresholds, etc. for measuring performance are diverse in literature. They are strongly related to human needs and preferences, and can be approached considering three interconnected perspectives: 1) individual, 2) contextual and 3) structural[10] (Figure 7). Under the individual perspective, preferences and requirements can be grouped according to physical, physiological and psychological aspects. Under the physical aspect, age, gender, skin type and pigmentation, as well as health conditions of the individual, among others, can be considered. Regarding the contextual perspective, factors such as educational, economic, social and environmental background of the population are relevant to the way of defining expectations, tolerances and acceptances of daylight conditions, which can then be translated into metrics. Finally, considering the structural perspective, metrics can be developed to access quantity or quality of daylight, related or not to the process of image-forming in human brain. At this point, it is interesting to complement this perspective with the one presented by Veitch (2018), who offers a structure of the effects of light in human beings which is divided into image-forming and non-image forming, the former being subdivided into visual performance, experience and comfort, while the latter is subdivided into circadian and acute effects (Figure 8).

Individual	**Contextual (Background)**	**Structural (Outputs)**
Physical Physiological Psychological	Educational Economical Social Environmental Technological Ethical Historical Cultural Religious Aesthetical Governmental	Quantity,quality? Illuminance Luminance Thermal Circadian

Figure 7: Factors that affect the choice of metrics and their tresholds.
Source: adapted from Brandon and Lombardi (2009) and Chen and Ng (2012).

[9] Oxford dictionary (online), accessed Oct/2017.

[10] Triad adapted and expanded from a scheme for analysis of outdoor comfort provided by Chen and Ng (2012).

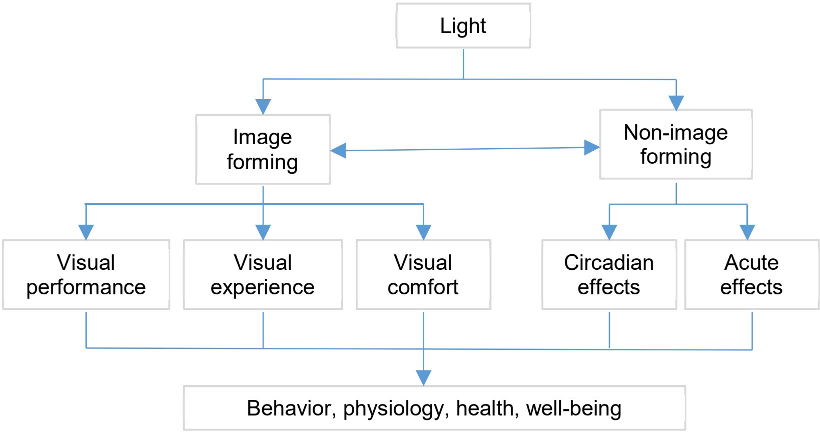


Figure 8: Effects of light on humans.
Source: adapted from Veitch (2018).

Heschong et al. (2010) present another subdivision that is useful to the analysis of the effect of the urban daylight climate on indoor performance, and which can be supportive to the definition of metrics. According to these authors, human 'comfort', energy impacts, space description (geometry, orientation, etc.), fenestration description, climate inputs, exterior context, occupant behavior and building systems (Figure 9) are components of a theoretical equation to support day(light) analysis. The more components of this equation there are to evaluate, the more complex is the analysis.

This study has a focus on the urban scale. Occupant behavior, measured energy impacts and the impact of building systems are not part of the scope. Within human comfort, only illuminance is addressed, and only in terms of sufficiency. This study is based on illuminance, which therefore will be detailed in the following sections. This decision is based on the fact that quantitative researches on indoor daylight that used the metrics related to visual effects of light using illuminance levels are widely used in design, at least in the field of architecture. This restriction in scope is also connected to the fact that recommended levels of daylight related to spectrum ranges, duration, period of exposure, and quality of its spatial distribution indoors, are still under investigation. Important to notice, the knowledge of non-image-forming (NIF) effects has been expanded. Efforts to measure light with respect to NIF effects are recent, ideas on how to translate basic scientific findings into lighting design specifications are nascent, "*the established knowledge in this field is still premature*" (CIE, 2015). Systems for describing and measuring radiation in this field are to be standardized (CIE, 2018a). And it is not yet possible to quantify unambiguously light's influence on the circadian system regulation, a challenge to improve architecture for wellbeing (Bellia and Fragliasso, 2021).

A person exposed to certain levels of daylight for image forming in the brain might get indirect health benefits related to non-image-forming effects of light. However, there is no consensus on how to measure these potential benefits.

Human Comfort	+ Energy Impacts	= Spatial & Fenestration description	+ Climate Inputs	+ Exterior Context	+ Occupant behavior	+ Building Energy Systems
Illuminance Sufficiency Uniformity Gradients Spatial plots Luminance Contrast ratios Uniformity Glare 3D imaging View quality Thermal Radiant Circadian Timing Duration Intensity Spectrum Relative context	Lighting energy Full load equiv. Annual kWh Peak kW Load profiles Cooling, heating, ventilation Additional load Annual kWh Peak kW Load profiles	Geometry Orientation Visual Properties Thermal properties Sensor locations Windows, skylights, shades, blinds	Sun Altitude Azimuth Hourly intensity Terrain adjusments Sky Uniform distribution Hourly intensity Perez distribution Partly cloudy Fog/haze Precipitation Thermal CDD/HDD Hourly temps Relative humidity Radiant components Wind speed Microclimate	Ground Diffuse reflectance Slope Multiple conditions Specular reflectance Seasonal variation Weatther variation Buildings Shapes Opaque boxes Transparency Diffuse reflectance Specular reflectance Vegetation Shape & locations Reflectance Transparency Seasonal variation Other View quality Cars Water	Task Type Furniture Location View direction Blinds operation Lighting Control Occupant Schedules Demographics Age Health Circadian sensitivity & status	Lighting Installed type, layout, control, multiple systems Heating, Cooling Annual load Dynamic response System efficiency Ventilation Annual load Dynamic response Variable windows

Figure 9: Components for analysis of (day)light in design.
Source: adapted from Heschong et al. (2010).

The assessment of daylight in terms of health focuses on visual requirements for execution of tasks and safety based on illuminance (lux) levels. The values of recommended levels are evolving according to the development of the field. However, there is no consensus on the topic of minimum illuminance levels either for tasks or for building typologies, which makes the establishment of benchmarks for long-term performance comparison a complex process. For example, Reinhart (2002) mention that The Canadian Labor Code of 1991 established illuminance levels >500lux for tasks positions where "*continuous reading or writing is performed*" in offices. One year later, the Brazilian standard recommended 150 lux for deposits and areas for non-continuous work, 300 lux for tasks with a limited visual requirement, and 750 lux for offices (Associação Brasileira de Normas Técnicas – ABNT, 1992). Subsequently, another Brazilian standard proposed different values: between 300 and 750 lux in schools, offices and rooms for medical regular attendance, 300 to 500 lux in departmental stores, at least 300 lux in multi-use rooms for entertainment activities (ABNT, 2013).

Carlucci et al. (2015) stated that indoor daylight was being assessed in researches through non-consensual indices and metrics related to [visual effects of light] mostly involving: *"(i) the amount of light, (ii) the uniformity of light, (iii) the quality of light in rendering colors, and (iv) the prediction of the risk of glare for occupants*", using mathematical equations, physical models in scale, and computer simulation.

Considering the nature of the timeframe for performance characterization, metrics can be distinguished between static or dynamic. Static metrics focus on the analysis of a particular time period. In literature, this period differs: a worst case condition under standardized overcast sky, the day with less illuminance locally recorded in a given year, the day of equinox or solstice at 12h, etc., as it can be observed by contrasting different approaches by Martins (2014), Berghauser Pont and Haupt (2009), Cheng et al. (2006a). Dynamic metrics focus on a period of time, for which several static measurements are compiled and represented often as a unique value to characterize one year, one season, one month, etc.; variations thereof can be found by comparing the variety of procedures adopted in Reinhart (2002), Heshong (2012), Bauer and Wittkopf (2015), Dogan and Park (2018). Those investigations under more realistic sun and sky conditions in different time frames are being accurately demonstrated since the late 1990's, based on climate-based daylight modelling (Mardaljevic and Christoffersen, 2013). Climate-based daylight metrics, here refered to as dynamic metrics, are those that incorporate variations of sky conditions and sun positions during a period of time allowing the analysis based on weather data for the site. In this sense, climate-based metrics can provide more representative results of indoor daylight performance.

After analyzing a sample of metrics mentioned in literature, considering their results, application, concepts, explicit or inferred purposes, the following categorization for metrics related directly or indirectly to daylight is proposed for clarifying its benefits and scope:

- Based on Photometric Units:
    - Image-forming:

Static: Daylight Factor (DF) [unit in %]

Dynamic: Daylight Autonomy (DA), Daylight Autonomy percentiles (DAqXXX), inverse Daylight Autonomy (iDA), spatial Daylight Autonomy (sDA), Residential Daylight Autonomy (RDA), Useful Daylight Illuminance (UDI), Useful Daylight Illuminance achieved (UDIa), Continuous Daylight Autonomy (cDA). The units variate among [%], [lux], or none.

- Non-image forming:

Equivalent Melanopic Lux (EML)

- Based on Radiometric units:

Dose [J/m^2] and dose rate [W/m^2]

Daily sun hours (solar insolation) [Wh/m^2 per day]

The concept of some of these metrics is detailed in the next section.

Metrics and their definition

Starting from non-image forming metrics, three examples thereof are EML, dose and DLA.

Equivalent Melanopic Lux (EML) is used to quantify aspects of NVI based on lux (L) multiplied by a reduction factor (Lucas et al., 2014). This process is being referenced by CIE (2015) for further developments.

Dose (J/m^2) measures the quantity of radiant exposure, while dose rate (W/m^2) measures the quantity of irradiance (CIE, 2018b). There are difficulties to define a recommended daily dose for ensuring human health. Especially because necessary dose values of UVB radiation (290–315nm) for cutaneous production of vitamin D is not consensual: it was found to vary according to latitude and altitude; time of day and season; presence of filters such as translucent materials, skin sunscreen and air pollution; as well as age and skin tone (light-skinned people require lower dose than persons with higher melanin levels) (Holick, 2004; Wacker and Holick, 2013). Despite the complexity of the topic, the CIE (2014) proposed a standard and minimum vitamin-D dose, analogous to the standard and minimum erythema dose for UV, alerting to the necessity of future adjustments.

Direct Light Access (DLA) is proposed as a climate-based daylighting metric to evaluate "*access to direct light*" in residential spaces according to Dogan and Park (2018). They compared DLA to a German standard. Part 1 of this standard, DIN 5034-1:2011-07, p. 13, stablished specific periods of the year in which the amount of direct light coming through the windows should be evaluated considering "*health and well-being*"[11] (Deutsches Institut für Normung - DIN, 2011), specifically in equinox and winter. Therefore, it is inferred that DLA is related to thermal requirements. Indeed, DLA was intended for cold climates, thus the authors warn against its use in hot and arid climates, where "*it may not be justified to optimize dwellings for direct solar access*".

[11] Unofficial translation provided by the author of this study.

Metrics related to image forming are greater in number. Examples thereof include the static DF and the dynamic UDI, DA, sDA, ASE, sDAmax, cDA and RDA, which are described below.

Daylight Factor (DF) (%) is the "*ratio of the illuminance at a point on a given plane, due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded*" (CIE, 2018b). In summary, assessments that use DF are done taking the overcast sky in consideration, while disregarding the prevailing climate, solar orientation, and site location (Mardaljevic and Christoffersen, 2013). According to Berghauser Pont and Haupt (2010), minimum percentages for DF rely on the "*conservative estimation*" that the illuminance provided by the sky corresponds to an overcast one of approximately 10,000 lux, of which at least 2% (200 lux) is accepted for indoor residential spaces, while 5% (500 lux) is the minimum target for office spaces.

Useful Daylight Illuminance (UDI) is established as the percentage of occupied hours when indoor daylight levels are considered 'useful' for the human occupant within a time frame of one year. The percentages are obtained based on the following levels of illuminance: a minimum value, below which light is considered 'insufficient', and an upper limit above which levels are deemed 'unacceptable'. These two limits frame a range of levels that are acceptable, desirable or tolerated, and that may be adjusted according to a specific demand. Also, for practical purposes, the authors of UDI proposed values of the limits based on field studies of occupant behavior under daylight conditions (Nabil and Mardaljevic, 2006): a lower limit of 100 lux is chosen considering its insufficiency for illumination and low contribution to artificial lightning; the upper limit of 2000 lux, later reviewed to 3000 lux, considers the improbability of using the light because it could cause visual and/or thermal discomfort.

Daylight Autonomy (DA) is the percentage of the occupied hours of the year when a minimum illuminance threshold is met by the sole daylight (Carlucci et al., 2015). Daylight Autonomy should not be confused with Daylight Availability that, as per IES (2018), is "*the luminous flux from sun plus sky at a specific location, time, date, and sky condition*". From DA, in turn, Continuous Daylight Autonomy (cDA) and Spatial Daylight Autonomy (sDA) were derived.

Continuous Daylight Autonomy "*corresponds to daylight autonomy with the exception that partial credit is given when daylight meets only parts of the target level at a given time step*" according to Reinhart et al. (2013). These authors exemplify that if 500 lux is the target level, but only 250 lux is achieved with daylight, a partial credit of 0.5 (resulting from 250/500) is registered for the corresponding time step.

Spatial Daylight Autonomy (sDA) is a measure of daylight illuminance sufficiency for a given area, reporting a percentage of floor area that exceeds a specified illuminance for a specified percentage of the analysis period (IES, 2018). There is no consensus in literature regarding the established concept, methods and criteria for quantifying sDA.

The standard provided by the Illuminating Engineering Society of North America (IESNA) - Lighting Measurement IES LM-83-12 (2012) defines for sDA a threshold of minimum 300 lux, at least 50% of the occupancy time from 8am-6pm. These limits are conveyed by subscripts ($sDA_{300,50\%}$) and, according to the document, were established based on the investigation of occupant preferences in open plan offices, meeting rooms, classrooms, public lobbies and public spaces in libraries; and may be extended to areas with similar visual tasks. The standard further states that the performance of an analysis area can be classified as 'nominally acceptable' (sDA≥55%) or 'preferred' (sDA≥75%). Mathematical representation of sDA computed in an area with "*a grid of N points, assuming a function S(j), which is 1 for each grid point j, which receives a sufficient illuminance for more than the given fraction of total occupancy time, else 0*", is (Bauer and Wittkopf, 2015):

$$sDA = \frac{\sum_{j=1}^{N} S(j)}{N} \quad \text{with} \quad S(j) = \begin{Bmatrix} 1 : s_j \geq \tau t_y \\ 0 : s_j < \tau t_y \end{Bmatrix}, \qquad \text{(Eq. 2)}$$

Where:

s_j = occurrence count of exceeding the sDA illuminance threshold at point j,

t_y = annual timestamp count,

τ = temporal fraction threshold.

Later, the calculus of sDA included "*the use of a dynamic shading system to limit direct sunlight exposure to no more that 2% of the analysis area at any given hour*", while the spatial daylight autonomy maximum, named sDAmax, focused on the percentage of floor area which receives daylight above the required illuminance (e.g. 300 lx) multiplied by a constant for more than 5% of occupancy hours (Dogan and Park, 2018). As per IES LM-83-12 for building design, the sDA needs to be evaluated together with a second metric, the Annual Sunlight Exposure (ASE), which focus on direct light to prevent visual discomfort. ASE represents "*the fraction or percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year over a specified daily schedule with all operable shading devices retracted*" (IES, 2018). ASE is a proxy for overheating and glare (Wymelenberg and Mahic, 2016; Dutra de Vasconcellos, 2017) - a proxy, because it is measured in the horizontal plane and not in the vertical plane that contains the eyes of the observer, and because it is not capable of considering some of the aspects that influence visual comfort. Glare depends strongly upon elements such as indoor layout, furniture, finishings, and especially the user behavior - which includes capability to control the incident light and indoor environment, time and duration of occupancy, corporal position, direction of the eyes. ASE is related to the Annual Light Exposure (ALE) [lux-hours] limited to objects i.e. art conservation, a metric that was addressed by CIE in the technical report of 2004 entitled "*Control of Damage to Museum Objects by Optical Radiation*" (Claro, 2015).

The metric mSDA (monthly sDA) was proposed to address the seasonal daylight availability. According to Bauer and Wittkopf (2015), it breaks the single values of annual metrics down into monthly values, a first step to understand daylight availability, which is relevant outside equatorial zones. They explain that the calculation of msDA is analogously to the annual timeframe, but temporal thresholds become relative to each month. It is expressed as:

$$msDA_m = \frac{\sum_{j=1}^{N} S(j,m)}{N} \quad \text{with} \quad S(j,m) = \begin{Bmatrix} 1 : s_{j,m} \geq \tau t_m \\ 0 : s_{j,m} < \tau t_m \end{Bmatrix}, \qquad \text{(Eq. 3)}$$

Where:

$s_{j,m}$ = occurrence count of exceeding the sDA illuminance threshold at point j for month m,

t_m = timestamp count for month m.

Dogan and Park (2017; 2018) discussed daylight metrics for residential architecture. Then, the authors proposed a framework that quantifies daylight autonomy and access to direct light in diurnal and seasonal bins in residential spaces in temperate and cold climates, using three new metrics: Residential Daylight Autonomy (RDA) and Direct Light Access (DLA), both combined in the Residential Daylight Score (RDS). RDA assessed purely daylight. DLA accounted positively for the direct light component, which was important for their focus: cold climate, high latitude. The authors stated that "*metrics like DA or sDA, which impose no upper illuminance threshold, may be more suitable to evaluate whether a space is considered well-lit for certain activity*", once in residential spaces higher levels of illuminance might be tolerable and welcome. They also asserted that the mandatory use of a dynamic shading system was not suitable for residential spaces, since direct light might be desired by occupants. Having these points in mind, and suggesting that rigid occupancy profiles should be reviewed, these authors proposed new metrics. The analysis is divided in 12 timeframes: 3 diurnal periods (morning, noon and evening) and 4 seasons (winter, summer, spring and fall), to assess seasonal daylight variations. According to the authors, this extra subdivision is particularly important for residential occupants in high latitudes and cold climates. The authors presented additional studies using these metrics; RDA assessment was based on sDA $_{(300,\ 50\%)}$, the same minimum illuminance level defined for non-residential uses, recognizing that further research need to be undertaken to verify the pertinence of these threshols in residencial spaces.

Similarities and differences between abovementioned metrics that focus on minimum illuminance levels, which are the starting point to be addressed by urban designers and planners, are summarized in the comparative Table 4.

Both CIE and IES define DF in their regularly updated online vocabulary (accessed in March, 2018). Only IES defines sDA, albeit without reference to shading constraints. By the time of conducting this research, none of the other metrics had been found in the official vocabulary list provided by these two reference institutes. This might reflect a certain endorsement of DF and sDA for performance assessment currently. This can favor the use of the same metric/thresholds for the establishment of benchmarks for comparison of buildings and urban settlements, a step that might contribute to daylight promotion. Meanwhile, the development of the seasonal metrics is promissor in the field.

Table 4:

Comments on metrics related to image forming*.

Indicator	Descriptor	Comments
Geoclimatic	Location	Latitude and longitude (Daylight Saving Time, DST) can be considered.
	Cardinal orientation	Irrelevant for some metrics (i.e., DF).
	Sun and sky conditions	Taken individually or combined, depending upon the metric.
Temporal	Time interval	Constant for static metrics, vary in dynamic ones (annual, monthly, etc.)
	Sub-interval	Flexible daily interval. Dynamic sDA and similar ones are measured usually from 8-18h, except RDA (morning-afternoon-evening).
Spatial	Indoor area	Total or partial (i.e., for sDA it can be 50% of the occupied measured area).
	Indoor distances	Unusual to define minimum or maximum distances between walls.
Quantity	Unit	Based on illuminance (lux) for indoor performance.
	Levels	Minimum levels are defined in all metrics. Some of the dynamic metrics define upper levels.

*i.e., the static DF and the dynamic UDI, DA, sDA, msDA, cDA, and RDA.
Source: own author.

In any case, according to Reinhart et al. (2006), none of the existing quantitative metrics at that time, neither static nor dynamic, could predict holistic ‘good’ daylighting, but only an aspect of it. This affirmation is still valid despite the advances in the field and the ongoing search for metrics that would be meaningful for different fields simultaneously, such as architecture and lighting energy.

Important to mention, a metric developed specifically for the design in urban scale does not exist, but studies are adapting the existing metrics from detailed architecture, as the next section presents.

2.3. Studies of indoor performance using computer simulation

Researches in the last decades have been dedicated to evaluation of indoor daylight performance using computer simulation considering both static and dynamic metrics in architecture, and more recently, in the urban scale.

Studies of indoor performance using computer simulation considering parameters related to climate-responsive design are plentiful, and some of them are very interesting for daylight. This section brings a panorama of those studies, starting from general fields, followed by the daylight-related ones.

2.3.1. Urban performance using computer simulation

The use of computer simulation in urban performance focusing on climate has received increasing attention in the last two decades, with publications large in number and diverse in topics. Following the entire process of Systematic Literature Review explained previously, less than 100 documents were analyzed in detail. However, according to the search strings adopted here, most of the retrieved publications could be separated in categories related to the effect of solar radiation (heat transfer and daylight) and/or wind on energy performance of buildings located within the urban context, energy generation through photovoltaic systems, simulation techniques, weather file, and digital maps.

Examples of publications categorized as ‘simulation techniques’ included parametric optimization and coupling for multi-scale assessment, simplification of building models to speed up urban simulation, energy performance of different urban typologies, synergies and trade-offs when designing for different performance objectives. The category of ‘weather files’ included publications about transition and adjustments between assessment scales, eventually considering effects of urban geometry on outdoor and indoor climate. The category ‘digital maps’ included efforts to spatialize and forecast urban morphology and performance, for instance, by using terrestrial laser scanner, aerial imagery, satellite-based sensing systems combined with statistics.

From the most relevant category for this study, ‘solar radiation’, studies on daylight where scrutinized. These addressed, among others, static and dynamic simulation in urban structure, indoor daylight through multiple transparencies in buildings, indoor daylight potential in obstructed buildings, reduction of solar incidence caused by pollution, potential of daylight to meet the needs of buildings' occupants in dense urban context, simplified tools for enhancing performance in early design stages.

One of the results of this research was the realization that the process of computer simulation for the purpose of enhancing performance in design can be organized, in general, as illustrated by Figure 10. This diagram represents a selection of processes, stages, choices, methods that can be found in simulation studies, and it is non-exhaustive. It was developed from literature review, structured for better comprehension under the three steps described by Hopfe (2009, p.37): pre-processing, simulation and post-processing.

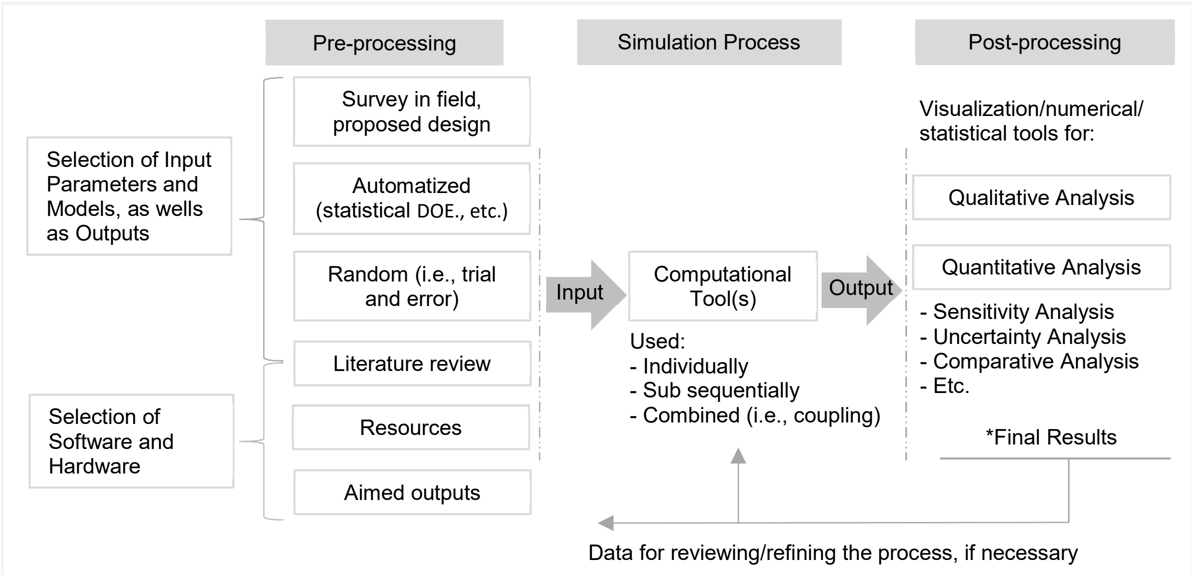


Figure 10: Diagram of applied computer simulation for enhancing design.
Source: own author.

Following this panorama, the studies focusing only on daylight, that are aligned with the scope of this work, were further investigated and are presented in the next sections.

2.3.2. Assessment of indoor daylight performance using computer simulation

This section presents some of these studies, exploring mostly the ones that approached the problem of obstruction due to high urban density.

At this point, it is important to clarify the term 'density' in this work, because studies approach this aspect differently, and that may cause difficulties in the comparison of results. Density is a generic term that can be appropriated in urbanism to characterize different factors in various disciplines: building density, built density, net density, gross density, parcel density, network density, general density, community density, descriptive density, prescriptive density, normative density, physical density, perceived density, performance density, residential density, population density, job density, among others. These terms were shortlisted from authors such as Acioly and Davidson (1998), Churchman (1999), Ng (2009), Berghauser Pont and Haupt (2010), Lehmann (2016), and Mohajeri et al. (2016), who describe the difference between these concepts.

For the purposes of this study, higher density shall be related to urban morphology, in terms of floor area ratio (FAR) and building coverage. In this sense, it refers to built density. The Floor Area Ratio (FAR) is the ratio of built area (the sum of the total area of a building) to the lot area (the total area of the site in which the building is built), while building coverage is the proportion between the ground floor area of enclosed buildings and the total area of the lot (Lee et al., 2011). Those measures are used by planners, regulators and developers to distinguish the concentration of an urban development. Examples of different urban configurations resulting from different FAR and building coverage are presented in Figure 11.

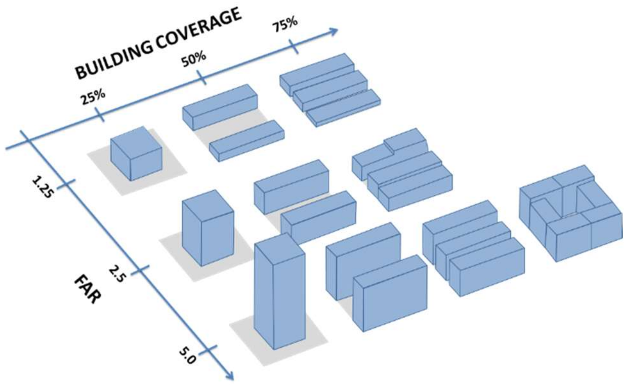


Figure 11: FAR *vs.* Building Coverage considering the same plot size.
Source: adapted from Lee et al. (2011).

The Density Atlas (Lee et al., 2011), Spacematrix (Berghauser Pont and Haupt, 2010), WUDAPT (Ching et al., 2018), Urban Block Generator (Shi et al., 2021), Google Earth (Sheppard and Cizek, 2009) and their components are interesting digital tools to explore the variability of urban morphology and built densities– especially in terms of heterogeneity and homogeneity of buildings in shape and height, and considering that the conceptual characterization of ‘high density’ in cities may vary. With the support of some of these tools, for instance, it is possible to observe that density in cities in the Southeast Asia is peculiar due to extremely great height of buildings. Figure 12 presents examples of urban morphologies found in London, Rio de Janeiro, Mumbai, Shanghai, which were explored visually using the tool Google Earth.

Churchman (1999) summarized the advantages and disadvantages of density, highlighting the complexity of the topic. Decades of debate made clear that high density (high FAR + high building coverage) is not a solution for every city, but it is probably suitable for highly populated ones.

Predominantly, large urban areas in the world have extensive suburbs of lower density when compared to historic cores (Demographia, 2018), representing a sprawl behavior that may cause several disturbances. High built density is seen as positively affecting land use, economy, commuting time, energy for transportation, social interaction, innovation and urban livability (United Nations, 2015).

Figure 12: Differences in urban morphology of cities visualized using a digital tool.
Ex.: London, Rio de Janeiro, Mumbai, Shanghai. Source: Google Earth, eye alt ~1-2km, no scale.

In the field of urban design, for instance, Steemers (2003) lists ways to increase density by increasing: a) building depth; b) building height or aspect ratio H/W; c) 'compactness', in order to avoid detached units. However, based on the analysis of housing in UK, this author states that such strategy needs to be balanced: "t*he way to increase density and energy efficiency simultaneously is to increase 'compactness' of the urban fabric whilst maintaining a limited building depth (in the order of 10–12 m), and where an appropriate solar orientation is ensured to access light, sun and air*". A concept explored for increase urban density is the daylight envelope, similar to the solar envelope: a virtual volume around a block to guide the design buildings, limiting their boundaries. This volume is defined to provide daylight to lower floors of opposite or surrounding buildings; given a street width, a maximum H/W is calculated according a targeted daylight factor (DF), considering latitude, window area, and outdoor reflectance (DeKay, 2010).

Computer simulation is being applied to understand to which extent it is possible to increase built density without compromising performance in diverse fields, including in urban daylight. Simulations is useful to estimate quantities when conditions for that are complicated, risky, time-consuming, expensive, or impossible (Baron, 2013). The following sections present studies that use computer simulation to evaluate indoor daylight performance by using static and/or dynamic metrics. With respect to those studies, it is relevant to observe that, due to the complexity of factors that interfere with daylight simulation, simplifications are a common occurrence in the models. One example thereof is to limit the assessment to illuminance levels in the façade, as a proxy of what would happen indoors (i.e., Ratti et al., 2005). Another strategy is the reduction of the number of simulations using statistics to prepare the experiment or use statistics to expand the comprehension of results to other situations (Martins et al., 2014). The 3D models were simplified to theoretical blocks, according to the typology of a canyon, grid or courtyard (Cheng et al., 2006a; Sattrup and Strømann-Andersen, 2013), with windows positioned only in the tested room/area. There was also no differentiation of functions such as residential, commercial, or public units inside the same model (Saratsis, 2015; Nault, 2016). The absence of irregular topography, vegetation, and water-bodies represented further simplifications aimed at reducing complexity of the models.

Static metrics in urban studies of daylight

Ng (2001b) evaluated daylight performance in high-density urban residential buildings. The author used site-measurements against simulations in Radiance and Lightscape. The static metric Vertical Daylight Factor was considered. The author states that in highly obstructed conditions, most of indoor daylight results from interreflected light. So, outdoor reflectances varied as follows: 0, 0.2, 0.4 and 0.6. The results indicated that both software solutions over-estimate daylight availability for lower floors and when the obstruction angle is high (>35◦ approx.). Errors increased with increased surface reflectances: for Radiance, the author recommended the use of values below 0.5 to minimize the differences. It should be noted that this research was conducted for the CIE Overcast Sky and using older versions of the software; no updated investigation has been found.

Cheng et al. (2006a) analyzed the influence of built form and density (FAR and plot ratio) on the solar potential of 3D models. More specifically, the 3D model was a theoretical grid of 5 x 5 buildings of the pavilion type, surrounded by 2 rows of buildings of different random heights, resulting in a SVF>0.2 (up to 0.26). The buildings of the matrix 5x5 had the heights varying uniformly, randomly, or as a pyramid, with higher buildings in the center of the block (Figure 13). The highly populated city of Sao Paulo (23.5°S) was chosen as a case study. The output solar potential was evaluated in terms of daylight on the façade, and PV potential on façade and roofs. The study demonstrated possibilities to increase usable floor area and plot ratio without undermining daylight and solar applications. The resulting daylight factor was found to be more dependent on plot ratio, whilst the solar potential on façade was more related to site coverage and the degree of horizontal obstruction.

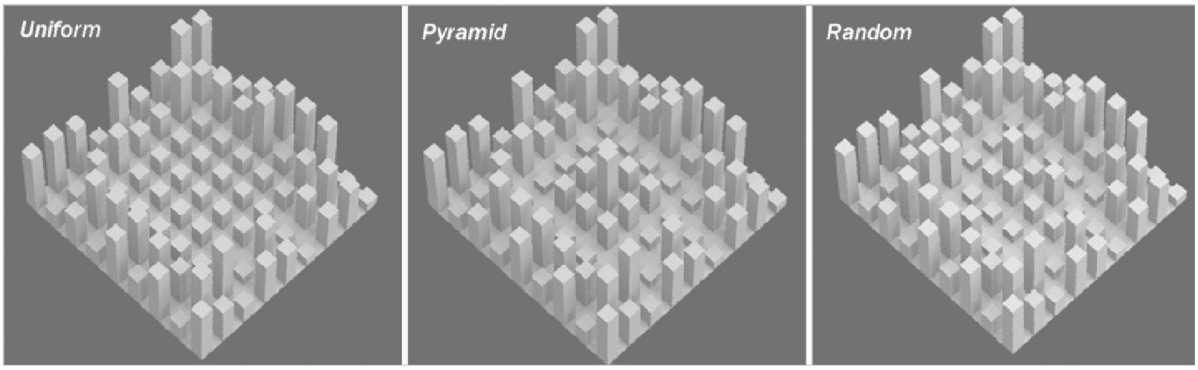


Figure 13: theoretical 3D model for daylight simulation in the urban scale.
Source: Cheng et al. (2006a). Used with permission.

Cheng et al. (2006b) extended the previous study by simulating additional models, variating the position of buildings on the site. The results suggest that in terms of daylight, arrangements with higher buildings, less site coverage and more open space are more preferable than those with lower buildings and higher site coverage. Additionally, the authors met with favorable results for daylight when the horizontal position and the heights of the buildings varied randomly on the site. This type of random variation is not a common strategy found in instruments for urban design. Comparisons between what the authors named ‘good layouts’ at high plot ratio and ‘poor layouts’ at low plot ratio reveal the possibilities to increase usable floor area and, at the same time, maintain and even increase daylight and solar potential. The results were in contrast to the conventional assumption that increasing built density would lead to deterioration of the immediate environment, in relation to solar access and lessening the potential for renewable energy application at the urban scale. They used computer simulation with a Radiance-based modeling system to calculate solar availability and, from the findings, they proposed a new layout for a part of the existing center of the city of Sao Paulo in order to favor daylight and SVF.

Li et al. (2010) proposed simple mathematical expressions and diagrams to calculate the daylight illuminance on a vertical plane of an obstructed urban canyon under non-overcast sky conditions. The study applied the software Radiance and measurements under real skies of Hong Kong. They observed that "*the shading effects due to surrounding buildings could substantially restrict the diffuse light coming from the sky (…). Moreover, most of the natural light for windows of lower floors is due to light reflected from the surrounding surfaces*".

Martins (2014) investigated how parameters of urban morphology and albedo influence energy savings of buildings in a coastal city within the tropics (Maceió, 9°39′ S), under the target of avoiding solar heat gain while providing minimum level of daylight, considering a static metric. They used the software CitySim to simulate models of urban density. Using statistics, the authors identified that total built density, verticality, compactness, and the mean prospectus H/W (ratio of the canyon height to canyon width) had a major impact on quantitative daylight in the test conditions.

Scalco and Pereira (2016) developed a method to evaluate the impact of buildings in daylight performance of a neighborhood in Brazil. They compared different urban configurations with the same built area using the software APOLUX and assuming partially cloudy sky. Regular, homogeneous building configurations with 5 floors, and building footprint of 75% of the gross area of the plot presented worst results in comparison to taller buildings with low building footprint. For future studies, among other topics, they recommended to: consider reflection by outdoor obstructions, evaluate the effect of different type of skies, and use dynamic simulation.

Dynamic metrics in urban and architectural studies of daylight

Reinhart et al. (2006) presented the advantages of dynamic performance metrics over the static ones. For that, they presented the results of a comparison of performance in the front and in the back half of an office by applying different metrics: daylight factor (DF), conventional daylight autonomy (DA), continuous daylight autonomy, Useful Daylight Index (UDI), Maximum DA (DAmax). Variations in the model included solar orientation, occupancy patterns, climate, illuminance requirements, and shadings in the window -the positions of blinds, light shelves, translucent panel (glazing), and overhangs. In conclusion, they advocate for the adoption of these dynamic metrics because: (a) their physical simulation models were validated for different building materials and geometries; (b) emerged user-friendly assessment tools simplified the calculation process; (c) inputs required are available; (d) their predictive power for design comparisons is larger than the one provided by daylight factor. Finally, they highlight the need for benchmarks, and the demand for metrics that evaluate multiple aspects of daylight. Overall, they upholded that dynamic metrics could lead to superior daylight designs.

Kleindienst et al. (2008) proposed a method that simplifies annual weather files for spatial and temporal daylight evaluation in early design stages. Two unobstructed geometries were simulated: rectangular room and a four-room squared museum. Starting from DA, the authors suggested an area-based metric in which a percentage of space above a target value is assessed. Ten cities were selected for performance simulation under the same metric, considering population size, variation in latitude, climate, and sun hours: Singapore, Addis Ababa, Bangkok, Harare, Hong Kong, Phoenix, Sydney, Boston, London, St. Petersburg. Results of indoor daylight performance among the cities were statistically compared.

Mardaljevic et al. (2011) tested and discussed the use of dynamic metric for residential spaces. More specifically, they applied UDI considering three ranges: supplementary from 100 to 300 lux; autonomous from 300 to 3000 lux, exceeded if >3000 lux. In the course of defining these thresholds, the authors mentioned that researches in non-domestic buildings indicated a small switch-on probability for desktop illuminances above 250 lux, and that "*it is reasonable to suppose that similar behavior might ensue*" in domestic buildings. A designed residential space found in Europe was simulated from 8h to 20h; different rooms with windows and skylights were evaluated. Illuminance levels in horizontal and vertical planes in the height of the eye were analyzed, metrics for non-visual effects of light were discussed, and potential lighting energy savings based on a numerical model were calculated. Conditions in 8 cities under middle and high latitude[12] were evaluated: Hamburg (Germany), Madrid (Spain), Paris (France), London (UK), Rome (Italy), Warsaw (Poland), Moscow (Russia) and Ostersund (Sweden). From this study, it can be inferred that illuminances of ca. 300 lux provided solely by daylight would encourage energy savings in both domestic and non-domestic buildings.

Heschong (2012) presented the results of a remarkable evaluation of metrics related to visual effects of indoor light. Awarded researchers and experts[13] in the field participated in the task force to answer, among other questions, "*What is a sufficient daylight?*". The goal was to generate and test metrics that could address "*1) daylight sufficiency, 2) daylight excessiveness, and 3) daylight quality*". The committee decided a priori to search for a unique value representative of conditions in the year, in other words, for an annual metric. Daylight sufficiency, "*one dimension of the visual quality in daylit spaces*", was approached as task illuminance over space and time. Apart from sufficiency, the research also investigated sun penetration, uniformity and other glare proxies. The methodology consisted in the analysis of a sample of 61 spaces (classroom/conference room, office/study area,

[12] Reference of latitudes: low= 0-30, middle= 30-60, high= 60-90 degrees.

[13] Including experts from the Lawrence Berkeley National Laboratory (LBNL); members of the Illuminating Engineering Society Daylight Metrics Committee; academics from Harvard University, MIT, EPFL, University of Washington, among others, in a research sponsored by the California Energy Commission in the U.S.A.

library/lobby/multipurpose room) located in the U.S.A. in Washington State (Seattle/Tacoma), New York State (—Albany, and New York City), and California (San Francisco/Oakland, Sacramento and Truckee), in rural and urban areas, from moderate to temperate climate, from sunny to overcast sky. It included qualitative survey, measurements of daylight parameters, detailed computer simulation of indoor daylight, and statistical multivariate linear regression analysis. Metrics tested in the program included DaqXXX, iDA, UDIa, sDA, DSP, cDA, DF, size of view of the sky, among others. Under their boundary conditions and pre-defined criteria, conclusions of the research were as follows:

- in terms of daylight sufficiency, the 'spatial Daylight Autonomy' was "*the best descriptor for daylight performance*" among all the tested metrics;
- the illuminance threshold level of 300 lux was recommended for daylight sufficiency metrics, at least for the space types evaluated;
- considering discomfort, once "*no level of annual daylight illuminance was found to be too high*" in the surveys and that "*low levels of daylight illuminance were found to most strongly predict occupant discomfort relative to contrast, reflections or glare*", it was concluded that "*no upper illuminance threshold (should) be used for determining the visual quality of a space*";
- the metric corresponding to "*the maximum number of hours per year that sunlight could potentially enter the space, assuming the blinds were always left open, and accounting for local weather*" was the most successful in predicting visual discomfort;
- blinds were simulated as closed, operated, and open. Observations and survey identified that blinds were more often opened than closed in the spaces, "*implying that the blinds were not managed to totally block sunlight at all times*". Additionally, results indicated that statistical "*regressions using 'Blinds Open' as the outcome variable had a better fit to the survey data than did the 'Blinds Closed'*";
- finally, the team pointed out that further studies should be conducted on other climates, space types, blind types and operation, as well as on descriptors of daylight quality, especially on visual comfort.

Drawing partially from this project, the Illuminating Engineering Society launched the IES LM-83-12 (2012), a standard that defined two climate-based metrics: sDA and ASE. The first one, sDA was established for the purposes of this standard with the thresholds [300 lux][50% of 8h-18h] ≥ 55% or 75% of the space, as explained in the section devoted to metrics. The second, ASE, was defined from [1000 lux] [250h of direct sunlight], requiring that a window should be simulated with the blind unless it "*will not be installed*" or ASE is acceptable. The blind should be triggered under direct sunlight, when 2% of the points ≥ 1000 lux.

Albuquerque and Amorim (2012) simulated the influence of the parameters room depth and solar protection on daylight performance of a non-obstructed room with one window (WFR=1/6). The aim was to support the development of guidelines on room depth limits for the Brazilian regulation on energy efficiency in buildings. The authors tested the presence and absence of overhang to the window, 4 solar orientations, and different room sizes. The metric DA and sDA were tested under different thresholds (i.e., minimum lux levels of 60 and 100 lux). The occupation period was diverse (6h-18h, 8h-16h, 1h after sunrise until 1h before sunset in winter solstice). Results pertaining to the rooms were obtained for cities with 11 different latitudes and climates within the country. The results took the authors to prescribe a room depth of 2.57 times the window [head] height under certain conditions (i.e., similarity of the room to the tested ones, WFR=1/6, reflectance of 80% for ceiling and 60% for walls). For other specific cases, computer simulation is recommended.

Reinhart et al. (2013) introduced the urban modelling design platform umi, a tool for the assessment of indoor daylighting and operational energy in neighborhoods, among its other capabilities. In this publication, tests in an urban unit with mixed use and different building typologies in the city of Boston (U.S.A.) are presented. The tests considered a minimum threshold of 300 lux for residences and 500 lux for commercial, occupation of 50% of 8h-18h, with possible outputs as DA, cDA, sDA. The tool would be further developed to integrate modules, which represented an additional benefit reinforcing its feature of allowing easy modeling and results visualization to students and design practitioners.

Sattrup and Strømann-Andersen (2013) proposed a method for comparison of daylight and energy performance in different block typologies, with different densities, considering that Northern European cities have "*a relatively uniform urban scale*" with buildings of 5-6 floors located in the center, and single-level family houses in the periphery. They simulated blocks as courtyard blocks, indented blocks, perimeter blocks, barcode, slab, or tower. All of them were organized in a 3x3 matrix, composed of buildings of up to 15m in height, with plot ratio varying between 100% and 400%. Apartments facing opposite façades of the central building were analyzed, with a WWR=30%, aiming at least DA [200 lux] [6h-18h]. The results indicated that daylight performance (DA) is very sensitive to the geometric design of the typology, and it varies in higher degree from energy consumption when different typologies are compared.

Reinhart (2014) compiled the relation of daylight and the depth of a space according to design guides from the USA, UK and Germany, none of them based on dynamic metrics. In these documents, the depth of a daylit area of a sidelit space lies between 1 and 2.5 times the dimension of the window head height. Computer simulations of models were also conducted to explore indoor daylight conditions. One of the simulated models was a reference office room, WWR=45%, positioned inside an urban canyon of uniform height, rotated in four cardinal directions. Considering three cities with latitudes>33°N, a linear decrease of the daylit area was observed as a consequence of the increase of the front obstruction.

Wagdy et al. (2015) investigated the optimum window-to-wall-ratio (WWR) for dwellings of informal settlements in Cairo (Egypt). They assessed $sDA_{(300,50\%)}$ of a south-oriented room of dimensions 4x6x3 (w x d x h, m) and reflectances 20/50/80 (floor, walls, ceiling, %), under different H/W ratio (streets' width 4-8m, front buildings' height up to nine floors). Among other results, they observed that daylight reflected from the ground had a lower impact on overall indoor daylight in dense settlements, under the simulated conditions in this hot, desert climate.

Paule and Kaempf (2016) compared performance results of two different software: one developed for detailed architectural scale, and other for urban scale. They aimed for a minimum of 300 lux in two points: one close and the other far from the window of an office in Bogotá (Colombia). The room was located in an upper floor of an existing building surrounded by urban area. Results were similar close to the window, and notably divergent in the back of the room. The authors suggest that this divergence is a consequence of different approach to reflectances in the software for urban scale *vs.* the one prepared for architectural assessment.

Saratsis (2015) proposed a framework to evaluate how vertical densification affects indoor performance of an urban area, aiming to support the development of zoning rules. Buildings of non-specified use prescribed under the legislation of New York City were adopted to define the models: 50 neighborhoods, with building height of 9-18m or 3-150m and WWR=100%, density in FAR 3-35. Each neighborhood belonged to one of 5 typologies: perimeter, atrium, courtyard, alley, double alley. The software applied was Urban Daylight, in which windows are equivalent to 100% diffusing glass, Tvis= 50%. The criteria was sDA [300 lux][50% of 8h-18h] ≥ 55% (LEED v4-2014). Blinds were triggered not as required by the standard IESNA LM-83-12, but as required by the certification LEED v4, which represented a complex process for the existing software; thus, a simplification was adopted: 50% cut-off value when illuminance was above 20 klx. The number of 6 bounces defined by the standard for architectural application was reduced to 4. As a result of the simulations in open floor plans, the authors observed a steady decrease of daylight in lower levels with increase in height of buildings, and registered good daylight levels in the top sections of buildings in all cases. They identified that most of the typologies did not meet sDA > 55%, even with low height and maximum-sized windows.

Nault et al. (2017) developed a metamodel for energy and daylight assessment in early stages of urban design, to replace detailed simulation. They simulated blocks with variation of 7 building typologies: adjacent, low-rise, mid-rise, high-rise, linear, L-shaped, courtyard. For that purpose, they used $sDA_{(300,\ 50\%)}$ as per IESNA (2012). However, in order not to assume any fixed building function, the occupation period was extended to 8h-22h "*to cover most daylight* *hours*", considering the city of Geneva (Switzerland), and open floor plans. Ambient bounces were set as 2. The outputs were treated with both multiple linear regression and Gaussian process regression to generate the metamodels. The results obtained with these simplified numerical equations were compared to the ones provided by detailed simulations: the small difference in values indicated that the metamodels might be a promising alternative for analysis in early stages of urban design.

Beck et al. (2017) evaluated the indoor performance of blocks in low latitude, in the city of Florianópolis, Brazil. They altered building geometry, occupation rates, FAR, among other parameters, aiming for DA [300 lux], UDI [300-3000 lux]. The blocks were positioned in a matrix (3x3), each formed by 14 plots (2x7). In each plot, daylight was assessed in a central building whose height varied from 6m to 36m, with WFR=1/6, and glazing Tvis=88%. Results quantified to what extent the rooms with windows in the front façade and located in the upper floors performed better than rooms with windows in lateral façade and in lower floors in the tests.

Santos et al. (2017) investigated the effects of changes in urban and architectural parameters on daylight performance of a room located on the ground floor of a continuous canyon. Under consideration was $sDA_{(300,50\%)}$ ≥75%, for the city of Cuiabá (15°S, 56°W, Brazil). In the parametric study, altered parameters included: street distance, height of front obstruction (front side of the canyon), room depth and orientation of the canyon. Linear regression was used to better analyze the phenomena. Among all evaluated parameters, room depth tended to be the most relevant for the optimization of indoor daylight.

Dogan and Park (2017) presented a study with 5 residential buildings within 5 typologies of urban context: bar, 'urban' (non-regular pattern), infill, tower, solitaire (detached). They calculated an RDA as SDA 300 lux, 50% of the space, for 12 periods of the year (4 seasons times 3 daily intervals: morning from sunrise to 11h, afternoon from 11h to 15h, and evening from 15h to sunset), with no upper illuminance limits, no shading, no internal partitions. They focused on high latitudes: Zurich (Switzerland), Madrid (Spain), Berlin and Stuttgart (Germany), Rotterdam (The Netherlands). As a result, they stated the potential of new metrics to assess aspects of daylight in residential spaces. The authors recommended further research on upper limits and noted that in hot and arid climates direct sun might not be desirable. An implicit suggestion is that both RDA and DLA should be reviewed for these climates.

Later, Dogan and Park (2018) focused on a comparison of dynamic metrics and the potential of their proposed new metric for residential spaces for cities in high latitudes, in this case Berlin and Rotterdam. They compared the performance of apartments in different floor levels of buildings, having adjacent and front buildings also modelled. The outputs were compared in terms of DA 300 lx; cDA 300 lx; UDI autonomous; $sDA_{(300,\ 50\%)}$; ASE 250hrs, 1000 lx; RDS, RDA, DLA as defined in 2017. Their conclusion was that "*the overall trends in both existing and proposed metrics are similar*", with differences most apparent depending on the level of obstructions and solar orientation of the window. The authors mentioned that simulations on the typology of open floor plan result in up to 20% worse performance than in test rooms of smaller areas, because internal partitions tend to optimize daylight indoor due to reflection.

Noticeable, Quek and Jakubiec (2019) proposed a method to calibrate dynamic daylighting and electric lighting simulation models based on indoor measurements of offices in Singapore.

Table 5 presents a summary of the selected researches that have adopted dynamic metrics in the last decade, in chronological order and with indication of the scale of the model. As it can be noticed, there is no consensus in the choice of metrics, thresholds or period of analysis. The concepts of DA and sDA were frequently adopted, including being adjusted for applications in the urban environment. For urban scale, almost all of the studies were theoretical, using simplified geometries, adopting the minimum of 300 lux in diverse typologies, even without differentiation between residential spaces or offices in urban areas. These characteristics find resonance in Heschong (2012) and in Mardaljevic et al. (2011).

Table 5:

Indoor daylight using computer simulation and dynamic metrics.

Year	Authors	Scale/Concept	Criteria	Test case	Location	Results
2006	Reinhart et al.	Building/ Theoretical and quantitative comparison of metrics.	DF, DA, DAcon, UDI, DAmax.	Office room varied orientation, occupancy, climate, lux required, shadings.	Boulder and Arcata,USA	Dynamic metrics should replace static ones.
2008	Kleindienst et al.	Building/ Method for simplified annual weather files for early design stages.	Daysim *versus* ASRC-CIE sky model.	Simple room and a four-room museum.	10 cities, different latitudes and climates.	Method for pre-processing annual data with results visualized in temporal maps.
2011	Mardaljevic et al.	Building/ Dynamic metric for residential space.	UDI (100 to 300 lux; 300 to 3000 lux, >3000 lux). Hours from 8h to 20h.	Residential rooms with windows and/or skylights were evaluated.	8 cities in middle and high latitude.	Discussed metric and potential energy savings.
2012	Heschong	Building/ Development and test of several metrics.	DF, sDA, cDA, DA, inverse DA, UDI, etc.	61 non-residential spaces.	8 cities in USA.	Recommended sDA; minimum of 300 lux without upper limit.
2012	IES Committee	Building/ Standardization: definition of two climate-based metrics: sDA and ASE.	sDA [300 lux][50% of 8h-18h] ≥ 55% or 75%. ASE [1klx][250h of direct sunlight].	Varied workspaces	Mentioned studies in USA, potential for cities of similar latitudes.	Concept of metrics and characteristics of simulation models.

(Table 5 continued)

Year	Authors	Scale/Concept	Criteria	Test case	Location	Results
2012	Albuquerque and Amorim	Building/ Case study: varied room depth and solar protection.	DA of 80% and 70%, 60-100 lux. sDA (>50% and >70%). Occupation: diverse.	Room with and without overhang.	Brazil, 11 cities with 11 latitudes and different climates.	Guidelines on room depth limits for daylight, adopted in the national regulation.
2013	Reinhart et al.	Block-neighborhood/ Tool umi for neighborhoods.	DA, cDA, sDA [300 lux for residential spaces, 500 lux for commercial] [50% of 8h-18h]	Neighborhood with mixed use and different building typologies.	Boston, USA	Further developed to integrate modules; easy for modelling and visualization.
2013	Sattrup and Strømann-Andersen	Block/ Method for comparison of performance in different typologies/densities.	DA [200 lux] [6h-18h]. Other details not mentioned.	Blocks up to 15m in height. Varied plot ratio.	Selection of Northern European cities.	DA varies more than energy consumption.
2015	Saratsis	Block-neighborhood/ Framework for analysis and development of zoning rules.	sDA [300 lux][50% of 8h-18h] ≥ 55% (LEED v4-2014).	50 neighborhoods of 5 typologies, building up to 150m.	New York, USA	Most of the typologies do not meet sDA ≥ 55%.
2016	Paule and Kaempf	Building-Block/ Case study: compared results provided by two different softwares.	300 lux	Room (office) surrounded by urban area.	Bogotá, Colombia	Results are divergent in the back of the room.
2017	Nault et al.	Block-neighborhood/ Metamodel to replace simulation.	sDA [300 lux][50% of 8h-22h].	Blocks with variation of 7 building typologies.	Geneva, Switzerland	Detailed simulations *vs*. metamodels provide similar results.
2017	Beck et al.	Block-neighborhood/ Case study: varied building geometry, occupation rates, FAR, among others.	DA [300 lux], UDI [300-3000 lux]	Buildings in plots with distances according to legislation.	Florianópolis Brazil	Rooms with windows in the front façade and in the upper floors performed better.
2017	Dogan and Park	Proposed Residential metrics: RDS, RDA, DLA.	RDA as SDA 300 lux, 50% of the space, 12 x per year.	5 residential buildings within urban context.	5 cities, middle and high latitudes.	Potential of new metrics.
2018	Dogan and Park	Building-Block/ Compared existing dynamic metrics *versus* the new ones proposed for residential spaces.	DA 300 lx; cDA 300 lx; UDI; sDA 300 lx, 50% time; aSE 250hrs, 1000 lx; RDS, RDA, DLA.	Apartments in different stories; with adjacent and front buildings.	Selection of cities in high latitudes.	Quantitative differences, potential advantages of DRS for residential spaces.

Source: own author.

2.3.3. Computer simulation and models for daylight

Algorithms and models that support daylight simulation are diverse. This section discusses sky models, light transfer models, 3D models and available software.

Sky models

In digital simulation the sky can be represented generally as a large hemisphere with a superimposed luminance distribution, or as collection of light sources (Geebelen, 2003).

This goal of representing atmospheric characteristics of the sky properly resulted in the evolution of sky models (Table 6). The Uniform Luminance Sky, a heavily overcast sky with constant brightness, is the simplest sky model; it is no longer used in modelling since it is not representative of meteorological conditions: since 1901 it has been recorded that densely overcast sky exhibits a relative gradation from darker horizon to brighter zenith (Mardaljevic, 1999).

Table 6:

Panorama of the sky models to characterize the distribution of luminance.

Authors	Aim of the Model	Year	Remarks
Moon and Spencer	Characterize the luminance distribution (overcast).	1942	Recommended by CIE in 1955 - standard overcast sky.
Kittler	Characterize the luminance distribution (clear sky).	1967	Recommended by CIE in 1973 - clear sky (completely cloudless).
Littlefair	Characterize the luminance distribution (Intermediate sky).	1981	Proposes the distribution of luminance for each solar altitude - denomination: *BRE Average Sky*.
Nakamura	Characterize the luminance distribution (Intermediate sky).	1985	Describes the luminance of the zenith for this proposed sky.
Kittler	Characterize the luminance distribution (from clear to overcast).	1985	Assumed that the sky condition varies homogeneously; from clear sky to overcast sky.
Perraudeau	Characterize the luminance distributions for each sky type.	1988	It arranges the skies in five categories: overcast; intermediate overcast; intermediate; intermediate clear and clear sky.
Perez	Characterize a model in function of the indexes of clarity and sky luminance.	1990	*All weather models* named and classified to parameterize the conditions of overcast, bright, intermediate, partly cloudy and very clear sky.
Perez, Kittler and Darula	Characterize the luminance distributions for each sky type.	1997	Classification of distribution of sky luminance in fifteen categories.
CIE	Characterize the luminance distributions for each sky type.	2002	Used the classification of distribution of luminance of the sky in fifteen categories developed by Perez, Kittler and Darula (1997).

Source: Pereira (2009, p.17); own translation.

According to a review by Pereira (2009), a sphere with uniform luminance was a starting point. In 1942, Moon and Spencer developed a model to define the luminance distribution of an overcast sky which was adopted as standard overcast sky by CIE in 1955. Later, Kittler characterized the luminance distribution for a clear sky, also recommended by CIE in 1973. Kittler characterized the luminance distribution from clear to overcast sky in 1985, assuming that the sky condition varies homogeneously. In 1997, Perez, Kittler and Darula adjusted a previous model and proposed a classification of distribution of sky luminance in fifteen categories, which was the basis of the model adopted in the standard ISO 15469:2003(E) CIE S 011/E:2003 (Table 7).

This standard determines a group of fifteen "*outdoor daylight conditions linking sunlight and skylight*", setting a basis for the classification of measured sky luminance distributions and giving a method for calculating sky luminance in design. Absolute luminance distributions of the sky can be calculated using values of zenith illuminance or horizontal illuminance. Skies range from 1 (overcast) to 15 (white-blue with turbid sky), variations from overcast, partly cloudy, and clear.

Table 7:

List of the 15 sky types.

Sky	Description
1	CIE Standard Overcast Sky, steep luminance gradation towards zenith, azimuthal uniformity
2	Overcast, steep luminance gradation, slight brightening towards the sun
3	Overcast, moderately graded with azimuthal uniformity
4	Overcast, moderately graded, slight brightening towards the sun
5	Sky of uniform luminance
6	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	Partly cloudy, with the obscured sun
10	Partly cloudy, with brighter circumsolar region
11	White-blue sky with distinct solar corona
12	CIE Standard Clear Sky, low luminance turbidity
13	CIE Standard Clear Sky, polluted atmosphere
14	Cloudless turbid sky with broad solar corona
15	White-blue turbid sky with broad solar corona

Source: adapted from the standard ISO 15469:2003(E) CIE S 011/E:2003.

Figure 14 illustrates sky types 1,4,5,7,12, 15 with corresponding scale of luminance, obtained using the software APOLUX, version of October/2017. The software can produce representations of all of the 15 skies based on the standard - ISO 15469:2004 (E) CIE S 011-E:2003, for different locations and time of the year, using hourly intervals. Here the sample of sky types was extracted for the city of Rio de Janeiro (south hemisphere, ca. 22◦S and 43◦E). The random time and date (sun at 13:30h, 27th Jan) were chosen to highlight the feature of the software to explore conditions beyond the usual solstice or equinox. It is possible to observe, for instance, the absence of luminance levels below 200 cd/m², as well as the variation of luminance levels among the skies, with some of them presenting a higher intensity surrounding 'the sun' close to the center of the circle and/or close to the horizon.

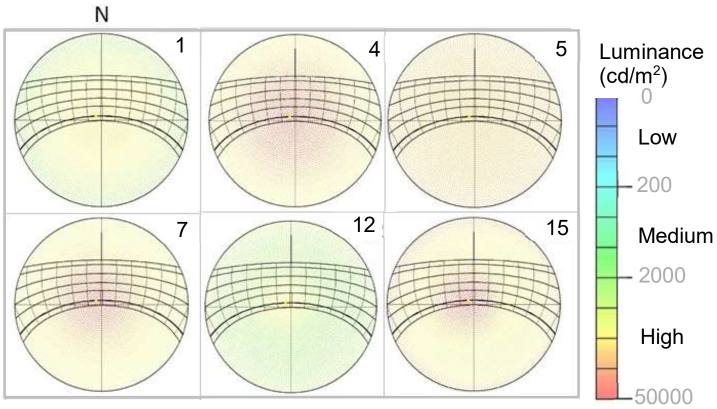


Figure 14: Example of sky types obtained with APOLUX for the city of Rio de Janeiro. Note: close to noon, summer (27th Jan, 13:30h). Source: own author.

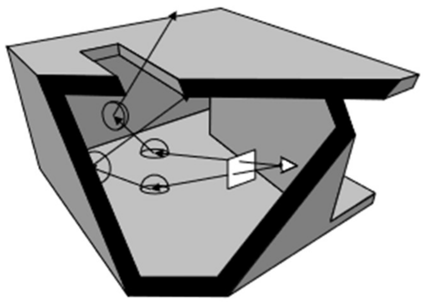
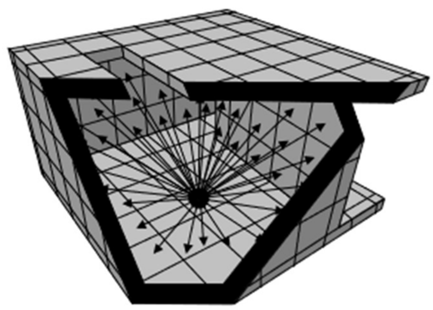
Light transfer models

The efforts to simulate the light transfer between surfaces of a scene resulted in the development of algorithms referred to as 'global illumination' models. They determine simplified solutions for the rendering equation. This equation basically computes the luminance at a point by computing the luminance values at all surrounding points, without accounting for interaction with the medium or spectral effects. More specifically, this core equation was built to express "*the amount of light leaving a surface at a certain point in a certain direction as the sum of the surface's own emittance and the light reflected and transmitted by the surface*" (Geebelen, 2003). The complexity of the iterations and models to execute the process have evolved since then. However, there remain two major techniques proposing solutions to this equation in order to calculate luminance of surfaces in a scene or environment with high accuracy. These techniques are ray tracing and radiosity. Both techniques are useful for diagnosis of illuminance levels indoor.

According to Geebelen (2003), in ray tracing the paths of each light ray are followed in the direction of light propagation i.e. from the light source towards the scene (forward ray tracing), or from the observer to the light source (named backward ray tracing). Radiosity was developed later and it subdivides the scene into a number of patches and nodes, specifying that all light exchange happens between those nodes (Table 8). Luminance in each node is a combination of the luminance values in the other nodes, and the luminance between other nodes can be solved by interpolation. In this way, radiosity reduces the problem to a system of 'n' equations that expresses the luminance in each node; the n × n coefficients of the system are named form factors, each of them describing the light transfer between a pair of nodes. According to this analysis, which was revisited by Claro (2015), ray tracing is view-dependent; performs the best with specular materials; treats transparencies and direct lighting properly; is capable of responding to any geometry, but does not compute overall light distribution in the scene. By contrast, radiosity is view-independent; performs best with diffuse materials and large light sources; treats indirect lighting properly; works best with faceted shapes and opaque surfaces; and computes the overall light distribution properly.

Table 8:

Conceptual and visual comparison between classical ray tracing and classical radiosity, beginning of the 21st century.

Ray tracing	Radiosity
View-dependent.	View-independent.
Handles specular behavior best.	Handles diffuse behavior best.
Handles any geometry.	Performs best with faceted shapes.
Can handle transparency.	Performs best with opaque surfaces.
Does not compute the overall light distribution in the scene.	Does compute the overall light distribution in the scene.
Has difficulties with indirect lighting.	Indirect lighting is treated correctly.
	

Source: Geebelen (2003). Used with permission.

Virtual 3D Models

The typology of the models used for computer simulation in studies of climate-responsive design in the urban and architectural scales can be summarized as presented in Table 9.

The choice of a 3D model depends upon the desired outputs, their amount, their influential factors, the aimed accuracy level, the processing time and demandingness, among other factors. Additionally, based on markings observed in literature, the models could be generally classified by their:

1) Physical scale: room, building, canyon, block, neighborhood/district/city,
2) Design: theoretical or existing (as built),
3) Concept: hypothetical or forecasted,
4) Typology and/or layout: heterogeneous or homogeneous,
5) Function: multiple or single use,

6) Pattern: non-structured or structured (i.e. local legislation, LCZ system),

7) Composition: reduced or ‘complete’ sample, with(out) buffer zone (extrapolated boundary),

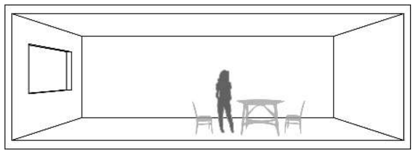
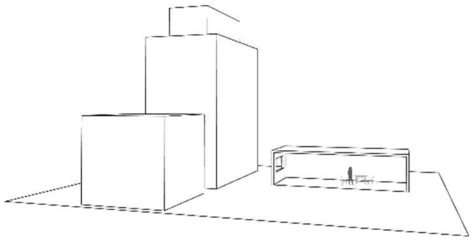
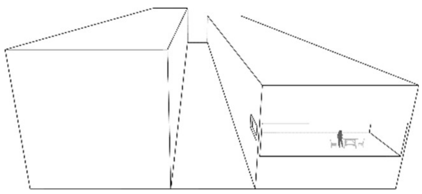
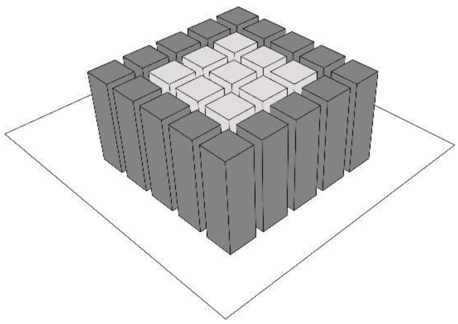
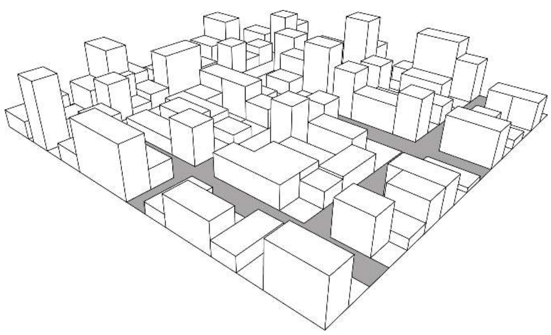
8) Input parameters: simplified or detailed, dependent upon the factors such as:

9) Climate/spatial scale: micro-, local climate,

10) Temporal scale: hour, annual, seasonal, etc.

Table 9:

Types of 3D models.

#	Physical Scale	Sketch of the 3D model	Example
1	Room/Unit		Kleindienst et al. (2008); Mardaljevic et al. (2011)
2	Buildings		Dogan and Park (2017)
3	Canyon		Santamouris et al. (2001); Strømann-Andersen and Sattrup, 2011.
4	Block		Ng (2003), Cheng et al. (2006), Sattrup and Strømann-Andersen (2013), Martins et al. (2016), Chen and Nordford (2017)
5	Neighborhood/ District/ City		Ratti et al. (2003), Compagnon (2004), Reinhart et al. (2013),

Source: own author.

More specifically, in terms of ‘design’, there can be found 3D models of an existing built area and/or a part of it which is a theoretical, proposed design. The ‘concept’ can explore hypothetical variations not related to reality or ‘as built’ model, or can follow existing models of structure. In terms of ‘pattern’, it can be non-structured (randomly selected, based on modular mathematical patterns, etc.), or based on a ‘rule’ (legislation, guideline, etc.). As ‘function’, it can incorporate diverse uses such as offices, residential buildings, public spaces, or be reduced to one or a couple of them. ‘Inputs’ are much related to desired outputs and factors such as contextual time and space. Natural components such as topography and greenery are incorporated when their effect is a focal point of the study.

The room unit was adopted in several detailed daylight analyses, with similar measures such as width usually close to 3m (e.g. Cabús, 2005; Reinhart, 2014; Albuquerque and Amorim, 2012); studies of the software Radiance were developed using the “*typical (dimension) of a deep-plan office module*” of 3.0 x 9.0 x 2.7m (wxdxh) with a single window of 2.6m width and 1.5m height (Mardaljevic, 1999). However, the experiments using test rooms rarely incorporated external obstructions. If present, these obstructions interfered only as shadowing agents; outdoor reflectances were not computed or attenuated for simplification purposes.

The typology of a continuous urban canyon is being intensively used in researches of daylight in the urban environment (Nasrollahi and Shokri, 2016), probably because it can represent complex repeated urban patterns in a simplified way (Strømann-Andersen and Sattrup, 2011). A notable predominance of studies with canyons of same-height sides was probably inspired by the homogeneous structure of several European cities.

The neighborhood scale is not a novelty in daylight assessment using computer simulation. Compagnon (2004) obtained building façades’ mean annual illuminance in a small urban scale in Fribourg (Switzerland), referring to this as ‘daylight availability’. Ratti et al. (2003) used an average normalized direct daylight factor at ground level to evaluate what they call 'daylight distribution' in urban settlements of London, Toulouse and Berlin, where 100% represents the illuminance that would fall on an unobstructed surface which sees the whole sky vault, and 0% represents nil illuminance. With the advances in computer processing, studies in this scale are becoming more feasible with more detailed models. However, simplifications in simulation settings and in the 3D model itself are still necessary. An example thereof is the reduction of number of bounces in settings, which is related to the accuracy of inter-reflections in the model.

With regard to settings and other details for daylight simulations in architecture, the standard IES LM-83-12 provides certain recommendations. Table 10 shows ranges of values for some of the parameters suggested by the U.S. Department of Energy Lawrence Berkeley National Laboratory – LBNL (1997, updated 2016) contrasted to the ones used to support the development of the standard IES LM-83-12. The values provided by LBNL are found in Radiance (v. 2.4): the ‘min’ value gives the fastest results, the ‘fast’ value gives a reasonably fast result, the ‘accur’ value gives a fairly accurate result, the ‘max’ value gives the most accurate result of rendering. The standard IES LM-83-12 focused on the architectural level, based on simulations that used Radiance. This standard defines some setting parameters (Table 11), not covering all rendering parameters of Table 10; for that, it recommends sensitivity studies to identify proper values of all settings according to the demand.

The LBNL (1997, updated 2016), DAYSIM Manual (Reinhart, 2006; Reinhart et al., 2017)[14] and MIT (2012) define the following parameters:

- ambient accuracy (aa), whose value is related to the error from indirect illuminance interpolation, a value of zero meaning no interpolation;

- ambient bounces (ab), corresponding to the number of diffuse inter-reflections computed by the indirect calculation, zero implies no indirect calculation;

- ambient divisions (ad), defining the number of sample rays that are sent out from a surface point during an ambient calculation;

- ambient sampling (as), indicating the number of additional rays that are sent in areas with a high brightness gradient;

- ambient resolution (ar), determining the density of ambient values used in interpolation.

Table 10:

Input parameters for the simulation of daylight.

Param.	Description	LBNL*				LM-83-12**
		Min	Fast	Accur.	Max	
-ab	ambient bounces	0	0	2	8	6
-aa	ambient accuracy	.5	.2	.15	0	
-ar	ambient resolution	8	32	128	0	
-ad	ambient divisions	0	32	512	4096	1000
-as	Ambient super-samples	0	32	256	1024	

Source: adapted from *LBNL (1997, updated 2016) and **IES LM-83-12 (2012).

Reinhart (2006) emphasizes that the time for daylight simulation of a building model can be long, therefore irrelevant details should be dismissed, given certain advantages of smaller models. Considering settings, a high ab-value increases substantially the calculation time; an ab=5 is sufficient for a room without a complex façade. The value of ‘ad’ should be high if a high brightness variation is expected. The ‘aa’ and ‘ar’ serve to calculate the luminance distribution _ for instance, if aa=0.1, ar=300, maximum scene dimension=100m, then the

[14] See also https://daysim.ning.com/

simulation resolution = (0.1 x 100) / 300 = ca. 3cm; in other words, the daylight that enters in the room through openings or details above ~3cm will be understood.

Table 11:

Input parameters for indoor daylight simulation referenced in the LM-83-12.

Parameter	Value
Occupancy (local time)	8am to 6pm*
Illuminance Threshold (lux)	≥ 300
Period of occupancy (%)	≥ 50
Indoor floor area –sDA (%)	≥ 55 or ≥ 75
Reflectance of indoor floor (%)	20
Reflectance of indoor walls (%)	50
Reflectance of indoor ceiling (%)	70
Reflectance of indoor furniture (%)	50
Outdoor ground reflectance (%)	20
Height of workplane above the floor (m)	0.80
Specularity of materials	0
Roughness of materials	0
Dirt depreciation factor of windows	5%
Window frame area	20%
Quality	2 (High)

* Accounting for daylight savings time and longitude adjustments. Source: adapted from the IES LM-83-12 (2012).

Software for daylight simulation

The development of simulation programs that are able to address different aspects of performance in design has opened a new path for quality of architectural and urban spaces in existing or planned cities. In this movement, programs for daylight analysis are being created, ceased, upgraded, and/or incorporated in others continuously.

Daylighting analysis software can be grouped in those which translate simplified calculation methods of components of daylight factor (direct and average internally reflected), and those based on ray tracing and/or radiosity (Geebelen and Neuckermans, 2003). Examples of software used in indoor daylight analysis include Radiance, Relux, ADELINE, DIALux, Light scope, Inspirer, Rayfront, 3D studio MAX, Superlite, Lumen Micro, Specter, ESP vision, Light works and DAYSIM, some features of which are described by Bhavani and Khan (2011).

APOLUX was developed for daylight applications in architectural and urban scale based on radiosity, and it is being used in academic studies[15]. Its algorithm for daylight simulation has been validated by authors such as Carvalho (2009) and Cunha (2011), including against

[15] A list of scientific publications related to the software APOLUX is available at: http://foton.arq.ufsc.br/, accessed in Aug/2018.

measurements of sky luminance according real sky conditions. Both authors compared the results of software simulations of a room to analytical references (equations) according to selected protocols prescribed by the Technical Report CIE 171:2006, a source document for software validation, and other documents by CIE. They adopted a range of +-5% as acceptable divergence. Carvalho focused on the validity and accuracy of luminous fluxes, reflectances and form factors, considering three sky types (clear, overcast and partially overcast), while Cunha extended the research to the standardized 15 sky types. Later, APOLUX received an additional function that calculates these 15 sky types for each hour in a year, by combining data contained in a weather file according to the Perez Model and the ISO 15469:2004 (E) / CIE S 011/E: 2003, and it presents the results in a .csv format. This feature is described in Claro (2015), who made it available in a special version[16] of APOLUX (October/2017) for specific application in this study.

As previously mentioned, accurate indoor daylight assessment in any scale may require strong computer capacity and be time consuming currently. Simplifications in algorithms are commonly adopted in software dedicated to assessments in the urban scale to gain speed. Examples thereof are Urban Daylight, umi and CitySim. Urban Daylight, incorporated into umi, assumes light on the façade to be diffuse (Saratsis, 2015). CitySim also simplifies the reflectance effect (Paule and Kaempf, 2016), with probable impact in the illuminance distribution indoors, but providing fast results for the urban scale. As software can be updated, these characteristics can be transformed in a period of time.

An existing alternative that enables executing routines for urban assessment with controllable accuracy represents the combination of a software of precision with interface tools. This is the case with Grasshopper (GH), a graphical algorithm editor in which components create an interface with other software. For instance, the components for GH named Ladybug/Honeybee Analysis Tools activate simulation engines such as Daysim and Radiance, useful for daylighting and lighting simulations[17], including parametric design. The advantage of such software is the simpler interface that does not require deep programming knowledge. Additional advantage is that files can be programmed to respond in a semi-automatized manner, multiple simulations with variations in inputs can be activated with one command, and results can be stored automatically. GH is built up on Rhinoceros, a program developed by the company McNeel for three-dimensional computer graphics and computer-aided design (CAD). One definition: Woodbury (2010) refer to parametric design in the context of computer-aided design system able to represent designs that vary in response to a change in the input data.

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[16] This version was reviewed by Prof. Dr. Anderson Claro after tests performed by Iara Santos in Aug/2017.
[17] <http://www.food4rhino.com/app/ladybug-analysis-tools>, accessed on 16/Feb/2017.

Later, during the development of this research, the software DIVA (Jakubiec and Reinhart, 2011) launched an interface for Rhinoceros (DIVA-for-Rhino) and for Grasshopper (DIVA-for-GH), becoming also suitable for extensive parametric studies. DIVA is an acronym for "*Design Iterate Validate Adapt*", a software ensured by the company Solemma LLC.

Differences in results obtained by different software can occur due to variations in "*simulation workflows, default inputs, and user-defined inputs through the Graphic User Interface (GUI)*", even if they use the same engine (Ghodan, 2018). For instance, DIVA is based on EnergyPlus, Daysim and Radiance. Radiance simulations uses stochastic processes, thus, re-running the same file can produce divergent results each time; the lower the resolution of the file, the greater the differences (Solemma, 2016). Stochastic processes are those in which [input] variables evolve and change in time (Baron, 2013). According to Reinhart (2012)[18], Radiance *"can efficiently and reliably model annual illuminance time series with a mean relative error of 20%*". Errors up to 20% from measured data show to be normal in daylight research using simulations, and those verified in studies using Radiance based software are diverse, depending upon different conditions (Jones, 2017).

Regarding the model of the sky, both DIVA and the Ladybug/Honeybee Analysis Tools are able to simulate different sky types using Radiance's tools Gensky or Gendaylit[19].

Gensky generates few sky conditions. Six are described in the version 0.0.63 of Jan/2018 of Honeybee: sunny with(out) sun, intermediate with(out) sun, cloudy and uniform (default) sky.

Gendaylit generates a higher variability of sky conditions following Perez models. As per Delaunay (1994), the sky luminance distribution model by Perez et al. (1993) is adopted. And Gendaylit also benefits from Perez et al. (1990), luminous efficacy models that convert irradiance into illuminance for the direct and the diffuse components. The version of Gendaylit described by Delunay generated as outputs: a) the radiance of the sun (direct) and the sky (diffuse) integrated over the visible spectral range (380-780 nm), b) integrated over the full spectrum, or c) the luminance. In order to achieve that, Gendaylit bases on the angular distribution of the direct plus diffuse daylight sources according to the direct and diffuse component of the solar radiation, date and local time. The script of Honeybee to run Gendaylit provided by Mostapha Roudsari[20] and the script of Gendaylit provided by NREL[21] offer details regarding points discussed in this section.

[18] <https://ocw.mit.edu/courses/architecture/4-430-daylighting-spring-2012/lecture-notes/MIT4_430S12_lec09.pdf> Accessed: Nov/2019

[19] Private messages by a member of Solemma and by Sarith Subramaniam, one of the developers of components for light simulation in LB/HB.

[20] https://github.com/ladybug-tools/honeybee/blob/master/honeybee/radiance/sky/gendaylit.py

[21]//github.com/NREL/Radiance/blob/53485a7fb48727293d62f98d7bac830aa34ccba4/src/gen/gendaylit.c

Later, Reinhart (2006) also explained that Daysim is capable of calculating direct and diffuse illuminances from direct and diffuse irradiances by using the Perez luminous efficacy model (Perez et al., 1990). From the converted direct and diffuse illuminances, it can simulate the sky luminous distribution of the hemisphere, adopting the Perez all sky model (Perez et al., 1993).

As a result of the development of this field in terms of software, during the last phase of this research, another software based on Radiance was launched. Named Adaptive Lighting for Alertness – Alfa (Solemma, 2018), it might contribute to overcoming the inclusion of spectral information in future detailed analyses of quantity and quality of daylight, including studies related to circadian cycles.

Independently on which software is going to be adopted, a useful path for conducting studies on daylight performance simulation is presented by Reinhart (2006) in ten steps:

1) define aimed performance targets;

2) intent a daylight concept for the building;

3) confirm if a simulation is necessary for analysis and if not, skip to step 10;

4) choose tools/ variations;

5) elaborate 3D model(s);

6) input the data on the software;

7) calculate luminances and illuminances;

8) calculate performance;

9) contrast performance *vs.* variations;

10) finally choose the daylight design.

2.4. Standards and guidelines for indoor daylight in the built environment

Given the benefits of daylight for humans, it is not surprising that several countries are establishing and improving institutionalized instruments to promote energy savings by favoring indoor daylight. For instance, aiming to reduce by 20% the EU's energy consumption by 2020, the European Commission established through the EPDB 2010/31/EU that natural light shall be considered in the calculus of the annual energy performance of buildings (Recast, E. P. B. D., 2010).

The German standard DIN 5034-1:2011-07 (DIN, 2011) starts its "general requirements for daylight in interiors" by listing the following assets of this resource: *"the psychological effect,* *including the subjective impression of brightness and the visual connection to the outside; the visual conditions, e.g. in terms of illuminance appropriate to the task and limitation of glare; the biological effect, affecting health, well-being and performance; (…) energy efficiency, concerning the reduction of energy demand in buildings through daylighting"* [22].

This section presents an overview of instruments related to indoor daylight in the built environment. Institutionalized instruments include guidelines, standards, codes, regulations, laws, protocols, provisions, rules, directives, recommendations, requirements, ratings, benchmarking, certification, labeling systems. They can be mandatory or not.

As in the field of energy in buildings, compliance paths for enhancing daylight in those instruments can vary between prescriptive, trade-off, or performance. The prescriptive path relies on strict criteria or rules, the trade-off path allows the choice among prescriptive options, and the performance path allows flexibility through the simulation of computational models (adapted from Santos and Souza, 2007; Government of Canada, 2018).

Instruments for daylight published after the year 2000 were reviewed taking into consideration the scales of room, functional units such as an apartment or office, the building, and finally the urban scale. It was decided to focus o instruments from countries that: a) have a long history of regulations, and/or b) might need to deal with urbanization and population growth.

In the course of this investigation, which is presented in detail in the next section, it has been observed that instruments promoting indoor daylight are plentily available in the room scale as opposed to other scales. In the building scale, they are usually related to the position of the building in the plot, distance from other buildings, mass dimensions and footprint of each building as a standalone element. In the urban scale, instruments dedicated to urban design and planning that favor daylight are rare. They combine requirements for both buildings and urban zoning starting at the levels of plot, adjacent street or canyon (the smallest unit of the city), with the aim to influence block, district, neighborhood.

Even when it comes to the explored room scale, it has been observed that the instruments are not applied or developed in an integrative way in design: daylight and artificial lighting systems are usually approached separately. This is partly due to the fact that the instruments are often prescriptive-based instead of performance-based. Additionally, some of them are influenced by rules of thumb or 'old' criteria established in line with static metrics. However, there are technical subsidies based on computer simulations to replace static metrics indoor, a necessary movement (Mardaljevic and Christoffersen, 2013) that will favor also climate-based design in the urban scale.

[22] Unofficial translation provided by the author of this study.

Although mostly oriented toward image-forming, often the development and implementation of these instruments are motivated by and/or fostered solely by the efforts to guarantee access to solar radiation in its broader spectrum – aiming to ensure solar passive heating in building envelopes, to benefit from expected bactericidal effects, to achieve energy savings in heating systems, to promote decentralized energy generation in photovoltaic and other systems.

Some details regarding the consulted instruments and related literature are presented below.

2.4.1. The room and unit[23] scales

Instruments pertaining to the room are strongly connected to elements that fall within the scope of work of architects and interior designers and constitute ‘daylight systems’ in this scale: climate-responsive fenestration or opening systems (considering window-to-wall area ratio; window-to-floor area ratio; head height[24]; skylights; glazing composition in terms of spectrum selectivity, visible transmittance and reflectance; openings function, design, position and orientation; devices such as shading-, tubular-, and redirection systems); spatial geometry and dimensions (shape, 3D distances, interior partitions, etc.); interior design (furniture, layout, surface finishes, decoration); integrative lighting controls (sensors, dimmable lamps, automatic controls, etc.) (compiled from Reinhart, 2014; National Institute of Building Sciences – NIBS, 2016; BIS, 2016; Gentile and Osterhaus, 2019). Nevertheless, few of these elements are commonly “ruled” by guidelines or regulations for architects and interior designers. Fenestrations, openings and windows are exceptions, since they are strongly associated with indoor daylight performance.

Table 12 summarizes some of recent recommendations or requirements for fenestrations according to different locations: Germany, Portugal, USA, China, India, Brazil and Australia. These are mostly prescriptive and are available for residential and/or non-residential buildings. It is possible to observe certain similarities among the consulted instruments, which usually provide information regarding the dimension of the window in absolute terms, in relation to indoor floor area, to the façade, or to the room dimensions. With respect to dimensions in absolute terms, some definitions of minimum dimensions for providing daylight were found. Limitations for the maximum dimensions, when they exist, aim to avoid thermal issues. Rooms of longer permanence according to type of activity (living rooms, bedrooms, waiting rooms, and offices) follow stricter rules than the others (bathrooms, deposits, corridors, etc.).

[23] Unit = apartment, office, floor plan, etc.

[24] Head height means the height of the top of a frame (window or door) above finished floor (IES LM-83-12, 2012).

Table 12: *Window, minimum recommended or required dimensions worldwide*.*

Case	Dimensions	Country	Year	Document	Document Source
Absolute	Frame 1.0 m to 1.1 m height	India	2016	Code, residential	National Building Code-Part 2
	Frame >1m width and >1m height	Germany	2011	Standard, workplace	DIN 5034-1: 2011-07
	>1.2 m height	India	2016	Code, offices	National Building Code-Part 2
Related to floor area of the room	≥ 10% of floor area if floor <= 600m^2	Germany	2011	Standard, workplace	DIN 5034-1: 2011-07
	WFR ≥ 12.5%	Brazil	2016	Regulation, residential	PBE-Edifica, RTQ-R: energy, prescriptive, climate dependent (here, savanna)
	WFR>10%	Australia	2015	Code	National Construction Code, 2015, v1
	>1/6 of the floor area (WFR > 16.7%)	Brazil	200-	Code, residential	Local building code: Rio de Janeiro, Florianopolis.
Related to area of façade of the room	WWR ≤ 40%	USA	2007	Standard, prescriptive, non-residential.	ASHRAE_90.1-2007
	WWR ≤ 60%	India	2016	Code	National Building Code-Part 2
	WWR ≤ 45%	China	2012	Standard	JGJ 75-2012
Related to dimensions of the room	> 55% of the width of the room	Germany	2011	Standard, residential	DIN 5034-1: 2011-07
	≥0.3 x width x height of the room (if height ≤ 3.5m)	Germany	2011	Standard, workplace	DIN 5034-1: 2011-07
	≥ 1.50 m^2 (if room depth >5m)	Germany	2011	Standard, workplace	DIN 5034-1: 2011-07
	if room >10m depth, windows on opposite sides	India	2016	Code	National Building Code-Part 2
Related to glazing/shadowing properties	According to climate, SHGC (0.25, 0.40, 0.45, etc.)	USA	2007	Standard	ASHRAE 90.1-2007, section of prescriptive method, non-residential
	According to glazing, obstruction, etc.	Portugal	2006	Regulation	RCCTE- Building's thermal behavior
	According to Tvis, climate, Uvalue, SHGC, obstruction	India	2016	Code	National Building Code
Sill height	> 0.61m above floor	USA	2009	Code	ICC (International B. Code)
	> 0.95m above floor	Germany	2011	Standard, residential	DIN 5034-1: 2011-07
	1m to 1.2m (offices); 0.7 to 0.9m (resid.) > floor	India	2016	Code	National Building Code-Part 2
	0.30m to 0.60m above the working plane	India	2016	Code	National Building Code-Part 2

*Data usually for regularly occupied rooms (living/bedrooms). Window, opening, vertical fenestration. WFR = window-to-floor ratio, WGR = window-to-ground ratio, WWR= window-to-wall ratio, SHGC= solar heat gain coefficient. Source: own author, Iara Santos.

Some examples of the dimensions found in those instruments include the recommendation of sill height from 0.61m to 1.2m above the floor. A WFR above 10% is found in different sources, as well as a value of WWR lower than 60%. Varying dimensions according to climate, Tvis, Uvalue, SHGC and presence of obstruction were also observed. In rooms of longer permanence, the minimum size of window (1m width) is present both in German and Indian instruments. Portugal and India are among those countries that consider some sort of obstruction as a factor for dimensioning the window. Some of the requeriments are connected to the aim of optimize thermal conditions and energy performance, as it can be seen in the columns entitled “Document Source” of Table 12.

The static metric Daylight Factor (DF) for minimum levels of indoor daylight is present in rating schemes such as the BREEAM in UK, TQB in Austria, and DGNB in Germany (Dogan and Park, 2018). Deutsche Gesellschaft für Nachhaltiges Bauen or German Sustainable Building Council- DGNB (2018) refers to the criterion “*Availability of daylight for the entire building*”, defining as key performance indicators a DF of 50% of the “*usable area*”, and minimum hours of “*exposure to daylight on 17th January and at the equinox*”, among others. The certification scheme Leadership in Energy and Environmental Design - LEEDv4 for non-residential buildings adopts the mentioned IES LM-83-12 with the metrics sDA and ASE for applications in countries of diverse latitudes such as the USA (Green Building Council - GBC, 2014) and Brazil (GBC - Brasil, 2014). The later proposed WELL Building Standard (International WELL Building Institute – IWBI, 2017) includes sDA and ASE for indoor assessment – $sDA_{(300,50\%)}$, $ASE_{(1000,250)}$, besides “*circadian criteria*”: a minimum equivalent melanopic lux, during certain hours per day; 75% of the area of all regularly occupied spaces within 7.5 m of windows; 95% of all workstations within 12.5 m of window, among other.

2.4.2. The building and (partial) urban scale

The 1916 Zoning Resolution of New York city regulated building height, bulk, and use, as well as open spaces dimensions (City of New York, 1916), affecting the density in Manhattan. More than that, this first zoning regulation in the USA set a reference to other cities in allowance of tall buildings while promoting access to daylight, air and sky openness (Weiss, 1992), both locally and worldwide. Recently, the National Institute of Building Sciences (NIBS, 2016) commented on the current U.S. Guidelines for Buildings, stating that their footprint should be optimized for daylighting in new projects; it should maximize south (optimal orientation) and north exposures, with a maximum floor depth of 60 ft. (18.3m) between these two cardinal orientations. Recently in the USA, a zoning based on the “cap-and-trade” concept is advocated[25] for allowing densification in the block with buildings of different heights, ages and types, in contrast to standard zonings, while preserving “views, natural air and sunlight” (Halle and Tiso, 2014). The “cap and trade” system is being applied for carbon emission control; it consists in distribution of permissions for emissions in an area until a certain limit (cap), allowing the commerce (trade) of permissions under certain conditions or the implementation of compensatory strategies for surpassing the limit (Center for Climate and Energy Solutions, 2018). Bringing this concept to design, this system would allow the trade of permissions to build vertically beyond a certain limit, promoting non-homogeneous skylines.

According to Assis (2002), the evaluation of performance in architecture in terms of access to sun and daylight was being supported by instruments for urban planning based on obstruction angles, without consensus regarding criteria and methods to define them. In this topic, Littlefair (2001) reviewed studies and guidelines for access to daylight, solar gain, and cooling in urban layouts, some of which were developed for the United Kingdom and have been available there since 1992. Some of them, shaped local urban geometry. Among the recommendations, the author mentions minimum requirements of the static metric Daylight Factor (DF) and that no significant part of certain rooms should be deprived of “direct light from the sky”. A set of obstruction angles was also provided for latitudes 35◦ to 60◦ and climates from Mediterranean to Sub Artic as presented in Table 13; according to the author, the maximum obstruction angle of 25◦ of that study was aligned with the recommendations for UK at the time, and the other angles proposed later compared well to the listed values, except for the locations in the “Far North”, closer to the Arctic. Obstructions should also not limit the sky between south-east and south-west for solar access, avoiding overshadowing; to that end, horizontal angles were also proposed. However, the author noted that obstruction angle should not be the only criterion used to set up urban layout, since an obstruction might not be continuous and its reflectance may affect the results for DF. Number of hours of sunlight per year and in winter season were also set as a requirement.

Table 13:

Obstruction angles for light from the sky.

Latitude (◦)	Climate	Angle (◦)
35	Mediterranean	40
40	Mediterranean	35
45	Temperate	30
50	Temperate	25
55	Cold temperate	22
60	Subarctic	20

Source: Littlefair (2001) based on Evans (1980).

[25] Proposal attributed to Prof. *Vishaan Chakrabarti (*Columbia University/UC Berkeley)

The instruments from UK were referenced in other locations. According to Ng (2003), building regulations in Hong Kong at the time of that publication were developed in the UK in the 19th century, requiring a WFR≥10% for all habitable space, and a distance between building blocks limited by a reference angle of 71.5◦. The author points out that such laws were developed under the past concept of "low-rise terrace typedwellings of constant skylines", a typology that is "no longer applicable to high-density cities with varying skylines". Forced in mega and high-density cities, such laws "limits design flexibility" and "encourages bad design", being ineffective with respect to enhancing daylight. Thus, he presented studies of a simplified method based on the metric Vertical Daylight Factor, measurements in loco, survey and simulation of blocks using the software Lightscape, whose results were presented to the Government of Hong Kong to serve as a basis for regulatory control of daylight performance of local buildings. The author state that HK is the most densely populated city in the world, where residential buildings are usually built with site coverage of 50% in a plot ratio[26] of 9 or above. This generates close towers of 40 to 80 stories, in which light and ventilation can be compromised. Another instrument in Hong Kong, the "Sustainable Building Design (SDB) Guideline", issued in 2011, was developed considering three key elements: building separation and permeability, building setback, and site coverage of greenery (Ho et al., 2015). Its requirements address the complexity of the dense urban context of Hong Kong and the local climate conditions, specially the demand for urban ventilation, and affect directly or indirectly the conditions of indoor daylight. For instance, one of the proposals increases urban permeability by requiring horizontal or vertical gaps in the built structure (Figure 15a). Interestingly, Lam (2000) identified in a sample of over 280 residential buildings in Hong Kong a WWR from 15% to 50%; however, about 90% of the sample had WWR between 25% and 35% (mean of 30%), 100% of the buildings had single glazing, 75% with clear glass.

In India, a national building code recognizes that "*Certain dispositions of building masses offer much less mutual obstruction to daylight than others and have a significant relevance, especially when intensive site planning is undertaken*" (BIS, 2016 - Part 2). In line with this, certain street width-to-height ratios are defined to provide at least 2h of daylight access to the neighboring buildings. The code suggests that distances between parallel buildings with up to 4 stories, distanced from 0.5 to 2 times their heights from each other, are likely to result in an Indoor Daylight Availability 15% to 68% when compared to 100% of an unobstructed façade. According to a member of the Urban Design Institute of Mumbai, the definition of "daylight availability" in the context of this code is related to daylight factor, and the rules would impose limits of occupation such as the pyramidal ones (Figure 15b)[27].

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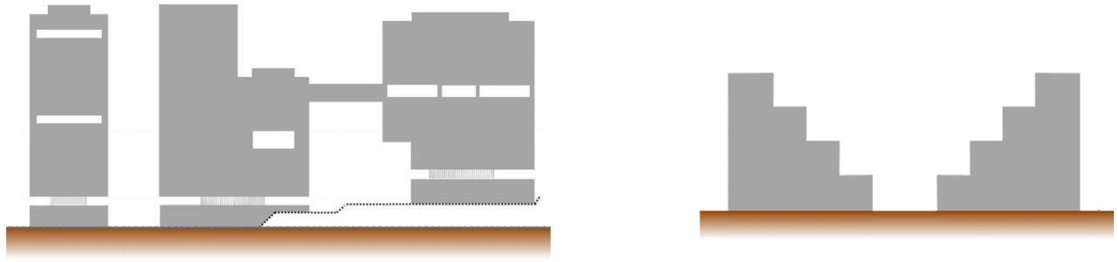
[26] Plot ratio represented the "total usable floor space/site area"

[27] According to a member of the Urban Design Research Institute of Mumbai, private message, July/2018.



(a) Buildings with gaps (b) Buildings with pyramidal shape

Figure 15: Sketches of urban sections illustrating instruments that affect daylight indoors.
(a) Hong Kong. Section of an urban area, building in grid typology with vertical gaps for daylight and ventilation. Source: adapted from Ho et al. (2015). (b) India. Sketch of a canyon section with shape defined by distances between parallel buildings according to the National Building Code of 2016. Source: adapted from a design of a member of the Urban Design Institute of Mumbai, private message, 2018.

Certification schemes initially developed for energy savings and sustainability purposes in buildings are adopting certain daylight criteria in the building level. The LEED in the U.S., DGNB in Germany, and BREEAM in the U.K. represent examples of such schemes. They are being extended to the urban level (Nault, 2016), an initial effort that might speed up the interest for studies that promote daylight in cities, especially in those where rapid urbanization is ongoing.

In any case, it was observed that current instruments for urban daylight climate, voluntary or mandatory, are still in their seminal form in terms of an integrated approach, considering spatial and temporal factors of the development of the urban site. Apart from innovative aspects such as the system of gaps through buildings proposed for Hong Kong, strategies with impact on daylight indoors are similar among the consulted instruments: limit WFR and/or WWR; adopt minimum distances between buildings, including by referring to obstruction angles. Their focus is on ensuring conditions of visibility or hours of sun for a period of time indoors, sometimes defined by or minding thermal conditions, influenced by or being inspired by instruments developed for referential cities worldwide.

2.5. Classification systems for comparison in climate-based design

Classification is "*the action or process of classifying something according to shared qualities or characteristics*", and is synonymous with categorization, grouping, grading, systematization, ranking, organization, codification; while a system is "*a set of principles or procedures according to which something is done; an organized scheme or method*".[28] Classification

[28] www.dictionary.cambridge.org, accessed on 19/Oct/2018.

systems, therefore, can be understood as systems of categorization conforming to pre-defined characteristics within a context. They are useful for simplifying interpretation, inference, access, and/or for building information, based upon a qualitative and/or quantitative approach.

A simple example is the use of classifications to group words of a text based on their similarity and frequency of occurrence in order to observe an attribute. Figure 16 is a word cloud generated from the previous paragraph to illustrate this process.

Figure 16: Word cloud built to illustrate an application of a classification process. Source: Own author, using the web-based tool Tag Crowd.

2.5.1. Classification systems in climate and/or urban studies

An example of classification system for urban studies related to climate is the Local Climate Zones – LCZ. They are defined as "*regions of uniform surface cover, structure, material, and human activity*" (Stewart and Oke, 2012), having recently been developed in an attempt to standardize urban temperature observations. In this system, cities are grouped into types according to characteristics of urban morphology/geometry combined with elements that relate with climate: albedo, surface admittance and anthropogenic heat output. For instance, the classification "LCZ 1 - Compact high-rise" indicates regions characterized by a "*dense mix of tall buildings to tens of stories*", with few or no trees, land cover mostly paved, and having concrete, steel, stone, and glass as predominant construction materials. Some of the criteria that define the LCZ 1 are a sky view factor considered low (SVF from 0.2 to 0.4) and an aspect ratio considered high (H/W>2), among others. SVF is the "*ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere*", while aspect ratio is the "mean height-to-width ratio of street canyons". Figure 17 illustrates examples: LCZ 1 (Compact high-rise), LCZ 2 (Compact mid-rise, characterized by buildings of 3-9 stories), and LCZ 3 (Compact low-rise, 1-3 stories). The geometric aspect of LCZ 1 represents the focus of the present study: dense, compact, verticalized area composed of buildings with or without homogeneous height, and small distance between façades.

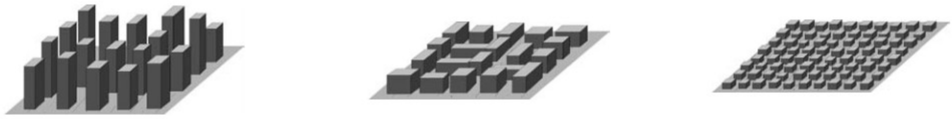


Figure 17: Examples of Local Climate Zones for urban studies.
Source: Stewart and Oke (2012). ©American Meteorological Society. Used with permission.

In climate studies, classification systems are applied to group either analogous climatic patterns, or locations with similar climates. The classification of the land surface in accordance with diverse climate zones is usually a requisite for conducting global diagnostic or predictive modeling investigations (Zscheischler et al., 2012). There are dozens of such systems with a focus on temperature. A widely used is the Köppen-Geiger climate classification (KGC), which has a focus on the annual and monthly averages of temperature and precipitation, and their relation to native vegetation types and distribution (Ahrens, 2011). KGC is being adopted in various fields of study such as climate and climate change, physical geography, hydrology, agriculture, biology (Kottek et al., 2006); and in studies on urban climates (e.g. in Oke et al., 2017). Kottek et al. (2006) developed a digitally updated Köppen-Geiger world map, which is being constantly updated based on the improvement of accuracy and availability of atmospheric data, using Google Earth System for visualization of climate classification of some cities[29], as a macroclimatic approach (Yang, 2017).

Interesting classification systems and tools for design with climate in architecture emerged from the works of J.M. Fitch in the 1940’s, Olgyay in 1963, Givoni in 1969 and 1992, Koenisberger et al. in 1977, Szokolay in 1987, among others. According Bogo et al. (1994), their work consolidated the study of climate for the building scale. Some of them were incorporated in softwares such as ClimateConsultants (Milne et al., 2007; Milne, 2016) and ClimateTool (Liedl, 2016), for instance, in order to facilitate the visual analysis of weather data, allow comparison of cities based on climate, and/or provide design guidelines for architecture with a focus on hygrothermal conditions.

Few classification systems are dedicated to parameters related to daylight, and fewer were used for cities comparison as a path for understanding or forecasting daylight behavior in other locations. Reinhart (2002) and Fonseca et al. (2017) are interesting proposals.

Reinhart (2002) obtained daylight performance of an open plan office using the metric Daylight Autonomy. The performance was simulated for cities in the USA and Canada, in a resulting classification represented over a map. Elements such as room dimensions and reflectances, presence of internal partitions, climate, and façade orientation were varied. Obstructions also varied: nonexistent at North, 30◦ at South and West, 60◦ at East. Such dynamic simulation

[29] http://koeppen-geiger.vu-wien.ac.at/, (accessed in March/2017)

conducted by this author has the advantage of investigating how daylight interacts with the built environment and tends to behave indoors, and how effective it is in meeting the occupants' needs. However, the city-by-city simulation requires more complex resources than the evaluation of weather databases, which can also provide valuable information for design.

Fonseca et al. (2017) proposed a daylight zoning for Brazil using this approach. To that end, they analyzed Solarimetric Atlas charts along with the weather file data for 20 municipalities. Among dozens of parameters, they selected sky cover and global horizontal illuminance as the most relevant to describe available daylight. Sky cover was evaluated considering 3 groups of sky: clean, partially clouded and overcast. Illuminance was evaluated considering 3 groups: less than 48 klx, between 48-84 klx, and above 84 klx. These illuminance groups were defined by analogy with sky cover, by dividing the maximum level found among the municipalities (around 120 klx) into a pre-defind number of segments: three. The study was successful in developing methods that generated the first zoning of this type for the region, but the goal of supporting designers with this information is debatable. In fact, the information provided by daylight climate zoning at a macro scale might be useful for design, but it remains unclear to what extent it would be sufficient to meet indoor daylight requirements. Understandably, the use of performance simulations was recommended by these authors for future studies.

Interestingly, both works by Reinhart (2002) and Fonseca et al. (2017) comprised a large range of latitudes, which is relevant for daylight purposes. Brazil is a large country with latitudes ranging from +05°N to -33°S approximately, considering its contiguous territory. Thus, the country is predominantly in the zone between the Tropic of Cancer and Tropic of Capricorn (ca. +-23°). This wide range of almost 40◦ combined with other conditions generates variations of daylight climate which are not experienced in other areas. As a reference, the mainland of Europe, excluding islands, ranges from ca. 36° to 71°, a total range of ca. 35°. The USA and Canada are also large countries located predominantly above the Tropic of Cancer (ca. +23°), experiencing stronger seasonal variations including more hours of daylight during summer and less during winter.

It is important to note that several proposed classification systems and quantitative analysis presented here used statistics. Examples are Andersson et al. (1986), Perez et al. (1990), Reinhart (2002), Kottek et al. (2006), The World Bank Group (2015), Meteonorm (2016), Nault (2016), Santos et al. (2017), Fonseca et al. (2017). The greater the complexity and/or the number of parameters and data involved, the more beneficial the tools of this science can be.

The use of statistics for support the analysis of data obtained from parametric simulations of urban design is also present in some cases. A noticeable example is Martins et al. (2016). They tested which urban typo-morphological factors have significant impact on the irradiation balance and static daylight (illuminance) on surfaces of simulated urban variations in one city. For that, Design of Experiments (DOE) is used. DOE highlights the most important information from a database of experiments by conducting the smallest possible number of experiments; its categories of methodologies include Factorial, Cubic Face Centered, Box-L. Behnken, Plackett Burman and Latin Square. The hypothesis testing considered a confidence interval of 95% (significance equal to 0.05), which is obtained from a test capable of identify whether two sets of data differ significantly. The authors verified a high influence of albedo, aspect ratio and distance in the results, and recommend for future studies the conduction of comparative tests of multiple international cities with “heavy urban density”.

Another statistical method which is useful for comparison and classification is cluster analysis, also referred to as clustering. Jain and Dubes (1988) defined clustering as “a special kind of classification”. Clustering is used to group elements based on their similarity in terms of pre-defined attributes. There are other methods to verify certain degrees of similarity among elements, such as the already mentioned Kruskal-Wallis, which is useful for comparing elements based on the same parameter (i.e., sDA), or ranking techniques, which are useful for classifying, grouping and visualizing elements according to defined criteria. The advantage of clustering is that it can group elements considering mixed data types such as continuous, categorical, ordinal ones (i.e., sDA and sky type).

There are many applications of clustering. In the field of design, Martins et al. (2014) applied clustering with k-means to morphological data of a part of a city, in order to identify their representative urban typologies. The process resulted in the identification of five typologies, which they named: individual sparsely habitat; open-set mid-rise buildings; colonial compact; modern high-rise towers and the densely low-rise buildings.
In the field of climate, Andersson et al. (1986) used clustering techniques to group cities in the USA by climate similarity; for instance, three daylight regions were established based on “*the ratio of the average global radiation to the average extraterrestrial horizontal radiation*”. The principle was a reference for the study by Reinhart (2002), to cluster 186 cities of North America into “*regions of similar daylight potential*”. For that, the k-means method was adopted with an “*arbitrary number of clusters*” of five, and using Euclidean distances.

The use of clustering can also be beneficial in one important aspect. It is a complex task to use the results of each parameter to compare and group cities, even with the support of individual graphic presentations. Thus, the use of statistical tools capable of synthetizing the parameters and their multiple data into one package of information, e.g. as a graph, might be useful to clarify similarities of cities based on multiple aspects.

Cluster analysis is detailed in the next section.

2.5.2. Cluster analysis

According to Jain (2010), cluster analysis is the study [and aplication] of methods and algorithms for clustering (grouping) a set of patterns, points, or objects, based on "*measured or perceived intrinsic characteristics or similarity*". It is an exploratory tool for organizing data into "*natural*", or "*sensible groupings*" that support understanding and learning. In this sense, cluster analysis (unsupervised learning) does not mark objects a priori with any category information, the main difference from classification or discriminant analysis (supervised learning). Prevailing in "*any discipline that involves analysis of multivariate data*", clustering main outcomes are:

- Underlying structure: to gain sensitivity in terms of data characteristics and eventual anomalies, and to generate hypotheses from that;
- Natural classification: to identify relationships, degrees of similarity among objects;
- Compression: to organize and summarize data through cluster prototypes.

According to Jain and Dubes (1988) and Tan et. al (2019), clustering has long played an important role in diverse fields, such as engineering, social sciences, marketing, biology, archeology, statistics, pattern recognition, information retrieval, remote sensing, machine learning, data mining, among others.

However, Jain (2010) alerts that clustering is a very helpful, but complex tool to use. Due to its distinctive attributes, the proper application of the concepts benefits from the users' experience in advanced statistics, with a deep background in the clustering process, especially for defining characteristics of the sample, proper techniques, sequence of the work, application of algorithms, evaluation of clustering results. Based on that author, as well as Hair et. al (2009), Vasconcelos (2017), Jain and Dubes (1988), and Tan et. al (2019), several steps to apply cluster analysis were compiled:

1) Define the problem and the hypothesis.
    a. What is the aim of the investigation?
    b. Why cluster is a recommended method?
2) Define the population and the sample.
    a. Which are the proper parameters and necessary sample sizes to have reasonable results without an overwhelming amount of data?
    b. What are the necessary and available resources, including time for the investigation, hardware, software, specific knowledge? How to compile the data?
3) Understand the sample.
    a. Prepare the sample: check its size, organize the data.

   b. Produce graphs of distribution to understand how it is spread, in terms of dispersion, variability, balance, probability, etc.
   c. Produce correlation graphs. This is helpful to visualize the data, better understand if there is a strong association among the parameters, visualize outliers, try to estimate an initial number of groups, gain sensibility to anticipate potential results, and prepare the next steps.

4) Estimate the number of groups for the cluster.
   a. Consider the goals and conditions of the research: is it helpful or important to have a small or higher number of groups? Is the aimed number feasible considering the sample size?
   b. If necessary and appropriate, use specific methods that can indicate an optimum number of groups based on the characteristics of the sample.
5) Define the method for data treatment.
   a. Consider the research goals, data type and distribution, among other criteria.
   b. Examples: normalize the data, i.e., scale to unit standard deviation, reducing the weight of certain parameters if the scale of among them is very different in a sample; treat outliers to increase accuracy.
6) Define the clustering method.
   a. It also depends upon research goals, data type and characteristics, available resources (i.e. time, hardware, software), specific knowledge, and sensitivity in statistics.
   b. Examples: among the methods, some of the most traditional are complete linkage, Ward, Ward d2, k-means.
7) Conduct the clustering.
   a. Form the clusters. Explore, visualize the results. Tables, bi-dimensional graphs, dendrograms, clustergrams, heat maps are examples of tools for this task. Many software are available for that process, including R, Matlab, SPSS, among others.
   b. Evaluate the resulting clustering according to proper strategies (validation).
   c. Analyze the results. Describe the characteristics of the general cluster (i.e., balanced/unbalanced), the characteristics of each group, the composition of the groups, the distance among elements, etc.
8) Propose possible explanations for the results.
   a. Define ‘theories’ that could explain the results of the cluster in terms of the number of groups, characteristics of the groups, composition of the groups, the distance among elements, etc. The results of the pre-analyze of the sample can be useful in this stage.

b. Investigate and discuss each of these potential reasons based on general or specific knowledge, scientific theories, influence of the selected methods etc.

9) Answer to the problem.

a. Investigate and discuss the hypothesis, review the conditions of the study, answer the initial question(s).

10) Suggest future studies.

a. List limitations of the study and suggest alternative methods and techniques that could be used in future studies.

Regarding these steps, comments about cluster concepts and methods are necessary.
First of all, the definition of a cluster relies on the nature of the data and aspects of the investigation, it is not always easy. Figure 18 illustrates that difficulty, by showing that the same collection of data can be clustered in different ways: two, four, or six clusters.

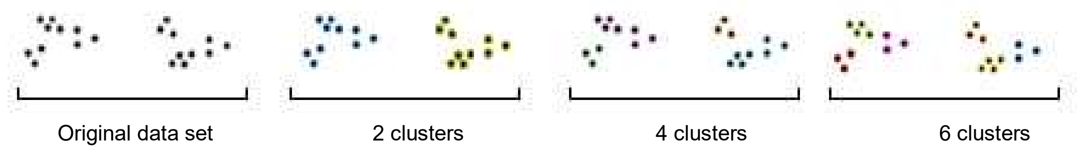


Figure 18: Possibilities of clustering a data set.
Source: adapted from Tan et. Al (2019).

Also, Tan et. al (2019) explain that there are different types of clusterings and clusters. Types of clusterings, referring to a collection of clusters, include partitional *versus* hierarchical, exclusive *versus* overlapped *versus* fuzzy, and complete *versus* partial. In the partitional type, data are simply divided into clusters, while in the hierarchical one, clusters are additionally organized as a tree. In the exclusive type, each object is assigned to one cluster; in the overlapping, each object can be assigned simultaneously to different clusters; in the fuzzy, each object is assigned to every cluster, according to a system of weights. In a complete cluster, all objects are separated by cluster; in a partial, objects might not be assigned to any cluster, for instance, if they are outliers or they do not fit to the generated groups.
They added that types of clusters include well-separated, prototype-based, graph-based, density-based, and conceptual clusters. In a well-separated, objects within a cluster are very ‘close’ to each other, and all the clusters are ‘far’ from each other. In a prototype-based, each cluster is described by an object that is considered ‘representative’ of the cluster – the prototype, which is usually a centroid, i.e., the average of all the points in the cluster, or the most central point in the cluster. In graph-based types, objects are nodes, while links translate connections among them. In the density-based, a cluster is defined by a region of a high density of objects surrounded by a region of low density. In a conceptual cluster, a specific concept of a cluster is required a priori to successfully detect a cluster.

Three examples of clustering techniques are k-means, agglomerative hierarchical clustering, and DBSCAN. The DBSCAN is a density-based, partitional, partial clustering technique _ and due to its nature, it is not explored in this research.

Regarding the k-means, Tan et. al (2019) state that it is *"one of the oldest and most widely used cluster algorithms*". The k-means is a partitional, prototype-based technique, which aims to find a user-defined 'K' number of clusters with a focus on centroids. Additionally, it is simple, useful for different data types, and quite efficient. The basic algorithm starts with the definition of K number of clusters by the user. This is followed by the choice of K points as initial centroids, randomly, or based on specific techniques. From there, a sequence of steps is going to be repeated: each point is assigned to its closest centroid until a collection of points compose a cluster. Each cluster's centroid is then recalculated. Points are then re-assigned to their closest new centroid, and the cluster is updated. The steps are repeated until the centroids do not change. The definition of 'closest centroid' is typically based on the Euclidian Distance, a concept that will be discussed later.

Tan et. al (2019) pointed out that the hierarchical clustering is relatively old and with widespread use, like the k-means. It can be generated by using the agglomerative approach, which is "*by far the most common*", or the divisive one. The agglomerative hierarchical considers each object a cluster, which is merged to the closest object in a process that is repeated until one cluster remains; thus, a definition of cluster proximity is necessary. In the divisive, all data objects start as a cluster, which is then split step-by-step; therefore, a definition of how to split is required.

A dendrogram is a like-tree diagram frequently used to reproduce hierarchical clustering results, representing graphically: a) cluster and subclusters relationships, and b) the sequence in which the clusters were merged, in case of an agglomerative approach, or split, in case of a divisive one. Figure 19 shows the resulting hierarchical clustering of objects in a dendrogram.

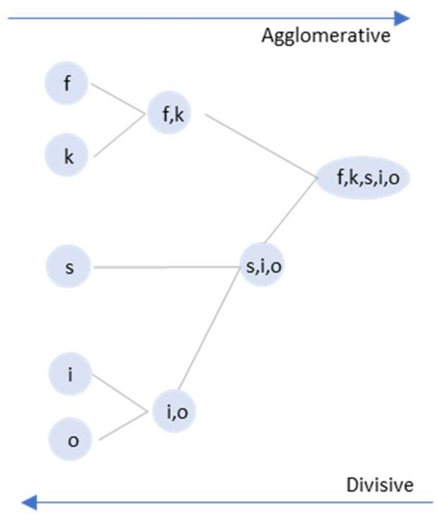


Figure 19: Example of hierarchical clustering of objects in a dendrogram.
Source: adapted from Everitt and Dunn (2001).

Cluster proximity definition varies in terms of concept and mathematical metrics. For instance, in terms of concept from a graph-based view of clusters, agglomerative hierarchical clustering considers proximity using techniques such as the single link, the complete link, and the group average (Figure 20). For the single link (named also MIN), proximity is taken between the closest two points located in different clusters, or under a simplified definition, the minimum of the distance (maximum of the similarity) between two points in different clusters. For the complete link (MAX), proximity considers the farthest two points in different clusters. In the group average, the average pairwise proximities of all pair of points of different clusters is considered proximity; it is an intermediate approach between MIN and MAX. From prototype-based techniques, in which each cluster is represented by a centroid, the proximity is usually defined by the proximity between centroids.

In Ward's method, based on centroids, proximity considers the increase in the sum of squared error (SSE) resulting from the merging of two clusters; it is similar to the group average technique under certain conditions, and as in the k-means, it aims "*to minimize the sum of squared distances of points from their cluster centroids*". To obtain the sum of the squared error (SSE), the distance of each point to its nearest cluster is squared, and the resulting values for all points are then summed up.

According to Murtagh and Legendre (2014), considering observation *i*, in a cluster (set) *q* with a center *q**, and the distance d:

$$SSE = \Sigma_{i \epsilon q} d^2 (i, q^*) \quad \text{(Eq. 4)}$$

The differences in the methods for calculating cluster proximities in hierarchical clusters, according to Tan et. al (2019), can be understood through the Lance-Williams formula and its complementary table with coefficients (Eq. 5 and Table 14). Let's consider clusters 'A' and 'B'. By merging these two clusters, a cluster 'R' is formed. The proximity 'p' of this new cluster 'R' to an existing cluster 'Q' is a linear function of the proximity of 'Q' to 'A' and 'B':

$$p(R, Q) = \alpha A\ p(A, Q) + \alpha B\ p(B,Q) + \beta\ p(A, B) + \gamma\ |p(A, Q) - p(B,Q)| \quad \text{(Eq. 5)}$$

where:

A, B, Q, and R: clusters, where R is composed of merging clusters A and B;

α, β, γ: coefficients according to the chosen cluster method.

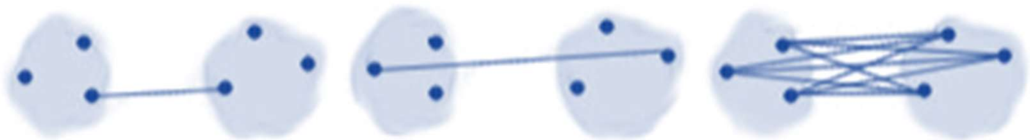
Table 14:

Coefficients for performing hierarchical clustering in the Lance-Williams formula.

Clustering Method	αA	αB	β	γ
Single Link	1/2	1/2	0	−1/2
Complete Link	1/2	1/2	0	1/2
Group Average	mA/(mA+mB)	mB/(mA+mB)	0	0
Centroid	mA/(mA+mB)	mB/(mA+mB)	$-(mAmB)/ (mA+mB)^2$	0
Ward's	(mA+mQ)/(mA+mB+mQ)	(mB+mQ)/(mA+mB+mQ)	−mQ/(mA+mB+mQ)	0

Note: 'm' is the number of points in the respective cluster A, B, or Q. Source: adapted from Tan et. al (2019).

As per Murtagh and Legendre (2014), the Ward method has been widely used since its first publication by Ward in 1963. Later it was proposed a derivate method, named Ward d2. This method Ward d2 can favor direct comparisons between input distances and those read off a produced dendrogram; it uses values on a scale of distances, in which input dissimilarities are Euclidean distances. In Ward d2, dissimilarities are squared before clustering.



(a) MIN (single link) (b) MAX (complete link) (c) Group average

Figure 20: Cluster proximity according to the single link, complete link, and group average concepts. Source: adapted from Tan et. al (2019).

Euclidean Distance is a mathematical metric to measure proximity/ distance/ similarity/ dissimilarity, used especially in engineering (Jain and Dubes, 1988). Another example is Manhattan Distance, whose differences are shown in Figure 21. Jaccard index is commonly applied for binary data, while Gower's distance for mixed data. According to Gower (1971) and Van der Loo (2020), Gower's distance compares two records and gives them a number between 0 (identical) and 1 (maximal dissimilarity).

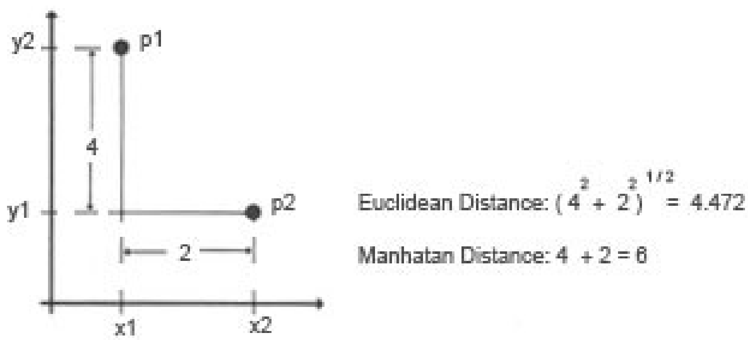


Figure 21: Euclidean Distance *vs.* Manhattan Distance. Source: adapted from Jain and Dubes (1988).

Statistically, proximity can refer to similarity or dissimilarity[30]. Similarity refers to how identical two data objects are, a measure that usually ranges from 0 (minimum) to 1 (maximum). Dissimilarity refers to how distinct two data objects are, usually measured from 0 (minimum) to an upper limit that depends upon the variation of the data.

Hierarchical methods have the advantage of do not require an initial number of clusters as input, since these are calculated automatically according to the degree of similarity among elements. However, the hierarchical are considered inflexible methods: steps of grouping are subsequential, and elements cannot be exchanged after the previous run of grouping. Non-hierarchical methods such as the k-means require an initial number of desired clusters, but they are flexible, allowing sample elements to change groups in each run of the algorithm; an alternative is to run hierarchical clustering before to define the numbers of clusters, initial centroids, and use these as input. Murtagh and Legendre (2014) describes this procedure, recommending to apply to the data first Ward`s agglomerative clustering, then to identify in the dendrogram the partition of the objects into K groups, and finally to adopt this partition as an input for the k-means partition.

Additionally, no metric is superior for all data types; if the data present noise, Ward`s can be superior to the single link, whereas if there are outliers, the single link can perform better (Everitt and Dunn, 2001).

In the process, the use of correlation techniques is beneficial. According to Saltelli et al. (2004), correlation coefficients are useful to investigate interactions among input factors, identifying pair-wise interaction structure. Scatter plots, Pearson and Spearman are some of the techniques for conducting sensitivity analysis. Scatter plot is the simplest one, in which points $(x^{(i)}{}_j, y^{(i)})$, i = 1, ..., N, are plotted for each independent variable X_j. The Pearson product moment correlation coefficient is commonly applied for linear models, calculated on the $x^{(i)}{}_j$, $y^{(i)}$ (i = 1, ..., N). The Spearman coefficient (SPEA) is used for non-linear models; it is different from PEAR because the raw values are replaced by a transformation R(.) of Y and X_j: SPEA (Y, Xj) = PEAR(R(Y), R(Xj)).

[30] <https://online.stat.psu.edu/stat508/lesson/1b/1b.2/1b.2.1>, Accessed May/2020

3. Methodology

Based on Lakatos and Marconi (2003), the inductive method is the one chosen to answer to the hypothesis, with the results from the observation of a sample being used in an attempt to draw guidance for a bigger population. The three fundamental steps of the inductive method serve as general structure of the investigation: 1) observation of the phenomena; 2) search for relation among them; 3) generalization of the relation.

From this general method, specific methods of procedure were selected to support the more concrete phases of the work, including: comparative, case study, and statistical methods. The comparative method helped to evaluate and/or identify relations in descriptive parts of the study, to build typologies for classifications in certain stages of the research, to clarify potential causes in explanatory levels. Case study served to approach in detail and characterize elements of the sample. The statistical one was used in descriptive analysis and for grouping elements of the sample, supporting in part the quantitative analysis.

From the specific methods, a group of techniques were selected for gathering the results from necessary observations. The techniques include literature review for establishing the basis of the concepts and data. The technique of scenarios is used through computer simulation tools, which allow to achieve results in a fast, cheap and accurate results, especially for collecting data of indoor daylight performance. Techniques of quali-quantitative analysis and advanced statistics were used for comparison of results and for addressing the hypothesis. Regarding the general techniques of observation, they are structured (systematic), non-participant or passive, individual (with support of experts specially in the analysis of the statistic results), done in a virtual laboratory through diverse computational software and plugins.

The structure of the methodology of the research followed the steps below:

- (0) development of a framework for conducting the analysis and test of hypothesis,
- (1) choice of sample of cities,
- (2) characterization of the weather data of these cities,
- (3) characterization of the indoor daylight performance of these cities, based on simulation of urban models using specific weather files,
- (4) comparison and analysis of the results of the two previous steps, focusing on the identification of: a) potential similarities among cities and b) parameters extracted from weather files that are influential in daylight indoor performance (sufficiency).

These steps were further organized as presented in Figure 22.

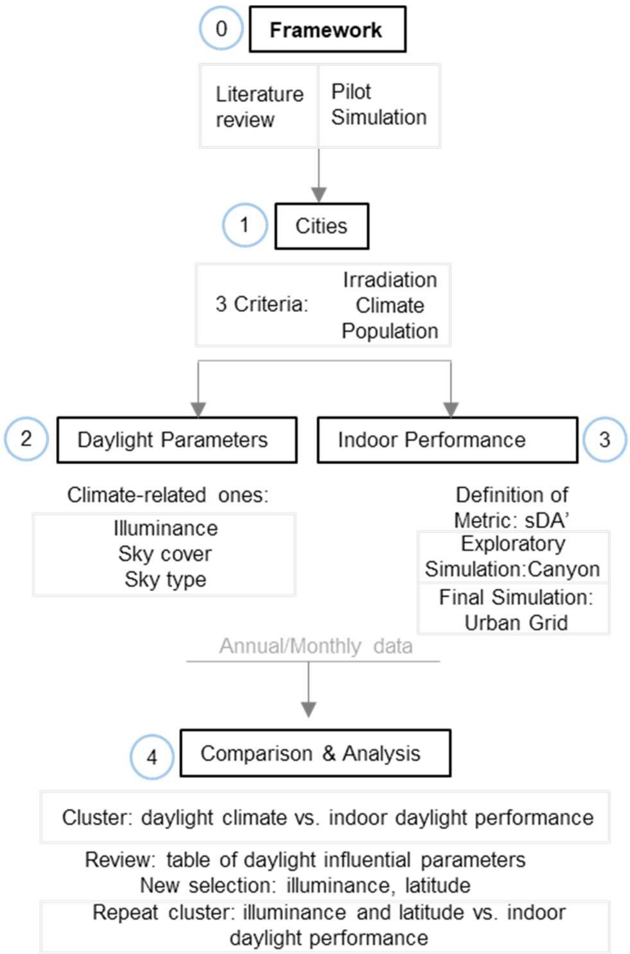


Figure 22: General structure of framework, with subdivisions of main steps. Source: own author.

Summarizing the methodology, a framework for comparison of cities in terms of daylight-related parameters *versus* indoor daylight performance is proposed for application in urban design and planning. The framework to conduct the process until the comparison of cities and test of hypothesis was developed mostly based on literature review, as well as pilot simulations conducted by the author of this work[31] and described in Santos et al. (2017). This framework was applied, starting from the comparison of a sample of cities in terms of their weather data *versus* daylight performance indoor. To that end, a combination of the approaches presented by Reinhart (2002) and Fonseca et al. (2017) served as a basic reference.

The sample of cities for comparison was selected from urban agglomerations with potential interest in densification, compactness and verticalization: megacities. This decision took into consideration the fact that ca. one in eight people live in the existing 28 megacities worldwide (United Nations, 2015), and this ratio is expected to increase by 2030. In order to increase diversification of characteristics within the sample, consideration was also given to their levels

[31] Publication produced by this author in cooperation with experts, that oriented part of this work.

of global horizontal radiation and their climate according to a temperature-based classification.

Parameters and proposal advocated by Fonseca et al. (2017) were adapted and complemented with the analysis of an additional climate parameter: the classification of sky type. This parameter was analyzed in an attempt to incorporate variations of sky luminance in indoor performance. Hence, for each selected city, data was gathered regarding three parameters: global horizontal illuminance, sky cover, and sky type (annual and monthly).

The approach by Reinhart (2002) was adapted in dynamic metric, 3D model and clustering technique. Like this reference, indoor performance refers to visual effects of the light focusing on minimum levels of indoor illuminance. However, the metric DA was replaced here by the one pointed out by Heschong (2012) as a better descriptor of performance: the sDA. Other results of this publication were adopted here: the thresholds of 300 lux, identified as "*the best predictor of expert and occupant assessments*" in three tested spaces, with a percentage of the occupation interval of 8h to 18h, without dynamic shading. Basen on Mardaljevic et al. (2011), this value of 300lux can reduce the switch on probability in non-domestic and probably in residential buildings. A variation of the metric sDA, the monthly spatial Daylight Autonomy (msDA), was also taken for daylight performance comparison. The original 3D model was changed to an urban site, accounting for the effect of shadowing and medium level inter-reflections in the surroundings - a combination rarely found in literature. Inputs and settings were identified after literature review and exploratory simulations. The final urban model followed the theoretical one proposed by Cheng et al. (2006a), with geometric characteristic related to a Compact Highrise Climate Zone (LCZ 1). This model was kept constant in terms of outdoor reflectance (40%) and medium inter-reflectances (ambient bounces = 4), while comprising variations mainly in geometric typologies (grid, canyon), building heights (homogeneous, heterogeneous), and window-to-wall ratio. The adoption of same metric and corresponding thresholds for all measured areas, independent from potential variations in building use, followed studies such as the ones by Saratsis (2015) and by Nault et al. (2017) for urban approaches. The measurements were obtained in a room with dimensions providing favorable conditions for daylight, which was located on the ground floor of the urban site.

Selected cities were grouped and compared both in terms of daylight-related parameters and indoor daylight performance (sDA and msDA), using cluster and ranking techniques. Two cluster methods were adopted, k-means and Ward d2 with results presented in dendrograms. The parameters were first extracted from climate (illuminance, sky cover and sky type). Later, illuminance data and latitude attributes were used in the comparison.

The steps of the methodology were then subdivided as shown in Table 15, and they are explained in detail in the next sections.

Table 15:

Summary of the methodology adopted in this study.

Steps	**Description**
Definition of Framework	Review of literature, focus on the State of the Art of: - Influential parameters to daylight performance, - Computer simulation of daylight performance, - Techniques for data classification and comparison.
	Conduction of pilot simulation of model for better understanding of the process, including: - Resources requirements for daylight simulation, - Experiments on input/output parameters.
Selection of cities for analysis	Definition of criteria for selection of cities: a) Population: > 10mi inhabitants, for which density might matter, b) Climate: vary conditions in different latitudes to explore differences among cities, c) Irradiation: available data related to daylight; selected cities with minimum and maximum levels per climate group.
	- Overlapping of these data using GIS. - Selection of cities for the tests to be conducted in the next steps.
Daylight: analysis of weather data	Definition of parameters: a) Illuminance: basic description of daylight, b) Sky cover: description of sky vault from overcast to clear sky, c) Sky type: complementary description of gradient of sky vault from the horizon to the zenith.
	Collection and analysis of these 3 parameters for each of the 9 cities, based on: a) monthly data, b) annual data.
Daylight: analysis of simulated indoor performance	Definition of metric of performance: - sDA, concept related to sufficiency as per Heschong (2012), focus on minimum indoor levels of illuminance (lux), - Definition of measurement area: ground floor of test rooms, - Definition of input parameters, format of outputs, software for simulation. Note: once the concept of sDA is well stablished in literature, but the thresholds diverge, here the term will be identified as sDA'.
	Preliminary simulation of a room for: - building a model based on a reference (Reinhart, 2014) - gaining knowledge in the adopted daylight software: Grasshopper LB/HB and DIVA.
	Simulation of exploratory simple model (urban canyon) for 1 of the selected cities: - Replicate/expand the parametric study by Santos et al. (2017) for a canyon, in order to gain sensitivity regarding variations of inputs (dimensions, WWR, bounces, outdoor reflectances, urban morphology, etc.) on indoor daylight performance, - From these results, select a reduced number of input parameters for the next simulation, which is more complex.
	Simulation of final model (urban grid) for all cities: - Selection of geometry: theoretical block, compact high-rise LCZ1, based on Cheng et al. (2006a), - Collection of performance data in the format of the weather data, in terms of: a) monthly data (mSDA'), b) annual data (sDA'). - Definition of examples of guidelines for indoor daylight performance based on sDA for those cities.
Analysis of Results: parameters starting from weather data *vs.* indoor daylight performance	Comparison of weather files *vs.* performance for identification of potential relation. Use of: - Quali-quantitative analysis based on graphs, - Cluster analysis: dendrogram and k-means, annual and monthly data, - Correlation analysis: quantitative parameters (illuminance and sky cover) *vs.* performance.
	With respect to the previous result, search for parameters extracted from weather files that are potentially most influential to performance. Use of: - Review and selection of potential parameters, including the same weather data reorganized in different formats, and latitude, - Ranking of these parameters by color, - Analysis of ranking and identification of the parameters that better correspond to daylight performance.
	Following the previous result, final comparison of parameters from weather files *vs.* performance was executed. Use of: - Cluster analysis: review of the dendrogram, using monthly data.
Final considerations	Comments on the results of the tests of the hypothesis. Comments on guidelines; limitation of framework, process and results, input/output parameters, statistical methods, future works, among others.

Source: own author.

Relevant to mention, the literature was used to define the scope of the investigation a priori: indoor daylight sufficiency in dense urban context for energy savings, considering dynamic metrics and parameters that urban designers can apply. From that, the selected processes were mainly inspired by the previously mentioned publications by Kleindienst et al. (2008) for choice of cities based on population and climate diversity, by Reinhart (2002) and Fonseca et al. (2017) for grouping of cities, by Cheng et al. (2006a) for performance simulation, combined with the use of advanced statistical techniques[32] for clustering, ranking and final comparison.

3.1. Selection of Cities

Based on literature review, a list of criteria for selection of cities was made. A first round of study of data availability and relevance was conducted.

The choice of cities for comparison was based on three criteria: a) one daylight-climate related parameter, b) one general climate parameter, c) one indicator of demand for urban solutions in which indoor daylight might be compromised.

Other interesting elements that characterize cities such as geographic dimensions, altitude and topography; tolerated or preferred daylight characteristics by the local population; degree and type of urban development; history of implementation of daylight guidelines; were not part of the research scope.

The global horizontal irradiation (GHI) level was selected as a daylight climate-related parameter. This choice took into consideration the fact that irradiation is easily available and usually is the source for calculation of illuminance data.

As a general, non-daylight climate parameter, the temperature and precipitation based Köppen-Geiger Climate Classification was selected as the second criterion. This considered that, as previously mentioned, KGC is often being used to compare and characterize cities. Indirectly, KGC also contains components of seasonality in its subdomains and reflects latitude in its distribution over the globe, both of which represent influential aspects in daylight climate characterization.

With respect to the indicator of demand for urban solutions, the attention was oriented toward growing cities with high populations. This is due to the fact that, since densification, compactness and verticalization are being pointed out as sustainable solutions for these cases, the resulting urban morphology can be implicated in poor levels of indoor daylight. In

[32] Methods defined partially after a statistical assistance for data analysis by Dr. Stephan Haug, TUMStat Team, and with technical statistical support by ABG Consultants.

line with these criteria, 41 urban agglomerations with more than 10 million inhabitants (megacities) were selected for potential analysis.

All these three selected criteria - global horizontal irradiation, classification according KGC, and characterization as megacity - were then assessed simultaneously using a Geographic Information System (GIS)[33], as Figure 23 represents. This method of using GIS was proposed to provide speed and potentially high accuracy in the processing of multiple data-bases, while rendering a visually useful result.

Global horizontal irradiation (GHI) data were collected from the Global Solar Atlas, which is provided online by The World Bank Group (2015). Latitude and longitude were collected also using this source, solely to better observe the distribution of the cities around the globe. Data pertaining to Köppen-Geiger Classification were obtained from Kottek et al. (2006). Data regarding megacities were obtained from UN (2015), considering the forecast for 2030. This information was overlapped and automatically retrieved through GIS in order to select the case studies. Cities within the same climate classification according to KCG that have respectively the highest and the lowest values of GHI were selected for further analysis, in order to reduce the sample of cities to two representatives per group. Cities in different countries were selected by means of extrapolating geographic boundaries and exploring different latitudes. Any weather file considered unsuitable for this study was dismissed, and its city was replaced with the closest one on the list within the group. The process resulted in the selection of less than ten cities, including the one with a climate familiar to this author, which served as a reference in the study.

[33] Results of GIS obtained with the cooperation of M.Sc. Daniele Gomes Ferreira.

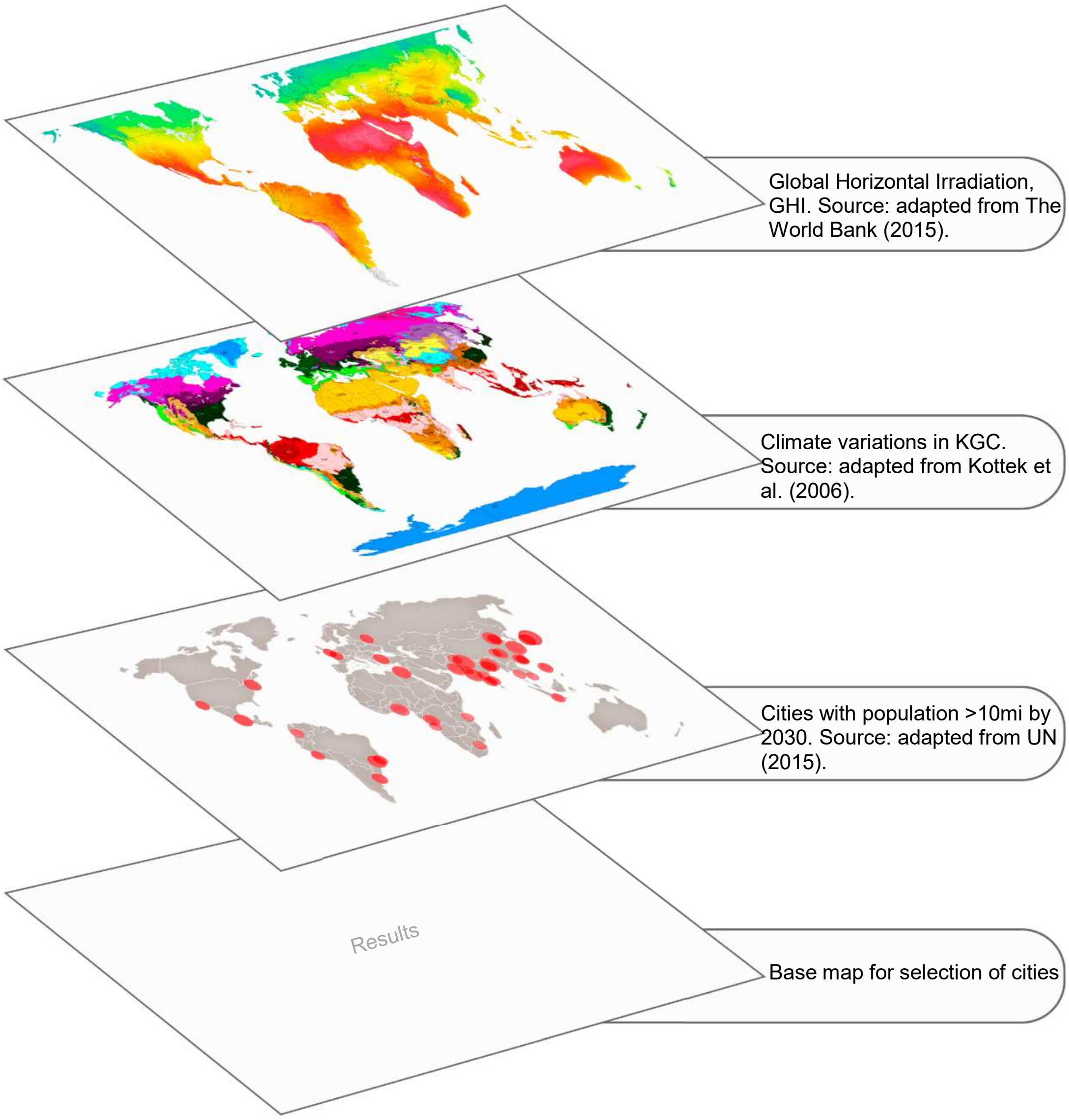


Figure 23: Partial world map of GHI, KGC and cities with >10mi inhabitants overlapped in GIS. Source: own author.

3.2. Daylight: Climate data

After the selection of cities, their climate data were obtained and compiled. Thus, this step was defined with two focus:

a) to define, obtain and treat daylight climate parameters to be compared with performance,

b) to analyze parameters in search for unexpected values and relevant information.

Based on literature review, three parameters that characterize daylight climate and that are potentially related to indoor performance were selected.

The parameters were global horizontal illuminance, sky cover, and sky type. Illuminance and sky cover were selected based on the study by Fonseca et al. (2017). Sky type as defined by the CIE was added, aiming to further characterize daylight conditions of each city.

Hourly-based weather file for each city was obtained from Meteonorm[34]. The weather file was imported in the software Climate Consultant[35] in its version v6, following a compatibility adjustment performed by their team that enabled it to read this database. In it, information on sky cover (%) and global horizontal illuminance (lux) were accessed and analyzed. Sky cover was compiled in percentages, instead of tenths, facilitating its comprehension.

The .epw weather file by Meteonorm was then imported in the APOLUX software, where features defined by the developer specifically for this study were executed in order to obtain data on sky type as per CIE 2003 for each city (example provided in Appendix C1). APOLUX requested a 3D model of a room to run the calculi of sky type. The default model with one side window and frontal obstruction provided by the developer was adopted (Figure 24).

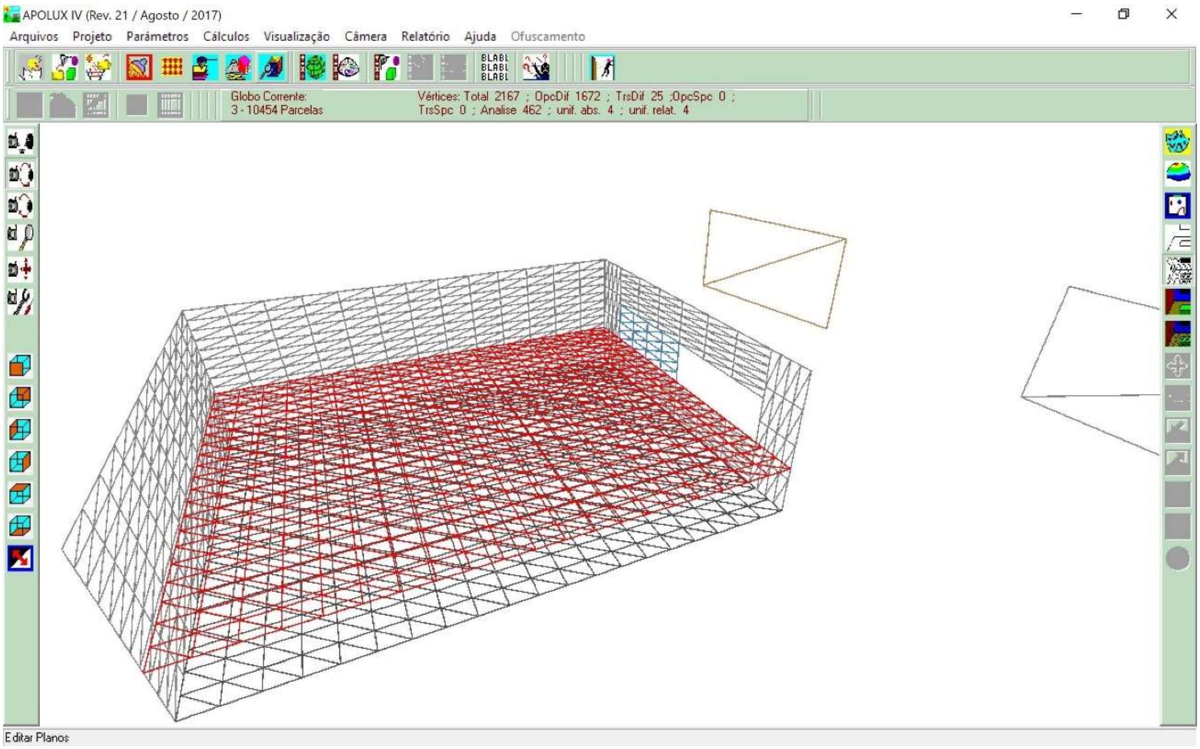


Figure 24: Print-screen of an environment within the APOLUX software.
Source: own author.

Meteonorm offers hourly (8760 hours) and monthly (12 months) data. In face of these options, hourly data were selected. Only the values within the hourly interval 8-18h corresponding to the same selected performance metric sDA' were compiled. This interval of 10h per day is one

34 https://meteonorm.com/
35 http://www.energy-design-tools.aud.ucla.edu/climate-consultant/request-climate-consultant.php

in which human visual and daily ‘productive’ activities are generally expected, often notwithstanding location. This process aimed to ensure the same timeframe for comparison between climate and performance data. Routines in Excel were created and applied in order to compile the data. The gathered hourly data per time interval were then used to calculate monthly data, and from this information, annual data were derived.

Regarding the case of sky type, a shorter interval of daily hours could minimize the errors of values calculated by APOLUX when the sun is closer to the horizon. Therefore, predominant sky types of the interval 8-18h and 9-16h were compared, and differences were highlighted for the final decision: results of the interval 8-18h were adopted.

For the purposes of this study and considering the fact that sDA’ is a value that represents the year, only annual data would be sufficient. Considering the intent of exploring the effects of climate variability on the results, monthly weather data were contrasted to monthly sDA’ - a metric that can be straightforwardly associated with most of the available weather databases because they are also conventionally reported in months. In this step, the climate data were organized in 12 months, from January to December.

Important to notice, illuminance and sky cover, both quantitative data, were processed and characterized annually and monthly in terms of average. Sky type, qualitative data, was retrieved in terms of the most frequent value found in the set (mode). In addition to the average (mean) value, the median value was obtained for complementary analysis[36].

For a statistical descriptive analysis of the variables, absolute and relative frequencies were selected for the qualitative variables, while measures of central tendency and dispersion were selected for the quantitative variables.

3.3. Daylight: Indoor Performance Data

Indoor daylight performance in different design conditions and climate were obtained through computer simulation. The 10 steps for the daylight simulation provided by Reinhart (2006), that are adapted in the left column of Figure 25, served as a reference for the entire simulation process.

[36] The mean value represents the sum of values divided by number of values in a set, while the median value represents the middle point of a set organized in ascending order.

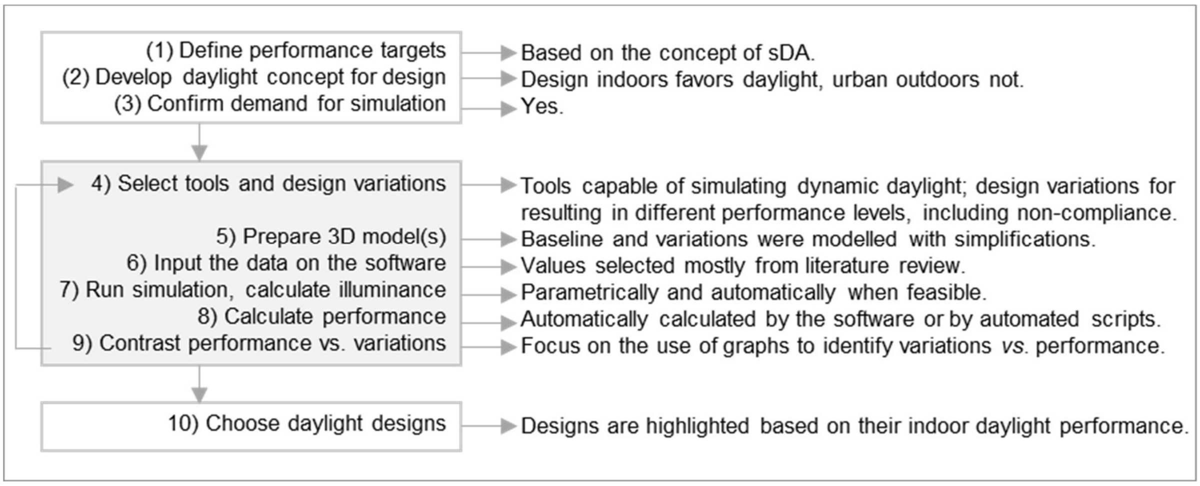


Figure 25: Path for daylight simulation in this study.
Source: own author, based on Reinhart (2006).

From this point, this section is divided into three phases (Figure 26):

1) Preliminary simulation, in which an experiment of another author was reproduced, aiming to replicate a model and gain knowledge in the software. Following the reference study, a test room was simulated for one city. This phase was repeated twice, due to the use of two different combinations of computational tools for indoor daylight simulation along with the research: LB/HB and DIVA, both for use with Grasshoper.

2) Exploratory simulation, from which relevant parameters were identified to reduce the number of combinations and resources used in the final simulation. This phase was conducted using a simplified model, a canyon, for one city.

3) Final simulation, from which the final results of indoor daylight performance served to evaluate the hypothesis. A model of higher complexity, an urban grid, was simulated considering variations and the climate of different cities.

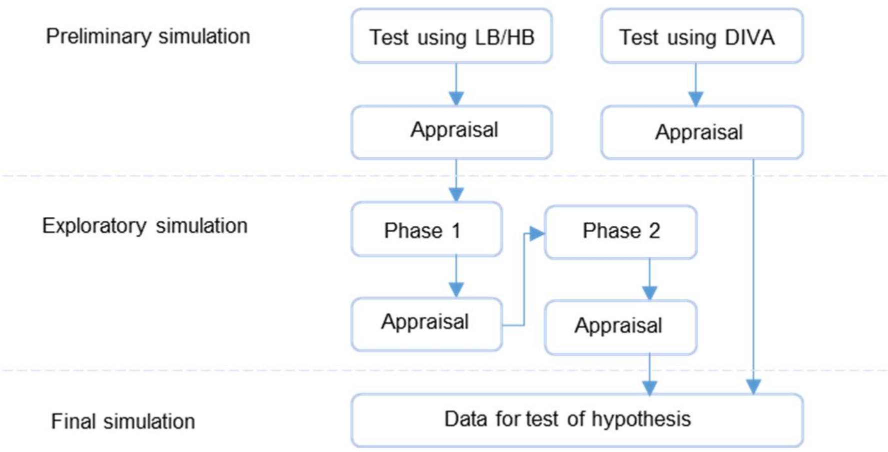


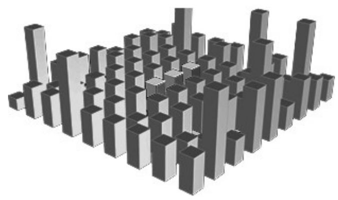
Figure 26: Phases of the indoor daylight simulation.
Source: own author.

Table 16 presents a summary of the main differences among the phases, including in terms of software, city (climate), input data, geometric model, etc. in a comparative way.

The next sections discuss in detail each phase.

Table 16:

Differences between the experiments of indoor daylight simulation.

Simulation phase:	**Preliminary**	**Exploratory**	**Final**
Goal:	Reproduce experiment to calibrate initial model, learn how to use software properly.	Simulate simplified urban models; select relevant parameters to be used in the next step: the final simulation.	Simulate a more complex urban model, and from that, extract the information for comparison among cities.
Geometric model:	Room	Canyon	Urban grid
Software/Plugins:	LB/HB, DIVA	LB/HB	DIVA
Output(s):	sDA	sDA	sDA/msDA
Measurement:	Room	Room in the middle of canyon	Rooms in the ground floor of three central buildings
Climate:	1 city (Boston)	1 city (Rio de Janeiro)	9 cities
Model based on:	Reinhart (2014)	Santos et al. (2017)	Chen et al. (2006a; 2006b)
Geometry variations:	Solar orientation	Solar orientation Urban Dimensions Room Dimensions	Solar orientation Urban Dimensions Urban Layout (canyon)
Other variations:		Material Glazing Settings (ambient bounces)	Material (outdoor reflectance) Glazing
Sketch of 3D model:	 (a)	 (b)	 (c)

Source: own author.

3.3.1. Preliminary simulation

The study presented by Reinhart (2014) was reproduced. This author tested a room in a previous version of the software DIVA, for the city of Boston. The goal was to successfully reproduce the experiment of this author: obtain as output the yearly sDA for the room. The checklist for the daylight simulation provided by Reinhart (2011) was used as an initial guide to organizing the tests.

Firstly, Rhino with Grasshopper and the plugins Ladybug/Honeybee were used in this preliminary simulation and the exploratory one. These tools allowed simultaneous simulation of multiple cases and climates, facilitating the implementation of the experiment.

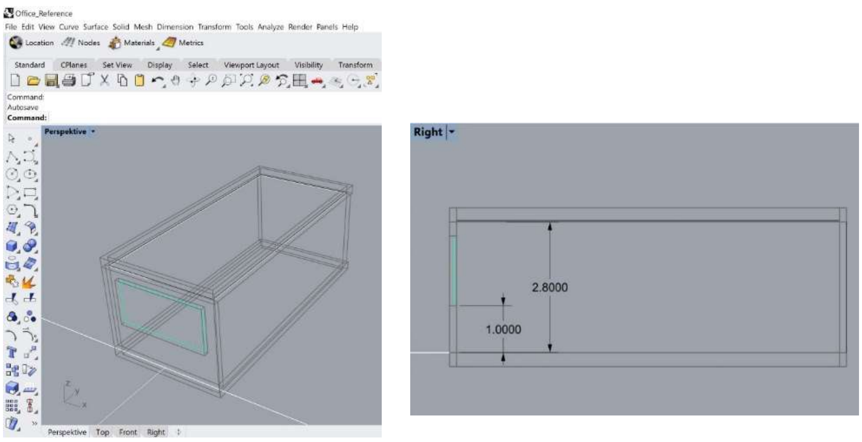
During this phase, the test room was also simulated in another software separately, the DIALux. At the time of this research, DIALux was not able to retrieve dynamic (hourly) results along the year, a crucial condition to obtain sDA. But this software could provide point-in-time indoor daylight results of 3D models. This feature was then used in exploratory analysis to increase the understanding of daylight behavior in the test room (Appendix D3, Figure 73), and eventually to contrast partial outcomes with the ones provided by Ladybug/Honeybee. Later, a version of DIVA for Rhino and Grasshopper was launched, containing specific tools for dynamic daylight analysis, including automated calculi of sDA and other metrics. The process of building, setting, and running the model for daylight was faster, less complex, and easier to control. Video tutorials and 3D example files provided by the developer SOLEMMA in its website helped to develop 3D models. Because of these benefits, this preliminary simulation was also conducted in this system. Then, these tools were adopted in the final simulation. Details of the input data including weather data file (climate), geometric model, software settings, and variations are described below.

Climate

City of Boston, following the reference presented by Reinhart (2014).
Weather file name: USA_MA_Boston-Logan.Intl.AP.725090_TMY3
Description: Boston Logan IntL Arpt, MA, USA, TMY3, 725090, 42.37, -71.02, -5.0, 6.0
Source/ Format: DOE / TMY3

Geometric model

The geometric model was built according to Reinhart (2014): a test room with one window. Two simplifications were adopted: mullions and internal doors were omitted.
A perspective and a right view of the room are illustrated in the Figure 27.
Room dimensions (w x h, m): 3.6 x 8.2 x 2.8.
Window dimensions (w x h, m): 3 x 1.4. Sill height: 1m.
Measurement: a grid of 0.45m. Height of the workplane of 0.8m above floor.



(a) (b)

Figure 27: Test room of the preliminary simulation: perspective (a) and right view (b). Source: own author.

Software settings

The settings and variations in the model were built as described in the reference (Reinhart,2014). Attention was given to reflectances, as well as number and height of the sensors for measurement.

When DIVA was used, a series of tests in this software were executed a priori in preparation for the development of the sub sequential models. Among these tests, checking of vector directions and visualization process were conducted (Appendix D1). Rhino v5 and v6 were used in the simulations. In case of Rhino 5, the settings of exporting objects were defined according recommendations of the User Guide (Appendix D2).

Output

The output was defined as sDA, measured in the interior of the room. The percentage was calculated and retrieve automatically by the software.

3.3.2. Exploratory simulation

This exploratory simulation was conducted considering the following goals:

a) to explore the behavior of indoor daylight in urban conditions according to variations in urban parameters of a simplified model, focusing on how performance can be influenced by inputs and parameter settings,

b) to reduce the number of parameters and their values used in the final simulation of the framework, which is more complex, by selecting the relevant ones based on the results of this simplified model, preventing an excessive number of iterations with similar results and saving computer processing time.

These goals were pursued by repeating and expanding the simulations presented in Santos et al. (2017). The model consisted of a test room located on the ground floor of a building within a hypothetical continuous urban canyon in one city (Figure 28).

The urban configuration, test room, location of measurement of points, parameters, and values, settings, and software were all kept the same as in that canyon referential study, except the city.

The input data and output analysis are detailed as follows.

Climate

Herein, the city of Rio de Janeiro was selected from a sample. This decision was based on the results of climate analysis, and due to the fact that the author is familiar with its climate.

City of Rio de Janeiro.
Weather file name: Rio_de_Janeiro_BR-hour
Description in the script: Rio de Janeiro, BR,-,MN7,0,-22.880,-43.280,-3,152
Source/ Format: Meteonorm Version 7.x / EPW

Geometric model

The geometry of the model consisted of a test room, centralized in one side of a continuous canyon. This condition is based on results of simulations by Sattrup and Strømann-Andersen (2013), which indicated that a continuous canyon tends to provide worse indoor daylight conditions than a non-continuous canyon when only the aspect of geometry is considered, for a specific climate condition.

The measured test room has the same dimensions of 3.0 x 2.7m (w x h), with one window of clear glazing, opaque sill, also following literature. The sill height of 1m above the floor was based on consulted guidelines for buildings, presented in previous Section. The window was then extended to an arbitrary height of 1.7m, considering a maximum vertical extension. These dimensions resulted in a WWR of 60%.

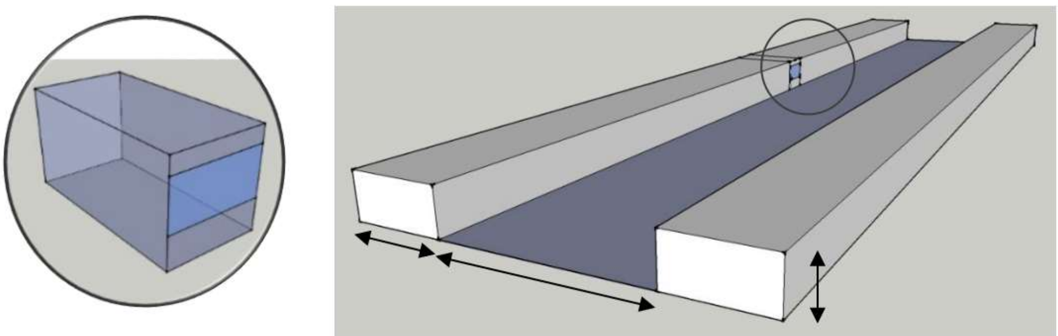


Figure 28: Simplified perspective of the model used in the parametric simulation.
Left: The reference room. Right: The continuous urban canyon containing the reference room.
Double arrows indicate the variable dimensions of street width, frontal obstruction height and room depth. Source: Santos et al. (2017).

Variations

The variations of the model in this exploratory simulation referred to the building depth (related to the depth of the reference room with 6, 7, 8, and 9m), solar orientation of façades (N, S, W, E), height of frontal obstructions (12, 24, 48, 72m), and street width (5, 10,15, 20m), as shown in Table 17. The ‘rule of thumb’ of approximately two times the height of the window head to promote daylight indoor (see Reinhart, 2014) served as a reference for the choices of room depths. The heights of front obstructions aimed to represent variations of obstruction angles caused by buildings of ca. 4 to 24 stories, considering the original definition of skyscrapers, and 3m between stories. The street width ranged from 5m, representing approximately a one-car line with one sidewalk, up to 20m[37].

Table 17:

Variations in input parameters of the 3-D baseline model for the exploratory simulation.

Parameter/ Variation	(1st)	(2nd)	(3rd)	(4th)
Depth of the reference room (m)	6	7	8	9
Height of front obstruction (m)	12	24	48	72
Street width (m)	5	10	15	20
Orientation of façade	W	N	S	E

Source: adapted from Santos et al. (2017).

The simulations were run as Phase I and Phase II: outputs of the first phase were analyzed to prepare inputs of the second phase, avoiding iterations without relevant results (Table 18).

In Phase 1, the baseline model was simulated with the variations tested in Santos et al. (2017), which are summarized in Table 18. Then, one change was implemented in the model: the number of ambient bounces was decreased from 6 to 3. The use of reduced number of bounces aimed to investigate whether the future model could be run in a lower resolution, thus speeding up the process of the research, without compromising the results. Phase 1 generated a database for analysis composed of 4 variations within 4 parameters, resulting in 256 outputs of performance for each Case. Results of this phase were analysed, and relevant conditions were selected for further simulations in Phase 2.

In Phase 2, extra variations were implemented in the configuration of Phase I that resulted in sufficient daylight conditions indoors: highest number of bounces and larger street width. Windows proportions, which are an element of concern in different guidelines, were varied in terms of WWR. The presence of pollution, a characteristic of several industrialized cities worldwide, was partially simulated through variation in the visible transmittance of glazing. The differences in finishing materials for the façade were explored through changes in reflectance of outdoor surfaces. Some of the variations were restricted to room depths of 6m and 9m, representing the best and the worst case in the tested scenarios (Table 18).

[37] Value close to the 60 feet (18.3m) wide streets in Manhattan, NY, one of the first references in such urban configurations worldwide.

Table 18:

Variations in the baseline model.

Case	Window			Urban configurations	Settings	Output
	WWR (%)	Tvis (%)	Façade Reflectance (%)	Canyon dimension	Ambient bounces	Illumi-nance
Phase 1:						
1.1-Baseline	60	88	40	Vary*	6	sDA'
1.2-Less ab					3	
Phase 2:						
2.1-Windows	15,30, 60, 90					
2.2- Reflect.			20,40,60			
2.3- Pollution		30				

Note: baseline as per Santos et al. (2017). *see Table 17. Source: own author.

Regarding the extra variations in windows, WWRs=15%, 30% and 90% were simulated, keeping the sill height=1m, except in the last case. The value of 30% was chosen to represent the half of the baseline, and 15% its quarter. The value of 100%, that would represent the maximum potential, was reduced to 90% in order to avoid crash in the simulation. A Tvis=30% based on Du et al. (2017) for studies on decreased visible transmittance due to urban air pollution was tested for the original baseline (WWR=60% and outdoor reflectance of 40%). The reflectances of façades varied by +- 20% in relation to the 40% of the baseline, considering the studies by Givoni (2006), Ng (2001b), Dornelles and Roriz (2008).

Finally, one last variation in urban configurations was implemented. The height of the side of the canyon that contains the test room was made equal to the front side. In this way, the heterogeneous morphology of the baseline became homogeneous.

The variations and values of input parameters were selected based on literature in the field of architecture and urban planning, particularly in the fields of materials and construction techniques, rather than using statistical methods that might retrieve more theoretical values.

Software settings

The exploratory simulation was conducted entirely using Grasshopper for Rhinoceros, with Radiance/Daysim interfaced by Ladybug/Honeybee in updated versions[38].

Regarding the input settings, they were based on the IES LM-83-12 (Table 19). The pursued output was the one "*nominally acceptable*" by occupants, an $sDA_{(300,50\%)} \geq 55\%$, the same as the level adopted in literature (see previous Table 5). This percentage also considered the

[38] Versions constantly updated between the years of 2016-2018.

findings of the referential study by Santos et al. (2017) that discussed the low probability of achieving levels above the "*preferred*" 75%. The threshold of 55% is then used to identify urban configurations to be adopted in the next step of the study.

Since inter-reflections are expected to be relevant for urban studies, the resolution of the model was kept identical to the referential study, including the ambient bounces of 6. This high value contributes to accuracy, but can make simulations in urban scale time-consuming; thus, it is rarely found in recent literature, i.e., Nault (2016).

Table 19:

Input parameters for the exploratory simulation.

Parameter	Value	Parameter	Value
Ambient bounces	6	Occupancy (local time)	8am to 6pm
Ambient division	4096	Illuminance Threshold (lux)	≥ 300
Quality	2 (High)	Period of occupancy (%)	≥ 50
Ambient sampling	4096	Indoor floor area – pursued sDA (%)	≥ 55
Ambient accuracy	0.1	Reflectance of indoor floor (%)	20
Ambient resolution	128	Reflectance of indoor walls (%)	50
Specularity of materials	0	Reflectance of indoor ceiling (%)	70
Roughness of materials	0	Outdoor ground reflectance (%)	20

Source: own author.

Outputs

Values of sDA' were measured in the work plane of the test room, for all variations and tested conditions. These values were retrieved automatically from the software and organized in tables for the analysis.

In terms of treatment tools and techniques, the results of the simulations were displayed in linear graphs for better visualization.

Statistical information were gathered with support of the Excel software with additional features (add-ins), R (v.3.5.0) and its interface R-studio (v. 1.1.456). Absolute and relative frequencies were employed to describe the independent variables related to urban parameters. As to results, their description was derived from measures of central tendency, dispersion and position, while their visualization was executed with boxplots. Boxplots were formed by the 1st, 2nd (median) and 3rd quartile from the bottom up, and by whiskers. The whiskers are the lines that extend vertically from the box indicating the variability beyond the upper and lower quartiles, while their extremes show the minimum and the maximum value of the sample, except for some possible outlier value, represented by a dot. The existence of outliers and the overall coherence of outputs were investigated in order to reduce the potential errors in the analysis. The outliers were detected by using the interquartile range, defined by the distance between the first and third quartiles. Lower and upper outlier detection limits were as follows:

- Lower Limit = First Quartile - 1.5 * (Third Quartile - First Quartile)
- Upper Limit = Third Quartile + 1.5 * (Third Quartile - First Quartile)

At last, the results of this exploratory simulation were compiled and analyzed, and then used as reference for the definition of elements (parameters and settings) of the final simulation: an urban grid of more complex geometry.

3.3.3. Final Simulation

The previous section concentrates on testing the daylight behavior in a room of small dimensions. Here, in turn, the focus is to obtain indoor performance results of an urban parcel. Thus, the measured area was expanded accordingly and several variations were tested. The performance was simulated adopting different software solutions than those used in the previous simulation: i.e. DIVA-for-Grashopper with support of modeling in DIVA-for-Rhino, which was launched after the exploratory simulation had been completed, and whose qualities pertaining to accuracy, simplicity of application and speed of process were considered advantageous for the research. The results of this final simulation were then analyzed, from which a sample of guidelines for daylight in the tested cities were outlined. Then, they were prepared for the analysis within the last step of this study: the final comparison in order to test the hypothesis.

Details of the input data and output analysis are described as follows.

Climate

The weather file names and description in the script of the nine selected megacities are:
1) BUENOS_AIRES_AR-hour/ BUENOS AIRES,AR,-,MN7,0,-34.670,-58.500,-3, 0
2) Dar_es_Salaam_TZ-hour/ Dar es Salaam,TZ,-,MN7,0,-6.880,39.300,3,61
3) DHAKA_BG-hour/ DHAKA,BG,-,MN7,0,23.700,90.370,6,15
4) Karachi_PK-hour/ Karachi,PK,-,MN7,0,24.850,67.030,5,30
5) LIMA_PE-hour/ LIMA,PE,-,MN7,0,-12.100,-77.050,-5, 0
6) London_UK-hour/ London,UK,-,MN7,0,51.507,-0.128,0,18
7) Rio_de_Janeiro_BR-hour/ Rio de Janeiro,BR,-,MN7,0,-22.880,-43.280,-3,152
8) SANTA_FE_DE_BOGOTA_CO-hour/ SANTA FE DE BOGOTA,CO,-,MN7,0,4.630,-74.080,-5,2560
9) Shanghai_CH-hour/ Shanghai,CH,-,MN7,0,31.230,121.470,8, 8
Source/ Format: Meteonorm Version 7.x / EPW

Geometric model

The details of the definition of the final urban model and software settings were based on the following question:

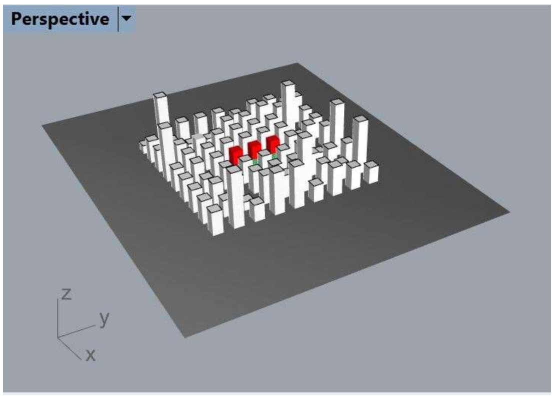
- If an indoor space is designed to favor daylight in a stand-alone building, until when would densification in the urban surroundings still allow minimum levels of indoor daylight?

In summary, information acquired from systematic literature review, considerations regarding the design aspects that can be influenced by urbanists, and the previous exploratory parametric simulations served as references for the definition of the 3D model and its variations. These were criteria for selection of parameters and their values: the metric (sDA), the statistical methods for final clustering, as well as the interest in obtaining diverse performance conditions to allow and enrich comparisons in order to test the hypothesis. Combinations that would potentially generate insufficient or maximum results (sDA'<<55% or ~100%) were avoided - the first case would not meet conditions for guidelines, and the second would soften differences necessary for comparisons. Computational resources were considered in the decision-making, especially because the above defined interest in gaining accuracy through a higher number of bounces compromised the time of processing.

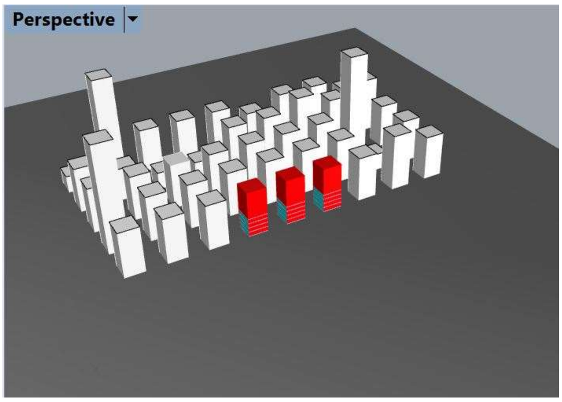
The baseline model (Figure 29 and Figure 30) was then selected based on those criteria. This baseline follows the matrix of uniform height buildings adopted in the remarkable study by Cheng et al. (2006a) (see previous Figure 13).

The matrix of baseline was reproduced maintaining the same average sky view factor of the model (SVF= 0.24), which is aligned to characteristics of a dense LCZ 1-Compact High rise urban region. More specifically, like Cheng et al. (2006a), the baseline model was built using 25 identical building towers in a 5 x 5 square array, surrounded by 2 rows of buildings with random, constant height. Absolute values of dimensions were not provided in the publication. Thus, the street width was set to 15m, which is a dimension that tended to meet minimum levels of daylight sufficiency in diverse combinations tested in the exploratory simulation, considering a room depth of 6m. Once the street width of 15m had been defined, it was possible to define other dimensions of the buildings: all of them with a square base of 15 x 15m, and initial height of 35m (approximately 2x the street width).

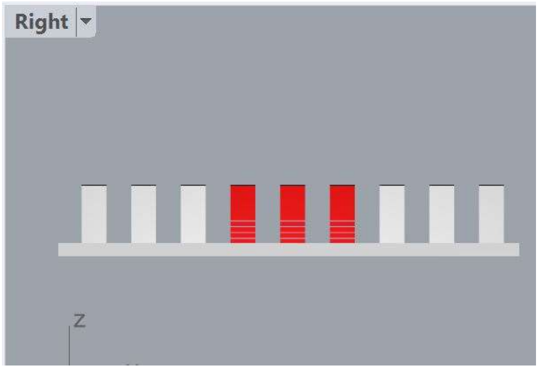
The area where indoor daylight is measured is a floor plan without differentiation of function (residential, office, etc.), as adopted in other studies in the field, i.e., Saratsis (2015) and Nault et al. (2017). This amplification of the area from a small test room to a big open floor plan aimed to represent the transition from an architectural to an urban scale, which is the goal of this study.



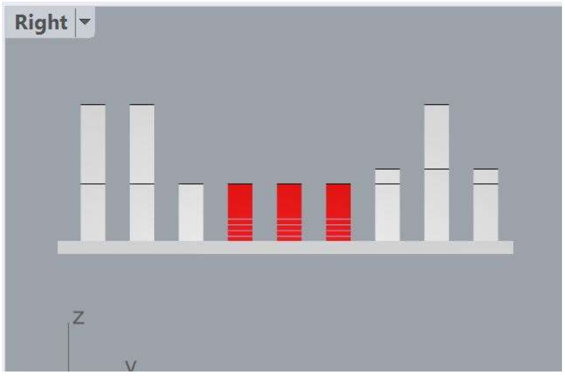
(a)



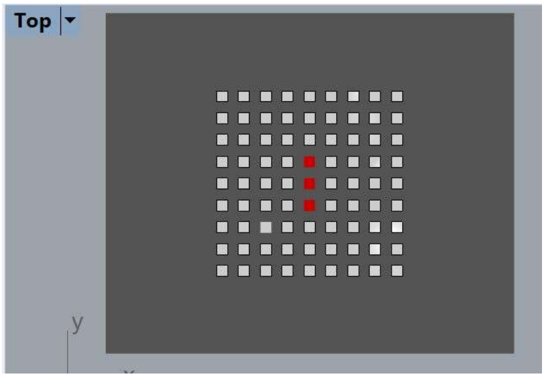
(b)



(c)



(d)



(e)

Description:
(a) Full perspective, highlighting in red the three central buildings where the measurements were taken.
(b) Partial perspective, excluding half of the model to show the windows of the three central buildings, in blue.
(c) Partial right view, showing that the central matrix was composed by buildings of same height.
(d) Full right view, including surrounding buildings of random heights.
(e) Top view, central buildings in red, other buildings in light gray and ground in dark gray.

Figure 29: Baseline model of final simulation.
Source: own author.

Figure 30 presents a detail of the measured ground floors in the three central buildings of the baseline model. Each floor's total height is 3m, with floor-to-ceiling height of 2.7m. Each floor plan measures 15m in width, which is the dimension of the building. To favor daylight, it measures only 6m in depth, considering the mentioned 'rules of thumb' of window-room dimension discussed in Reinhart (2014), and the results of the exploratory simulations. This is an optimistic approach, considering that "*typical plan depths for naturally ventilated and day-lit* *office buildings are 12-15m*" (Ratti et al., 2003)[39], but it reinforces the focus on the effect of urban geometry over daylight performance indoors. Oriented towards North and South, the floor plans were divided inside each building by an internal corridor of 15m x 3m.

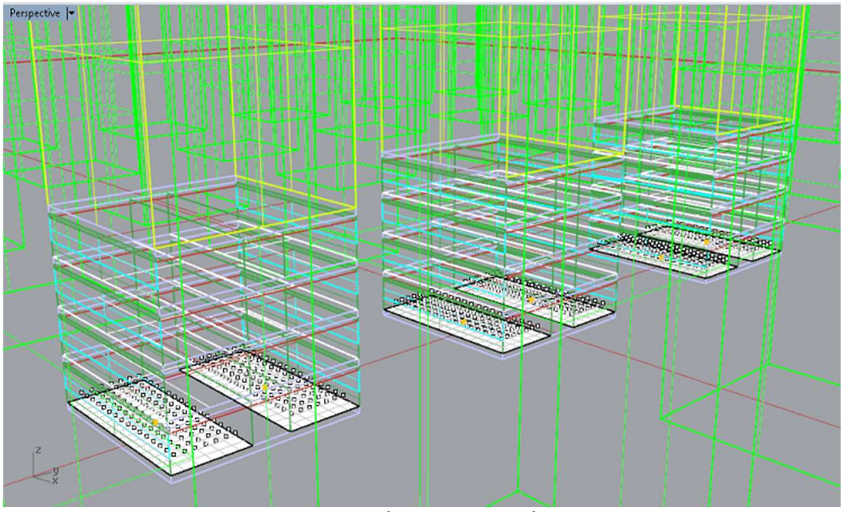


Figure 30: Baseline model developed in the software DIVA-for-Rhino.
Note: view of the measured points in three central buildings of the matrix. Source: own author.

After the baseline was defined, its variations were selected. Two types of height variations were chosen for the matrix: uniform height or alternating higher and lower heights[40].

In total, three cases of uniform height were tested: 35m (baseline), 70m (equivalent to 2x the height of baseline), and 100m (ca. 3x of the height). These values represent built densities that increase vertically from approximately 10 to 20 and finally to-30 stories.

To test heterogeneous heights like Cheng et al. (2006a) have experimented, the sequential heights of 15m and 70m were alternated in the matrix. These values represent about the half and the double of the height of each original building.

Following Strømann-Andersen and Sattrup (2011), the typology of canyon was selected to represent a horizontal increase in density.

Summarizing, aiming to concentrate the analysis in few relevant cases, these following variations were selected:

- 3 urban typologies (homogeneous grid, heterogeneous grid, homogeneous canyon)

- 3 variations in the heights of the homogeneous grid (35m, 70m, 100m)

- 3 window sizes (WWR of 100%, 60%, 30%)

The variations were combined and executed according to Table 20. A variation of the outdoor

[39] These dimensions probably refer to open floor plans with windows in multiple façades in certain climates.
[40] The random and pyramidal variations adopted in Cheng et al. (2006a) were abandoned, as it is less likely that they could be included in urban design and planning instruments.

reflectance from 40% to 100% was also tested.

Table 20:

Variations in the simulated models of urban grid.

Case	Description	Characteristics	FAR	Building Coverage
A*	Baseline	Grid,H=35m,WWR=100%,ab=4, outdoor reflectance=40%	x	y
B	Baseline as heterogeneous height	H vary	1.2x	y
C	Baseline smaller windows	WWR=60%	x	y
D	Baseline smallest windows	WWR=30%	x	y
E	Baseline higher	H=70m	2x	y
F	Baseline higher smaller windows	H=70m, WWR=60%	2x	y
G	Baseline highest	H=100m	3x	y
H	Baseline as canyon	Canyon	1.2x	1.2y
I	Baseline higher outdoor reflection	Outdoor reflectance=100%	x	y

*Case A baseline: FAR (x=2.4), Building coverage (y=0.20). Source: own author.

Software and settings

The indoor reflectances and settings of the software corresponded to the ones used in the exploratory simulations. However, due to computational capacity, the number of grid points was restricted to a maximum of 5000, with a distance of 1m between each measured point. These factors influenced the decision regarding the measured urban area: only floor plans on the ground floor of the three central buildings had their illuminance levels computed for comparison.

Another alteration as compared to the exploratory simulation was the reduction in the number of ambient bounces. When setting parameters, adopted were the ones defined as "*medium quality*" in DIVA-for-Grasshopper, reporting simple spaces without detailed shading and moderate inter-reflections (Table 21). This decision considered the amount of time required for simulation, and the fact that in the urban scale, some of the architectural details are not available, or need to be simplified for the sake of feasibility of the study. Accordingly, the number and type of variations were also restricted due to the processing time.

Materials available in the database of the DIVA-for-Rhino software were adopted. Outdoor reflectance was set to 40% for building envelope. However, after the first round of simulations, one case that resulted in a poor to moderate performance was selected and had its outdoor reflectance of 40% was increased to 100%, thus theoretically heightening the potential for contribution of surrounding façades. Outdoor ground reflectance was fixed at 20% as per IES LM-83-12.

The measured indoor space was conceived in its baseline with clear glazing and a WWR of

100%, 60% and 30% of the façade in which they are located, along the solar orientation: North or South. A WWR = 100% was chosen following an example by Saratsis (2015) in order to favor maximum daylight potential; it was possible to simulate this percentage in the chosen software. All the models, with homogeneous and heterogeneous height, as well as the canyon, were tested with WWR = 100%. The baseline was also tested with 60% and 30% WWR, in order to observe the effects of the reduction of window sizes. The grid of uniform height of 70m that compose one of the simulated cases was also tested with WWR = 60%, aiming to evaluate the resulting combination of increased height with smaller window size in the grid. The percentage of 60% and the sill height of 1m were based on instruments or guidelines mentioned in Table 12, especially considering the maximum percentage registered in the code of India. The percentage of 30% resulted from the application of the restrictive guideline of WFR ≥ 12.5%: for a measured floor of 15m x 6m = 90m^2, a WFR = 12.5% results in a WWR = 27.8% (~30%).

Table 21 presents the characteristics of the settings of the final baseline urban model and its variations in a comparative table. The variations were simulated for all selected megacities.

Table 21:

Characteristics of the baseline model and its variations.

Item	Baseline	Variations
-Urban Geometry		
Typology	Grid	Canyon
Buildings distribution	Matrix 5 x 5 + 2 rows	
Street width (m)	15	
Building width x depth (m)	15 x 15	75 x 15 (canyon)
Building height (m)	35	Homogeneous: 70, 100 Heterogeneous: 18, 70
-Indoor geometry		
Floor plan, w x d (m)	15 x 6	75 x 6 (canyon)
Floor to ceiling height (m)	2.7	
WWR (%)	100	60, 30 (sill height= 1m)
Settings		
Indoor reflectances (%)	Walls 50, ceiling 70, floor 20	
Outdoor reflectances (%)	40	
Glazing - Tvis (%)	88 (clear)	
Sensors	0.85m height, 1m between each other	
Run parameters	Medium: -aa .1 -ab 4 -ad 1024 -ar 256 -as 256 -dr 2 -ds .2 -lr 12 -lw .004 -dj 0 -lr 6 -sj 1 -st 0.15	
- Outputs		
Data	Illuminance levels in each sensor	
Metric	sDA’	monthly sDA’

Source: own author.

Outputs

The pursued output was the indoor daylight performance for each tested variation. DIVA offers diverse options for the calculation of the sDA; in this case, the option without daylight saving time (DST) was selected. Future studies can apply the DST convention and evaluate the differences.

Each urban case was run parametrically in the system of DIVA, for all cities simultaneously, to minimize effects of the stochastic model of the software.

Important to notice, daylight levels were measured at the ‘workplane’ level of the ground floor of three central buildings of the matrix. The average of these three values was automatically calculated by the software and then represented the final result of simulated each urban case.

The hourly results provided by DIVA were accessed and organized in a table. From this table and using a script based on the equations by Bauer and Wittkopf (2015), monthly sDA’ were obtained for those cities. The analysis was conducted considering the threshold of 300 lux, 8-18h of an integral period of occupation, sufficiency above 55% of the total spatial area measured at the height of 0.80m of the ‘workplane’.

3.4. Classification of Selected Cities into groups

This last part of the research is mainly organized into the steps presented in Figure 31.

Data obtained in the previous section were revisited. This time, all nine cities were organized into groups, based on the similarity of their data obtained in the two categories:

- Data of daylight parameters that can influence indoor performance, and
- Data on indoor daylight performance.

More specifically, cities were grouped only by the category ‘parameters’. Separately, they were grouped by ‘performance’. Finally, the groups formed by ‘parameters’ *versus* ‘performance’ are contrasted to observe whether there is correspondence among the groups, aiming to test the hypothesis. All comparisons were divided by time frame: monthly and annual data.

This process used different tools, then subdivided into Part 1 and Part 2.

In Part 1, the analysis in these phases was conducted considering the ‘raw’ available data, their resulting descriptive statistics, and visual assessment of basic graphs.

In Part 2, the analysis was based on advanced statistics: cluster analysis was applied. For a complementary analysis, tools including ranking and Pearson correlation were also applied.

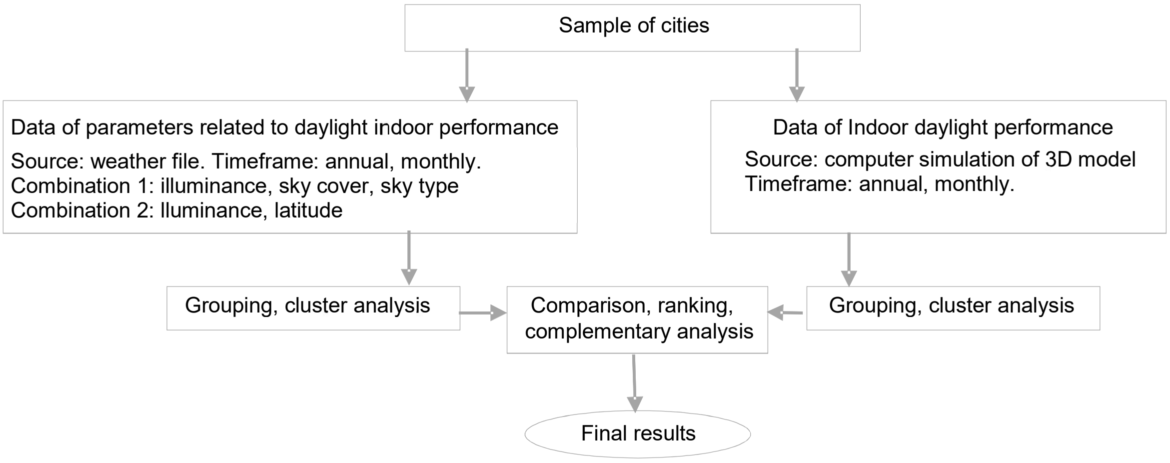


Figure 31: Summary of the last steps of this research.
Source: own author.

3.4.1. Part 1: comparison per data type

In Part 1, the analysis is organized in the following sequence:

- Daylight climate;
- Daylight indoor performance;
- Daylight climate *vs*. indoor performance.

For the comparison of cities in terms of daylight climate parameters, the urban agglomerations were grouped considering their results of global horizontal illuminance: first looking at the annual data, and then at the monthly data. The process was repeated considering the results of sky cover. Finally, the results of sky type conditions served as a condition for grouping.

The comparison of cities considering indoor daylight performance was conducted focusing on variations in urban geometry. Results of variations in the glazing area and façade reflectance were ignored, aiming to isolate the effect of morphology in performance.

Graphs were visually compared, searching for similarities between those of climate parameters *versus* those graphs of performance.

For comparing numerical results, it was adopted the concept of distances; for instance, "*the number 2 is closer to 5 and more distanced to 10*". For the categorical parameter CIE sky, it was adopted the concept of equivalence: if two cities had sky type '10', they were considered similar. In the process, a visual quali-quantitative approach of graphs was also useful and therefore was adopted.

Different thresholds or ranges for identifying similarity were tested. As a consequence, the analysis generated different results, with cities belonging to different groups, according to the approach. The implications of that were also discussed.

3.4.2. Part 2: comparison per combination of data type (cluster analysis)

The aim of the investigation in Part 2 was to group cities by parameters which are different in type, nature, and scale. Cluster analysis was identified as a proper tool for this task. It can generate groups based on clear criteria, using equations that are consolidated in the statistical literature (i.e., as described by Tan et. al, 2019).

Thus, advanced statistical techniques were used to cluster climate data, then the performance data. The resulting clusters were daylight climate (annual separated from monthly one), which were contrasted respectively to performance expressed as sDA' (annual and monthly). In so doing, it was possible to examine whether:

- is there any correspondence between the graphic of daylight climate and performance,
- the classification of cities' similarity varies according to a timeframe.

The compiled steps for conducting a cluster analysis were used as a reference in this process (see chapter 'Background', section 2.5.2).

The intended number of clusters was inferior to three, considering that the number of nine cities is relatively small. The works by Reinhart (2002), who adopted five clusters for a region, and by Fonseca et. al (2017), who divided a territory into three daylight zones, also played a role in this decision. These studies were developed for regions of a large range of latitudes, a characteristic related to the sample of cities for this clustering analysis.

In this context, the agglomerative hierarchical method Ward d2 was selected, with results visualized through dendrograms. These graphs present the 'history' of proximity among the grouped cities, which is an interesting advantage. Additionally, the Ward d2 method is well known and capable to deal with mixed numerical and categorical data. Other selected characteristics of the method were the type exclusive and complete, in which each one of all objects is assigned to a unique cluster. The distances among the data were calculated using the Euclidian distance for numerical data, and the Gower's distance for mixed data types.

Another traditional clustering method was applied: the k-means, which is used in situations with large databases, using as input the number of clusters identified automatically in the Ward d2 process. Then, the results of Ward d2 and k-means were compared. This comparison using two mehtods aimed to provide a more comprehensive understanding of the effect of the chosen method on the resulting groups and evaluate/validate the generated clusters.

Complementarily, the association between daylight climate parameters and simulated daylight performance was evaluated.

Along the process, measures of central tendency (e.g. mean, median, and mode) and measures of dispersion (e.g. standard deviation) were adopted, according to the characteristics of the data. Results were displayed in boxplots or graphs. In some of these graphs, dots were connected by lines for facilitating the visualization and analysis.

The generated groups of cities from the clustering were debated considering the information extracted from the raw data and/or from the previous system of grouping adopted in Part 1.

A ranking process was conducted to explore the results, considering other possibilities of parameters for clustering. This process aimed to identify which parameters extracted from weather files could have a higher potential of being associated with daylight performance. A dendrogram of performance was used as a reference and it was complemented with a table to support a ranking process. In this table, parameters from weather files were listed, characterized by colors according to quali-quantitative information, and compared based on their similarity to the results of performance.

Finally, the graphs and statistical results were evaluated under the perspective of urban design and urban daylight climate. Evidence supporting or refuting the hypothesis were extracted and discussed, and answers to the main questions of this research were presented.

Important to mention, a statistical consultant company (ABG), specialized in academic studies, provided support in different steps of the analysis. They gave support in the decision of the necessary sample sizes, data treatment, correlation analysis, observation of outliers, evaluation of cluster results and validation, scripts, and available software. Their suggestions were discussed with other experts in statistics along the way, to enhance perspectives about methods, necessary tools, and analysis of results.

3.4.3. Treatment tools and techniques

Excel v.2013 was adopted for organizing data and preparing some of the graphs.

The free software R v 3.5.1 and its interface R-Studio were selected for the statistics. It was capable of processing the amount of annual and monthly data of this research automatically in a few seconds, using scripts that are free, available online, and openly discussed by the community of statisticians and general users. A basic script containing functions used in the software is summarized below. For the cluster analysis, it highlights functions for calculating distance for numerical and mixed data types, as well as a hierarchical and non-hierarchical cluster: i.e., dist, daisy, hclust, and k-means. For correlation between parameters, functions of types Pearson and Spearman were adopted.

All these functions are based on consolidated literature in statistics. They are well documented[41], and often used for this type of quantitative analysis. Above all, these methods were selected because of the characteristics of the database: numerical ones in case of sDA' and msDA', and mixed data in case of the cluster of weather file parameters.

```
> # Example of script: creating a cluster for sDA' of cities. Consider an Excel file 'A1', where results of sDA are presented. Cities are organized as rows, and the column containing the name of cities is omitted. Cases of variations in urban geometry are organized as columns.

> # in Rstudio: Import Dataset as Excel.

 > # Install necessary packages

> #Normalizing/standardizing database, saving intermediate files with different names to facilitate (z, m, s, etc.):

> View(A1)

> z <- A1

> m <- apply(z,2,mean)

> s <- apply(z,2,sd)

> z <- scale(z,m,s)

> #Calculate Euclidean Distance:

> distance <- dist(z)

> #Calculate hierarchical cluster using method Ward d2 (hc.wd2) through function hclust:

> hc.wd2 <- hclust(distance, method = "ward.D2", members = NULL)

> #Calculate non-hierarchical cluster using method k-means, considering k the number of clusters obtained from Ward d2 and n the number of initial configurations of centroids until selecting the best one:

> km <- kmeans(z, k, nstart = n)

> #Plot and visualize graphs:

> plot(hc.wd2)

> fviz_cluster(km, data = z,… )

> #In case of variables of mixed types, like sky type, calculate distance using the function daisy and Gower:

> dist <- daisy(A1,metric = "gower")

> #For calculating Pearson and Spearman correlation, considering a:b as the interval of columns for analysis:

> p.correlation <- rcorr(as.matrix(file[,a:b]),type="pearson")

> s.correlation <- rcorr(as.matrix(file[,a:b]),type="spearman")
```

---

[41] Note: Details of several funtions were obtained in the online platform Rdocumentation: www.rdocumentation.org

4. Results and discussion

The results and discussion obtained through the application of the framework are presented from this point.

4.1. Selected Cities Worldwide

The selection of cities was based on data pertaining to global horizontal irradiation, on variety of climate according to a well-known classification system, as well as on the projected population size of over 10 million inhabitants by 2030, as previously explained.

Results retrieved automatically from these data overlapped data in GIS are shown in Table 22. From among all 41 future megacities, 11 cities were classified as climate Aw (corresponding to 26.8% of the total number of cities), 7 cities are Cfa (corresponding to 17.1%), 6 BWh (14.6%), 3 Cfb, 3 Cwa, 2 BSh, 2 Cwb, 2 Dwa. Additionally, there were 1 Dfb, 1 Am, 1 Am, 1 Csa and 1 Csb. These abbreviations are explained in the Appendix A.

For each climatic group, the following cities exhibited the highest and the lowest values of global horizontal irradiation: Dhaka and Dar es Salaam in Aw group, Chongqing and Buenos Aires in the Cfa, Luanda and Lima in the BWh, London and Bogotá in the Cfb group.

The cities finally selected for analysis are highlighted in Table 22: Dhaka, Dar es Salaam, Shanghai, Buenos Aires, Karachi, Lima, London, Bogotá, and Rio de Janeiro. The last one was included because the author is familiar with its climate. Chongqing and Luanda were replaced by Shanghai and Karachi, respectively, due to the characteristics of the weather file accessed at the time that could compromise the results of the study.

The latitude and longitude data of the selected cities gives a panorama of their distribution around the globe (Figure 32). Geographically, four cities are located in Latin America, three in Asia, one in Europe, and one in Africa.

Table 22:

Future megacities organized according to their group of KGC climate, in ascending order of GHI.

#	City	Country	GHI	Latitude, Longitude	Climate
1	**Dhaka**	Bangladesh	1664	23.7, 90.36667	Aw
2	Manila	Philippines	1698	14.5946, 120.99501	Aw
3	Kolkata (Calcutta)	India	1701	22.54111, 88.33778	Aw
4	Lagos	Nigeria	1753	6.45, 3.4	Aw
7	Krung Thep (Bangkok)	Thailand	1815	13.751911, 100.645256	Aw
5	Kinshasa	Dem. Republic Congo	1819	-4.481432, 15.846089	Aw
6	Thành Pho Ho Chí Minh	Viet Nam	1824	10.700153, 106.656299	Aw
9	Bangalore	India	1942	12.96991, 77.59796	Aw
8	Mumbai (Bombay)	India	1946	18.96667, 72.83333	Aw
10	Chennai (Madras)	India	1957	13.09, 80.27	Aw
11	**Dar es Salaam**	Un.Rep.of Tanzania	1999	-6.818, 39.279	Aw
1	Chongqing	China	1023	29.55, 106.50694	Cfa
2	**Shanghai**	China	1327	31.16667, 121.46667	Cfa
3	New York-Newark (NY)	USA	1354	43.0467, -77.0953	Cfa
4	Tokyo	Japan	1457	35.54843, 139.78041	Cfa
5	Osaka-Kobe (Osaka)	Japan	1476	34.636745, 135.22865	Cfa
6	São Paulo (Sao Paulo)	Brazil	1686	-23.5507, -46.6334	Cfa
7	**Buenos Aires**	Argentina	1753	-34.617803, -58.439558	Cfa
1	Luanda	Angola	1929	-8.83333, 13.23333	BWh
2	**Karachi**	Pakistan	1967	24.870862, 67.114544	BWh
3	Hyderabad	Pakistan	1950	17.36667, 78.46667	BWh
4	Ad-Dammam	Saudi Arabia	2091	26.40552, 50.03404	BWh
5	Al-Qahirah (Cairo)	Egypt	2143	30.042895, 31.57251	BWh
6	**Lima**	Peru	2147	-12, -76.8333	BWh
1	**London**	United Kingdom	1017	51.50722, -0.1275	Cfb
2	Paris	France	1145	48.859489, 2.320582	Cfb
3	**Bogotá**	Colombia	1518	4.252428, -74.184135	Cfb
1	Chengdu	China	918	30.66361, 104.06667	Cwa
2	Guangzhou, Guangdong	China	1366	23.138962, 113.28056	Cwa
3	Shenzhen	China	1469	22.535383, 114.05471	Cwa
1	Lahore	Pakistan	1692	31.497754, 74.360106	BSh
2	Delhi	India	1715	28.653458, 77.123767	BSh
1	Johannesburg	South Africa	1981	-26.1633, 28.0328	Cwb
2	Ciudad de México	Mexico	2180	19.434612, -99.07912	Cwb
1	Beijing	China	1392	39.905, 116.39139	Dwa
2	Tianjin	China	1412	39.14667, 117.20556	Dwa
1	Moskva (Moscow)	Russian Federation	1046	55.75583, 37.61778	Dfb
1	Jakarta	Indonesia	1702	-6.173292, 106.841036	Af
1	**Rio de Janeiro**	Brazil	1766	-22.911, -43.2094	Am
1	Istanbul	Turkey	1492	41.008098, 28.97839	Csa
1	Los Angeles-Long Beach-St.Ana	United States of America	1941	33.7775, -118.1885	Csb

Notes: GHI (kWh/m^2 per year). #Number of cities with equal KGC. Source: own author. GIS interface developed in cooperation with Daniele G. Ferreira in Oct/2018.

Figure 32: Selected cities distributed in the world map with approximate latitude and longitude. Source: adapted from R-bloggers.com (mapping in R with ggplot).

Appraisal

Before the analysis, the climate classification of cities that resulted from the overlapped data in GIS was compared to the classification provided by another source (Appendix B) to investigate eventual differences. This process generated awareness: some results were different among the sources, reinforcing that classification varies according to the weather database and model for calculation. This was the case, for example, in Dar es Salaam and Bogotá. However, only one database was chosen for this study. The classification based on Kottek et al. (2006) was adopted without alterations.

In general, the use of GIS demonstrated to be a positive choice for a fast, quantitative-based selection of the megacities. Valid to notice, the definition of criteria for automated selection of cities in GIS was not straight-forward. It required intermediate investigation and tests to check whether the aimed information was available, coherent, and ‘ready-to-use’ in this digital tool. Thanks to current technology, plenty information was found. This is an additional valuable advantage of GIS, which is recommendable for future similar researches.

From the population data shown in Table 22, it is observed that the majority of the selected cities are located in the tropical and subtropical regions. An advantage of these areas is that they are considered to have a high potential for using daylight (Cabús, 2005), due to the characteristics of solar incidence throughout the year. Few cities located in higher latitudes will reach more than 10 million inhabitants by 2030: London, Moscow, and Paris are examples.

4.2. Daylight: results of the climate data

For each of the selected cities, annual and monthly data pertaining to parameters that characterize daylight climate were obtained and analyzed. For the purposes of this research and considering the literature review, three climatic parameters were chosen: global horizontal illuminance, sky cover and sky type.

Starting from the parameter average global horizontal illuminance by city, their data between 8h and 18h (10 hours/day), are presented in Table 23 and generated the graphs below. The linear graph in Figure 33 shows the profile of illuminance levels through the months of a year. The overlapping of lines in the linear graph makes the comparison among cities difficult in terms of details of variability. Hence, Figure 34 is presented, allowing for quantification and comparison of the illuminance among cities.

Table 23:

Average global horizontal illuminance (lux), 8h to 18h, from January (1) to December (12).

Month	B.Aires	Bogotá	D.Salaam	Dhaka	Karachi	Lima	London	Shanghai	R.Janeiro
1	69212	52018	55465	42880	38312	68159	5988	21312	62740
2	63808	50819	56485	48192	44429	68004	12316	28622	60784
3	51697	46950	51024	59135	53016	66251	22810	33138	57666
4	38500	42881	41981	61090	60829	61536	35197	42507	45590
5	27382	39584	44155	59405	61407	48795	44519	47396	42515
6	20346	39769	43927	51636	60529	41574	44373	42511	35934
7	21968	41697	45314	51331	48502	42260	44768	48860	41512
8	32009	44420	48971	47765	48838	40881	41080	46777	44570
9	43602	44738	52725	51311	56626	51546	29253	40971	46114
10	53684	45617	54009	47189	50133	51898	17448	34145	52640
11	67686	42896	57752	47057	39841	55881	8094	25173	55829
12	68196	47387	57673	42413	34043	61889	4863	21512	59849
Year	**46508**	**44899**	**50790**	**50784**	**49709**	**54890**	**25892**	**36077**	**50478**

Source: own author.

In Figure 33 each dot represents a monthly value. The dots are interconnected by segments, which simplifies visualization of illuminance curves through the year. It is possible to observe, for instance, that Buenos Aires and London, respectively, have peaks of minimum and maximum in June. In this regard, it is important to remember that these cities lie in the opposite hemispheres of the globe, and have the highest latitudes within the sample. London exhibits the lowest illuminance levels of the sample during 8 months of the year, reaching values close to 5 klx in winter time. Buenos Aires exhibits the maximum illuminance value of the sample, reaching ca. 69 klx in summer time, but its values vary notably throughout the year.

Illuminance levels in Bogotá vary less than in the other cities. Interesting behavior is observed in the data from Karachi: two positive peaks are registered, one in May and the other in September. This is also observed in the data pertaining to Dhaka and Shanghai, albeit manifesting as smoother curves.

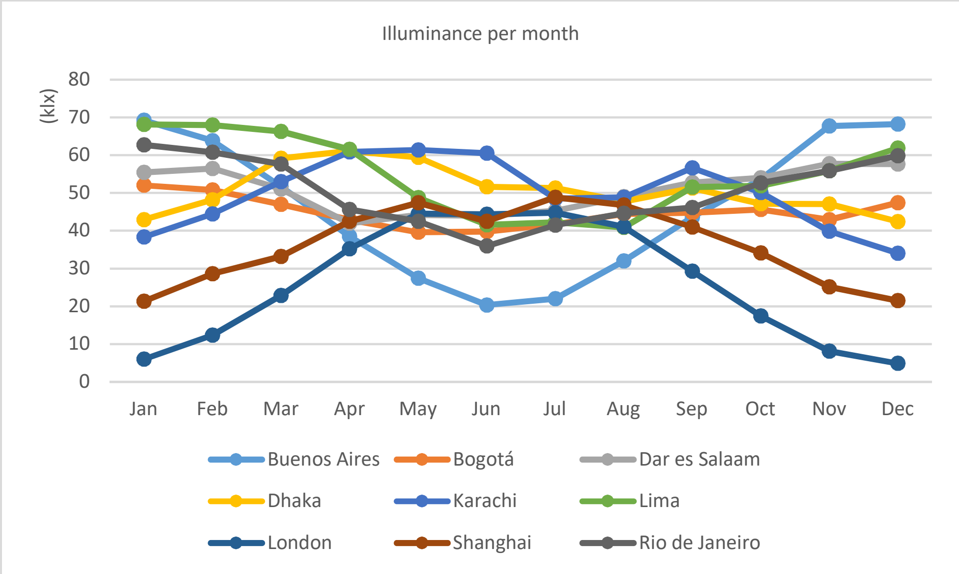


Figure 33: Curves of global horizontal illuminance (klx) of all cities troughout the year. Source: own author.

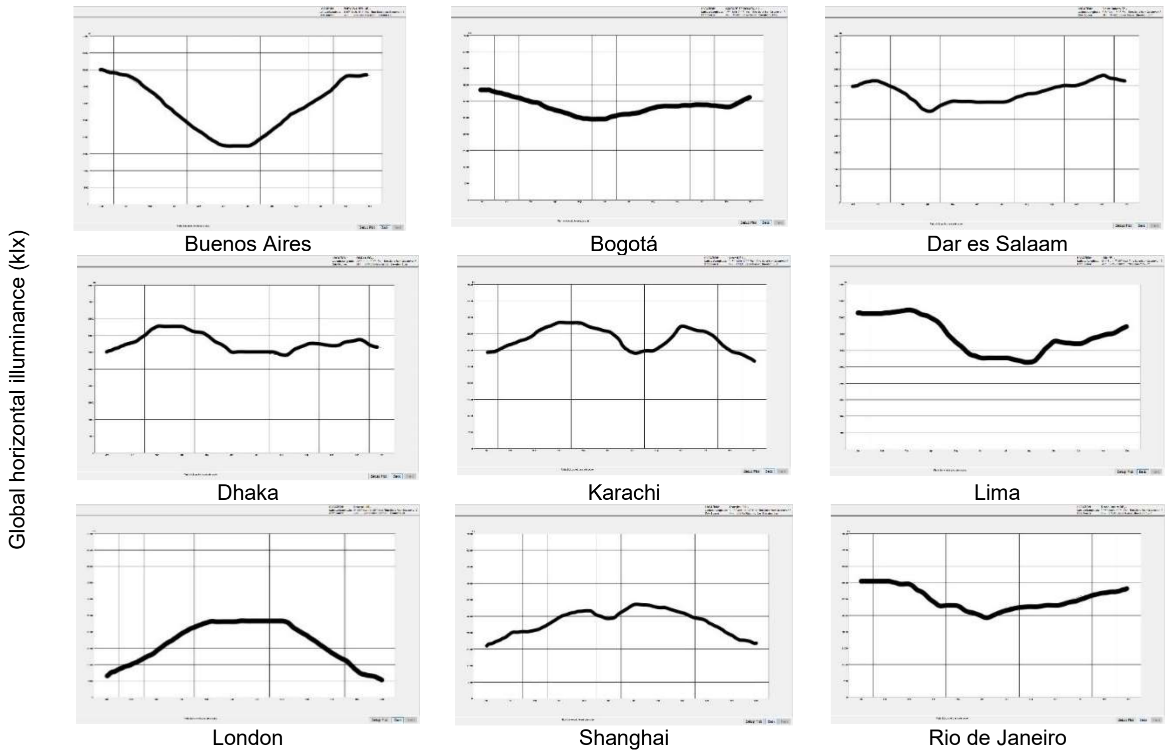
Figure 34 presents the monthly illuminance by city, from January to December, as line graphs (a) and boxplots (b). Line graphs were plotted using ClimateConsultants. Boxplots were generated in R-studio, using as input only daily intervals from 8h to 18h.

Considering the boxplots of illuminance, Buenos Aires and London exhibit higher variability of values through the 12 months. Noticeable, they lie further away from the Equator.

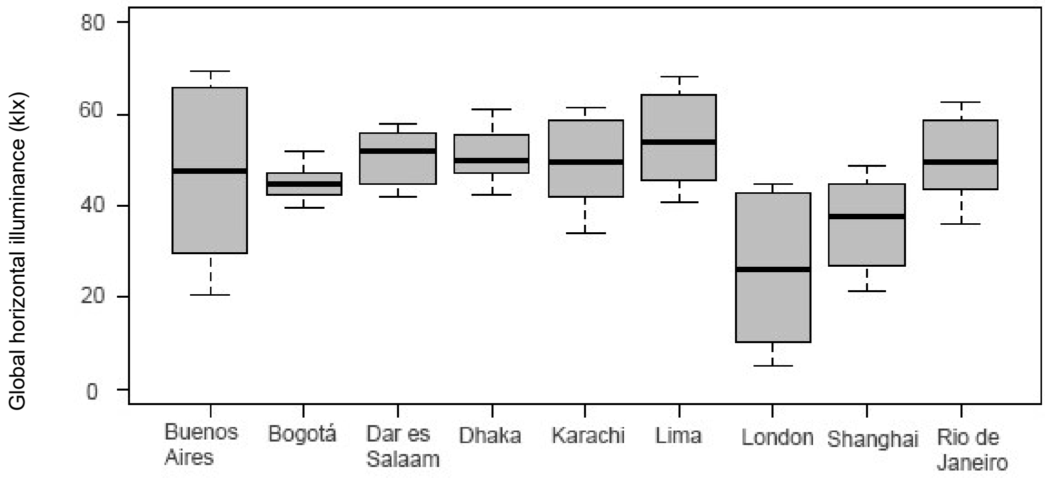
In contrast to these two cities, Bogotá is the closest one to the Equator in the sample. And Bogotá exhibits lower variability, with values very close to ca. 45 klx.

The higher median is found for Lima, while the lower is displayed for London, followed by Shanghai. Karachi, Lima, Rio de Janeiro and Shanghai exhibit certain similarities in data dispersion, represented by boxes of similar vertical sizes, although their medians are considerably different. Dhaka and Dar es Salaam seem to be statistically similar (box size/distribution of quartiles, median, maximum and minimum values); this point could be verified by performing a statistical test.

The medians of this monthly sample concentrate in the range of ca. 35-55 klx, except for London, with median close to 25 klx and values starting from ca. 5 klx.



(a) Graphs from Jan to Dec (X-axis), 0 to 70klx (Y-axis).



(b) Boxplot per city, considering only daily intervals from Jan to Dec, 8h to 18h.

Figure 34: Global horizontal illuminance (klx) by city, monthly data, line graphs(a) and boxplots(b). Source: own author.

The resulting annual illuminance of the cities in daily intervals 8h-18h (Figure 35), indicates the following sequence of the cities ascending from the minimum to the maximum values: London, Shanghai, Bogotá, Buenos Aires, Karachi, Rio de Janeiro, Dhaka, Dar es Salaam and Lima. Most of the cities exhibit annual average of global horizontal illuminance around 50 klx per year. This proximity of the annual value of 50k is especially observed among the cities of

Karachi, Rio de Janeiro, Dhaka, and Dar es Salaam.

Lima exhibits the highest value of the set, close to 55 klx. London and Shanghai display averages considerably lower than the levels shown by other cities of the set. In fact, London register the lowest level (ca. 26 klx per year), followed by Shanghai (ca. 36 klx).

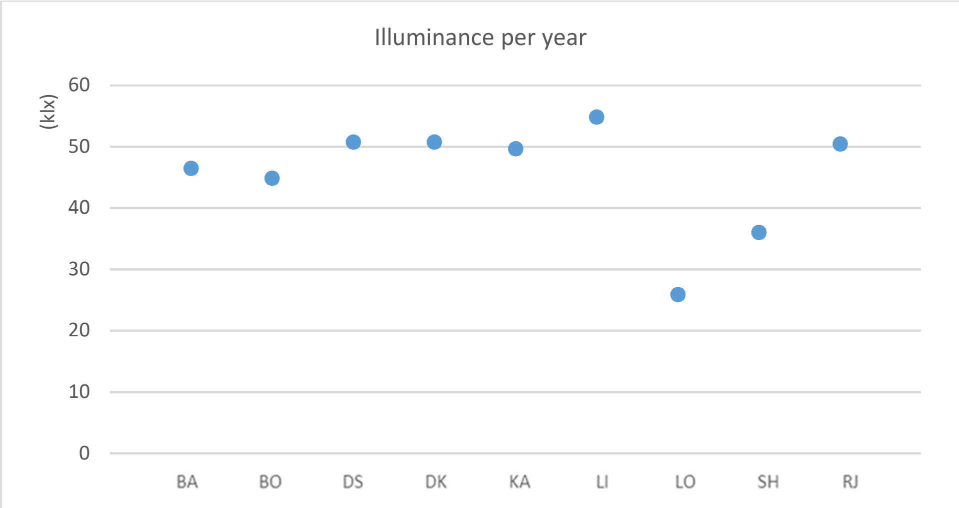


Figure 35: Average global horizontal illuminance (klx) by city, annual data, in daily intervals 8h-18h. Cities: BA (Buenos Aires), BO (Bogotá), DK (Dhaka), DS (Dar es Salaam), KA (Karachi), LI (Lima), LO (London), RJ (Rio de Janeiro), SH (Shanghai). Source: own author.

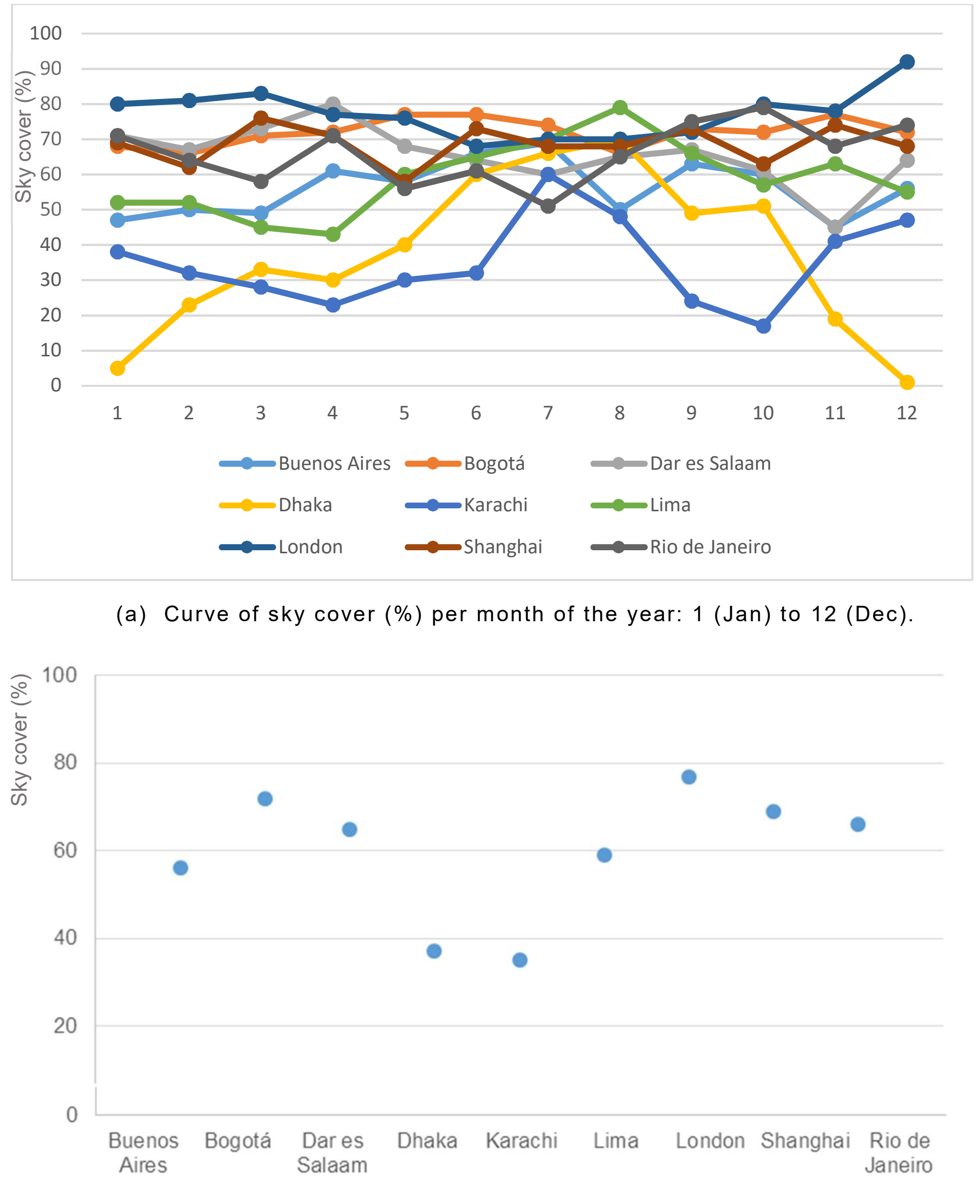
Regarding data pertaining to sky cover, the monthly and annual results were organized in Table 24, from which the Figure 36 was generated.

Table 24:

Sky cover (%) by city, from January (1) to December (12).

Month	Buenos Aires	Bogotá	Dar es Salaam	Dhaka	Karachi	Lima	London	Shanghai	Rio de Janeiro
1	47	68	71	5	38	52	80	69	71
2	50	66	67	23	32	52	81	62	64
3	49	71	73	33	28	45	83	76	58
4	61	72	80	30	23	43	77	71	71
5	58	77	68	40	30	60	76	58	56
6	66	77	64	60	32	65	68	73	61
7	69	74	60	66	60	70	70	68	51
8	50	66	65	70	48	79	70	68	65
9	63	73	67	49	24	66	72	73	75
10	60	72	61	51	17	57	80	63	79
11	45	77	45	19	41	63	78	74	68
12	56	72	64	1	47	55	92	68	74
Annual	**56**	**72**	**65**	**37**	**35**	**59**	**77**	**69**	**66**

Month: 1 (Jan) to 12 (Dec). Source: own author, using features of Climate Consultant v.6.



(a) Curve of sky cover (%) per month of the year: 1 (Jan) to 12 (Dec).

(b) Sky cover (%), annual average.

Figure 36: Sky cover by city, in daily intervals 8h-18h.
Source: own author.

Considering monthly data, sky cover values are generally concentrated between 45% and 85%. Notwithstanding, there is higher diversity within some cities. The annual variations of sky cover are greater within Dhaka, Karachi, Lima, while smaller in London and Bogotá. Actually, the sky of Dhaka and Karachi vary notably, exhibiting months with less sky coverage (tending to clear sky), and others with high coverage (tending to overcast). London reaches percentages above 90% in December - in other words, almost the entire sky vault is frequently covered; interestingly, during this month, this city also has the lowest illuminance level of the entire sample (see previous Figure 33).

However, higher levels of sky cover are not necessarily an indicator of lower illuminance levels, considering the analyzed cities and the adopted database, as it can be observed by contrasting the graphs presented in Figure 35 and Figure 36b. The annual percentages can be organized in the following ascending order: Karachi (35%) is similar to Dhaka (37%); almost 10% higher, Buenos Aires (56%) is followed by Lima (59%); again, increased by ca. 10%, Dar es Salaam (65%) is similar to Rio de Janeiro (66%) and Shanghai (69%); while in Bogotá (72%) and London (77%) the major part of the sky is covered during the year.

Complementarily, the sky type data for each city in the interval 8h - 18h was contrasted to the conservative interval 9h - 17h (Appendix C2). Given the results of this comparison, that showed few differences among the intervals, the predominant sky types between 8h-18h were chosen for the next stages of analysis (Table 25).

Table 25:

Predominant sky type for each city based on frequency of occurrence from 8h-18h, from January to December.

M	Buenos Aires	Bogotá	Dar es Salaam	Dhaka	Karachi	Lima	London	Shanghai	Rio de Janeiro
1	12	1	1	13	13	14	1	1	1
2	14	1	1	15	14	14	1	1	2
3	13	1	1	14	14	14	1	1	1
4	13	1	1	15	14	14	1	1	1
5	13	1	1	15	14	1	1	1	13
6	13	1	14	1	8	15	1	1	11
7	13	1	1	1	1	15	1	1	11
8	13	1	1	1	1	1	1	1	1
9	13	1	1	1	15	1	1	1	1
10	2	1	1	14	14	1	1	1	1
11	12	1	14	13	14	1	1	1	1
12	2	1	1	13	14	14	1	1	1
A*	13	1	1	1	14	14	1	1	1

M: Month; A*: Annual mode. Source: own author, data obtained using APOLUX.

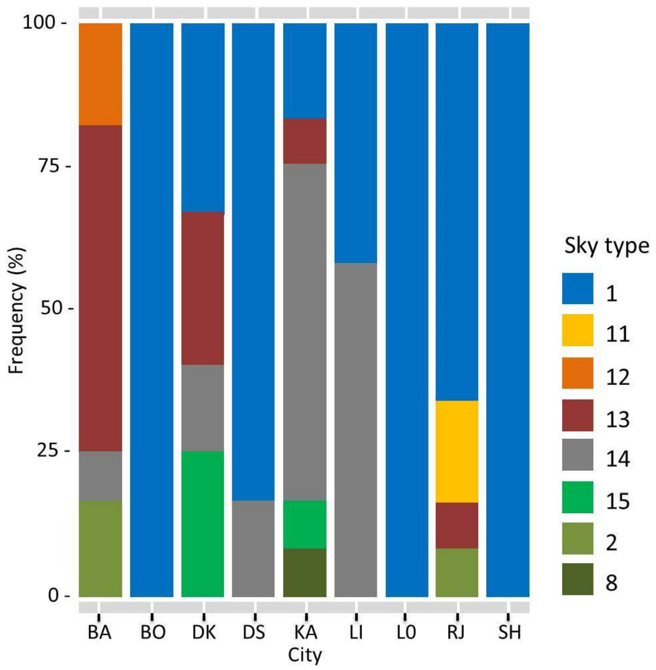
Considering the monthly sky type data, eight sky types were found in the sample (Table 26): types 1, 2, 8, 11, 12, 13, 14 and 15. The type 1-CIE Standard Overcast Sky predominates. Less predominant sky types are types 8 and 2. In London, Shanghai, Bogotá, this type 1 was predominant in the 12 months (100% of the frequency), while in Dar es Salaam it predominates during 10 months (83.3%). By contrast, conditions related to clear sky predominate in Buenos Aires. Dhaka oscillates between the group of clear and overcast conditions, this last one is slightly predominant. The partly cloudy type rarely predominates in a month; Karachi is an exception where the sky type 8 predominated in 1 of the 12 months. In Lima, sky types 1 and 14 predominate in 5 months each, convoluting the decision regarding which of them could represent the annual conditions of the city: considering that the sky type 15 is also present, the sky type 14 was selected.

These overall results reinforce that the variability of data reduced to an annual value might oversimplify the representation of climatic conditions with implications for design.

Table 26:
Monthly sky types found in the cities.

City:	BA		BO		DS		DK		KA		LI		LO		SH		RJ	
Sky Type	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
1	-	0	12	100.0	10	83.3	4	33.3	2	16.7	5	41.7	12	100	12	100	8	66.7
2	2	16.7	-	0	-	0	-	0	-	0	-	0	-	0	-	0	1	8.3
3	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
4	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
5	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
6	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
7	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
8	-	0	-	0	-	0	-	0	1	8.3	-	0	-	0	-	0	-	0
9	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
10	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
11	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	2	16.7
12	2	16.7	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
13	7	58.3	-	0	-	0	3	25.0	1	8.3	-	0	-	0	-	0	1	8.3
14	1	8.3	-	0	2	16.7	2	16.7	7	58.3	5	41.7	-	0	-	0	-	0
15	-	0	-	0	-	0	3	25.0	1	8.3	2	16.7	-	0	-	0	-	0

#	Count of number of months per year in which this sky type prevails.
%	The percentage of the year in which this sky type prevails in the city. Source: own author.



CIE Sky types (summary)	
1	CIE Standard Overcast Sky
2	Overcast, luminance gradation
3	Overcast, moderately graded
4	Overcast, moderately, slight brightening at sun
5	Sky of uniform luminance
6	Partly cloudy sky, no gradation, slight brightening at sun
7	Partly cloudy sky, no gradation, brighter circumsolar
8	Partly cloudy sky, no gradation, solar corona
9	Partly cloudy, obscured sun
10	Partly cloudy, brighter circumsolar
11	White-blue sky, distinct corona
12	CIE Standard Clear Sky
13	CIE Standard Clear Sky, polluted atmosphere
14	Cloudless turbid sky with broad corona
15	White-blue turbid sky with broad solar corona

Figure 37: Sky type, frequency of occurrence by city, during the year, in daily intervals 8h-18h. Note: graph developed with support and script by ABG.
Source: own author.

Appraisal

From this section, a concern arises from cities that, despite the fast growing population, do not present consistent weather files to serve to a more detailed investigation of daylight. This mean that the data in the weather files were incomplete, incoherent or non-available at all in the two databases that were considered as references to this study. And the data availability was a determinant for the selection of the nine megacities. The database EnergyPlus presented the advantage of being free and with interface ready-to-read by other tools, including ClimateConsultant. However, at the moment in which this part of the study was conducted, the database of the Meteonorm was richer, and its technical manual describing characteristics of the data, their obtention and calculi was also transparent. In this context, Meteonorm was adopted.

At a certain point, it was valuable to discuss the results of these weather files with architects or engineers that are familiar with the climate of each selected city, especially those who were raised under those climates, in order to have a perception of the coherence of the retrieved and reorganized data. Therefore, it is recommended that similar studies count with the contribution of locals and/or experts in a certain location to comment initial observations.

Important to notice also that the number of meteorological stations capable of measuring certain parameters of daylight are concentrated in high latitudes, while the number of fast-growing cities is increasing in low latitudes. The implications of the lack of measured data in urban daylight analysis might be an interesting topic for future studies, specially considering the increasing concerns for health.

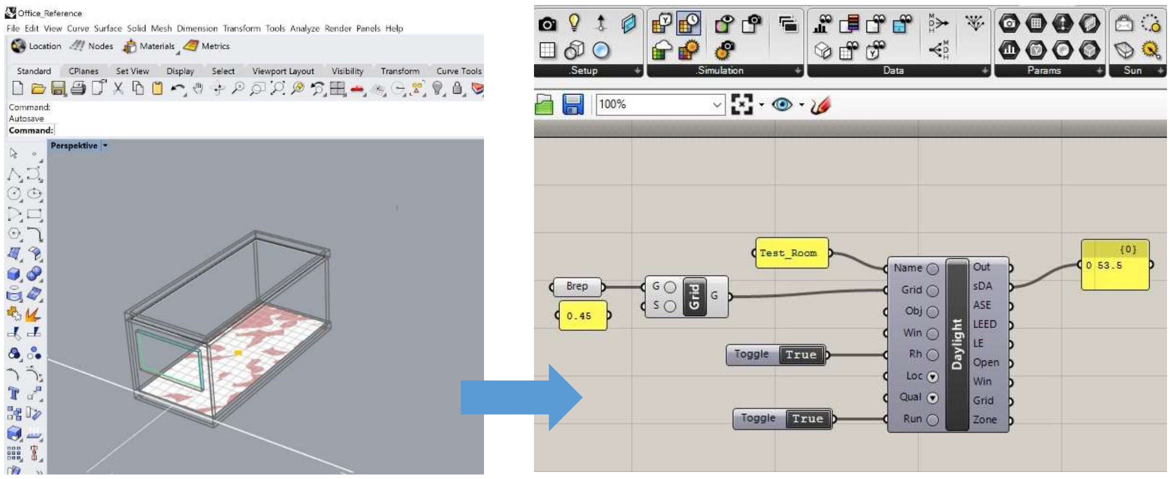
4.3. Daylight: results of the indoor performance data

This section presents the results of the indoor daylight performance simulations separated into three subsections: preliminary, exploratory, and final simulation.

4.3.1. Results of the preliminary simulation

Results of preliminary simulation tests of a room were compared to the results of a reference (Reinhart, 2014). The goal was to reproduce the experiment, achieving results under a small percentage of difference. Variations of up to 10% were pursued, considering the alert of

differences in simulations due to the stochastic model of Radiance, and that for simplification, the mullions and door of the original model were omitted. Relevant to remember, Ng (2001b) found differences of about 20% in indoor daylight results of lower floors in high dense spaces of Hong Kong calculated by two software. And Jones (2017) mentioned differences of 20% as conventionally accepted for simulation studies in daylight in comparison to measured data.
A difference in sDA of ca. 6% was found when the tools Grasshopper and Ladybug/Honeybee were used to run the model. Replacing these tools by DIVA for Rhino/Grasshopper, tests generated a smaller difference in comparison to the reference: up to 3.5%. The model in DIVA is illustrated in Figure 38. Based on these results, the research proceeded to the next phases.



(a) (b)

Figure 38: Result of preliminary simulation of a model combining the software Rhino (a) using DIVA for Grasshopper (b). Source: own author.

4.3.2. Results of the exploratory simulation

The exploratory simulation for a test room with one window, within a simplified continuous canyon, was executed for one of the selected cities to further investigate tools and processes, to observe tendencies of indoor daylight behavior and to test parameters and values. A representative city of the sample was chosen for this step: Rio de Janeiro. This decision was based on the fact that the author of this study is familiar with the climate of this city, and that could facilitate the detection of misleading results during the process. Interestingly, the value of average annual illuminance of this city is close to other three cities of the sample (44.4% of the set), as it can be observed in the previous Figure 35.

The exploratory simulation was divided into two phases, as previously exposed. In phase 1, the experiments from the pilot study published by Santos et al. (2017) for the city of Cuiabá were reproduced for Rio de Janeiro. Then, additional alterations to the model were proposed and simulations conducted to further investigate daylight behavior in this city within Phase 2.

Phase 1

The results of this exploratory simulation are presented in Figure 39 as line graphs. The 'y' axis shows the results of sDA'(%) for each variation, meaning the percentage of floor area of the room which exceeded 300lux during 50% of the occupied hours of the year (8am-18pm). The dashed lines highlight sDA'=55% of the floor area, which is the pursued minimum percentage of sDA'. The 'x' axis shows the heights of the frontal obstruction, representing buildings on the opposite side of the canyon. The results pertain to the baseline (Case C) and its version with a reduced number of bounces (Case A). The lines in the graph are grouped by color: tones of blue represent simulations with 3 bounces, while orange refers to 6 bounces. Each tone represents a street width of 10, 15 or 20m, respectively.

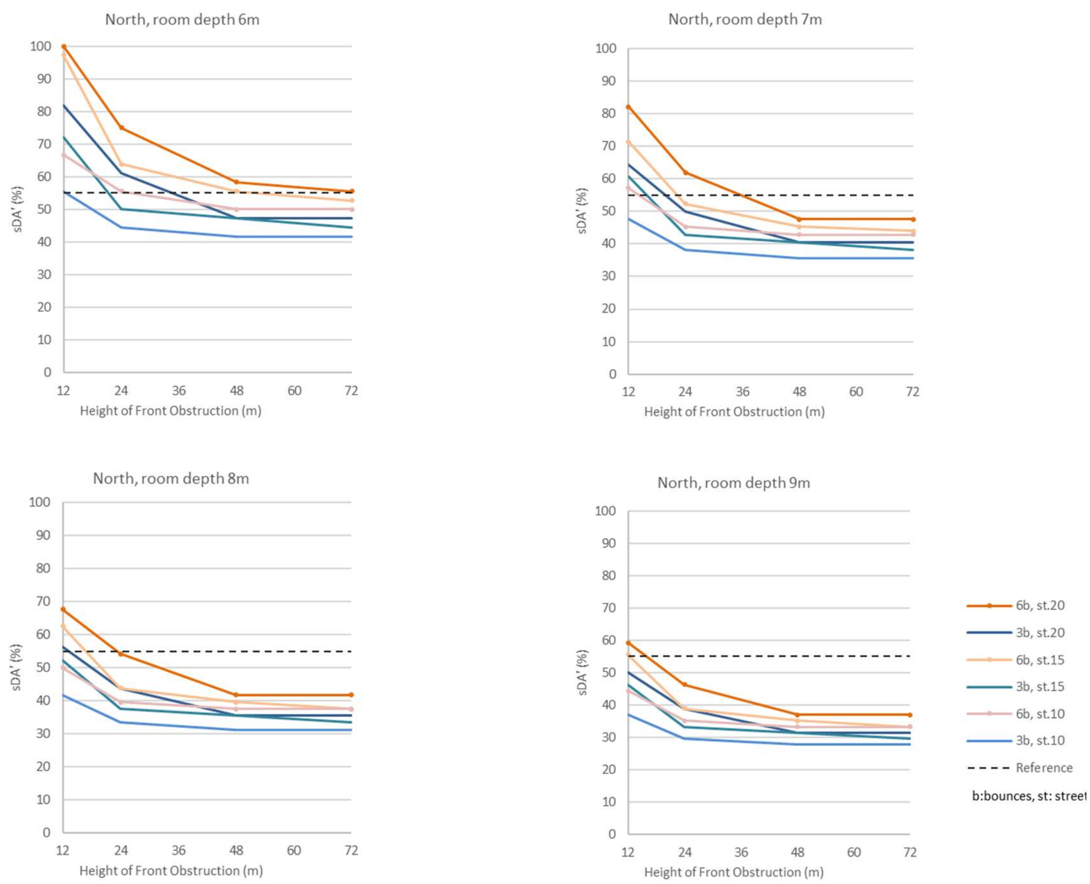
At the South, the minimum sDA' was achieved for small room depths of 6m and 7m, irrespective of the number of bounces (3 or 6). The room of 6m depth exhibited the highest performance level, with results close to 100% in all tested cases. The room of 8m depth satisfied sDA' with 6 bounces in all cases; however, 3 bounces required a street width above 15m. The room of 9m depth achieved or was close to achieve the minimum level in all simulated cases, but only with the setting of 6 bounces; with 3 bounces, none of the cases met the goal. The greater the room depth, the lower the influence of frontal obstruction.

At the North, minimum performance was more difficult to achieve than at the South. Only one condition satisfied sDA' regardless of the obstruction height: 6m depth, street width of 20m, using 6 bounces. For this case, the street width of 15m would require a frontal obstruction height limited to 50m approximately, plus 6 bounces. For a room depth of 9m, only wider streets with low frontal obstructions and 6 bounces surpassed the minimum. By using 3 bounces, the minimum sDA' is achieved in a few cases, some of which are: a) for 6m depth, a street width of 15m and frontal obstruction of up to ca. 20m height; b) for 8m depth, a street width of 20m would allow for an obstruction of up to ca. 13m height, based on interpolation of values.

At the East, the behavior was more similar to the North, especially for deeper rooms. The room of 6m depth outperformed as well, satisfying the minimum sDA' for all cases and bounces. When the room depth increased by 1m, converting to 7m, all cases simulated with 6 bounces were sufficient; however, for 3 bounces, the frontal obstruction height needed to be limited to ca. 14m, 24m and 34m, respectively, for the street of 10m, 15m and 20m width. Deeper rooms of 8m and 9m required limitations in frontal obstruction height even with 6 bounces.

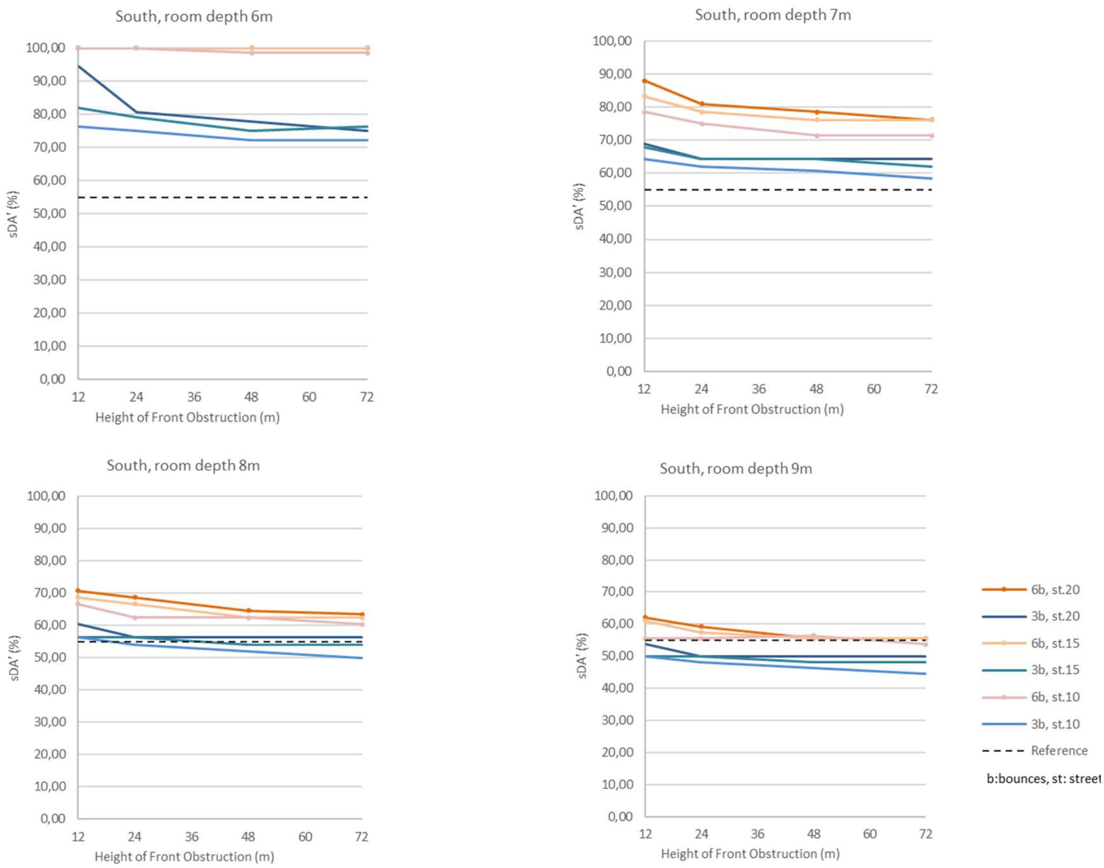
Towards North and East, the variation of results according to H/W was more relevant, while the South exhibited a more balanced response with smaller differences due to street width variations. In some cases, a relatively small increase in the street width resulted in a higher tolerance to the increase in the height of frontal obstruction. For all orientations, variations in sDA' tend to decrease with frontal obstructions rising above the height of 48m. In general, it was observed that, with an increase in room depth, the influence of 3 or 6 bounces on the results decreased.

From the analysis of these results and of those presented in the referential pilot study published by Santos et al. (2017) for the city of Cuiabá, two peculiar sets of results were excluded from the above graphs. The street width of 5m always rendered insufficient results, and the West was almost equal to the East. Like in Cuiabá, the test room in Rio de Janeiro exhibited the best performance towards South in all tested situations. Also, as expected, in all cases the highest result was rendered by the room of 6m depth, combined with 20m street width and 12m height of frontal obstruction, while the 9m room depth with 5m street width and 72m frontal obstruction height generated the lowest result. The room depth of 6m performed better than the other cases, for which a street width of 15m tended to attend minimum levels under higher bounces in the simulated conditions.

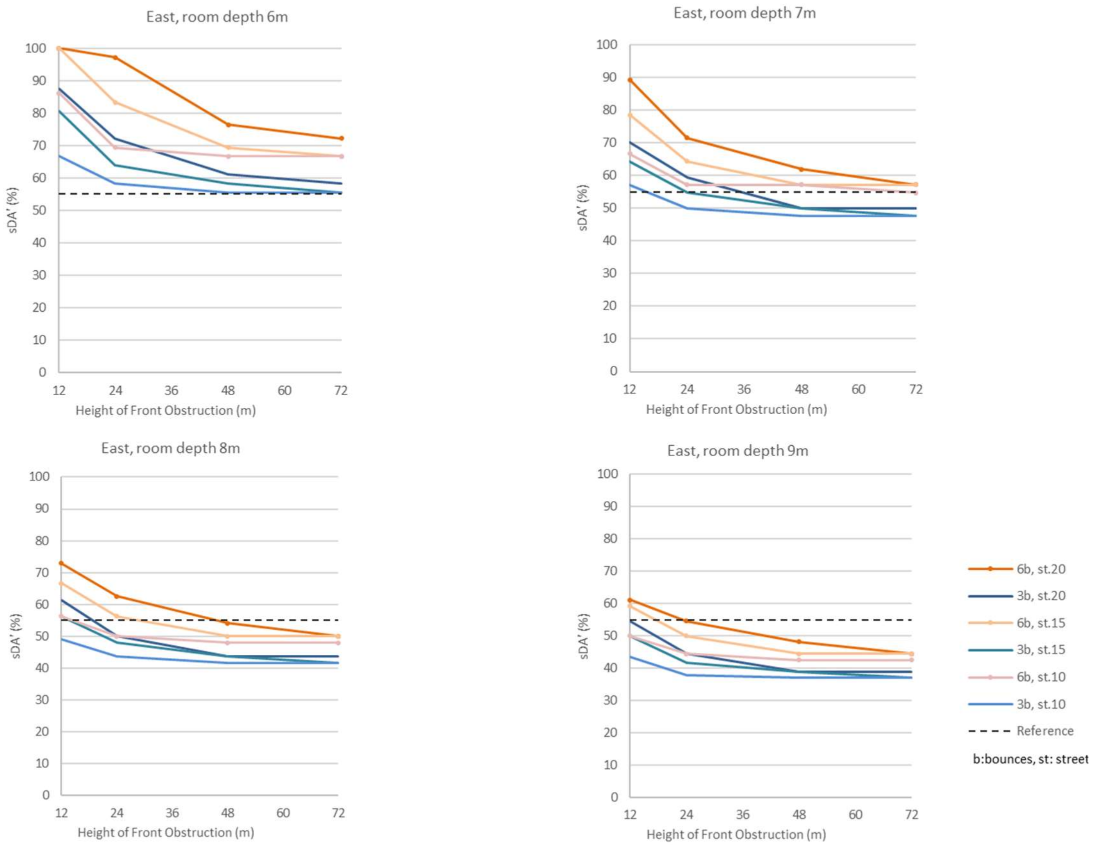


(a)North

Figure 39 (continued on the next page)



(b) South



c) East

Figure 39: Results of experimental simulation of a test room within continuous canyon.
Note: Rio de Janeiro, 3 and 6 bounces, room depths (6, 7, 8, and 9m). Source: own author.

Table 27 presents the descriptive statistical analysis of the sDA' results according to variations in the input parameters in Phase 1. The green color highlights the values that surpass the minimum sDA', while the yellow indicates those values that are above 50% and almost reach the minimum. The values of the quartiles were used to build the boxplots, in which the results can be visualized easier (Figure 40 and Figure 41). In the Baseline Case, with ab=6, the overall results tend to exceed the minimum sDA' in most of the cases. It was far below the goal for streets of 5m width, North façade, and room depth of 9m. The highest average was obtained by the room of 6m depth, followed by the South orientation.

When the number of ambient bounces in the settings of the Baseline was reduced to 3, few conditions achieved compliance considering the average: south orientation, room depth of 6m, street width of 20m, and frontal obstruction of 12m height. The street width of 15m and room depth of 7m almost achieved the goal.

Table 27:

Descriptive analysis of results of Phase 1.

Canyon, Phase 1			Baseline					Baseline, less bounces (ab=3)				
Parameter	Variation	Results	Average	SE	1st. Q	2nd Q	3rd. Q	Average	SE	1st. Q	2nd. Q	3rd. Q
Solar orient. (°)	E	64	57,68	1,95	47,03	55,56	66,67	48,52	1,47	40,48	47,22	55,56
	N	64	47,15	1,92	36,38	43,31	55,56	40	1,42	31,48	38,1	45,37
	S	64	70,4	2,16	56,81	66,67	78,57	58,1	1,53	50	56,25	64,29
	W	64	57,93	1,92	47,62	56,25	66,67	48,76	1,48	40,48	47,42	55,56
Room depht (m)	6	64	75	2,41	56,25	72,22	98,61	60,85	1,78	47,22	58,33	72,22
	7	64	60,62	1,78	47,62	57,14	71,43	50,89	1,32	40,48	50	60,71
	8	64	51,86	1,41	41,67	50	62,5	44,29	1,13	35,42	43,75	52,08
	9	64	45,69	1,2	37,04	44,44	55,56	39,35	1	31,48	38,89	46,3
Street depth (m)	5	64	45,49	1,41	37,04	44,44	53,82	39,38	1,05	33,33	38,89	45,49
	10	64	57,93	2,03	46,58	55,91	66,67	48,2	1,45	40,28	47,62	55,56
	15	64	62,92	2,2	50	58,34	71,13	52,34	1,61	42,73	50	59,52
	20	64	66,84	2,24	54,17	61,97	76,29	55,46	1,79	44,1	53,7	62,88
Height frontal obstruction (m)	12	64	66,72	2,43	53,82	64,59	80,36	55,76	1,92	45,37	55,1	64,29
	24	64	58,76	2,17	45,77	56,25	69,1	48,81	1,57	38,89	47,92	57,29
	48	64	54,31	1,97	42,73	52,09	62,2	45,74	1,43	37,97	43,75	51,04
	72	64	53,38	1,94	42,73	50	58,78	45,07	1,4	37,04	43,75	50
All parameters		256	58,29	(17,82)*	44,44	55,56	67,19	48,85	(13,37)*	38,89	47,62	56,25

*Standard deviation (SD), not the Standard error (SE).

[green] sDA ≥ 55% (goal)

[yellow] sDA ≥ 50% (close to the goal)

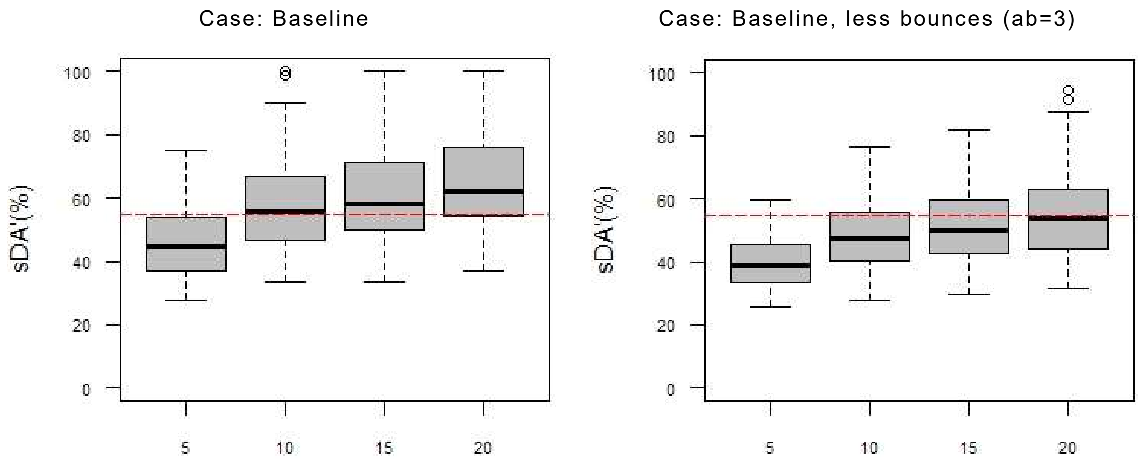
Source: own author.

Considering the average of all results obtained in Phase 1, presented in the row 'All parameters' also in this Table 27, it can be observed that the baseline surpassed the minimum sDA', while its version with less bounces did not achieve it. Comparing both cases, the standard deviation of the baseline was higher than in the version with 3 bounces, indicating that the latter case might be less sensitive to input variations.

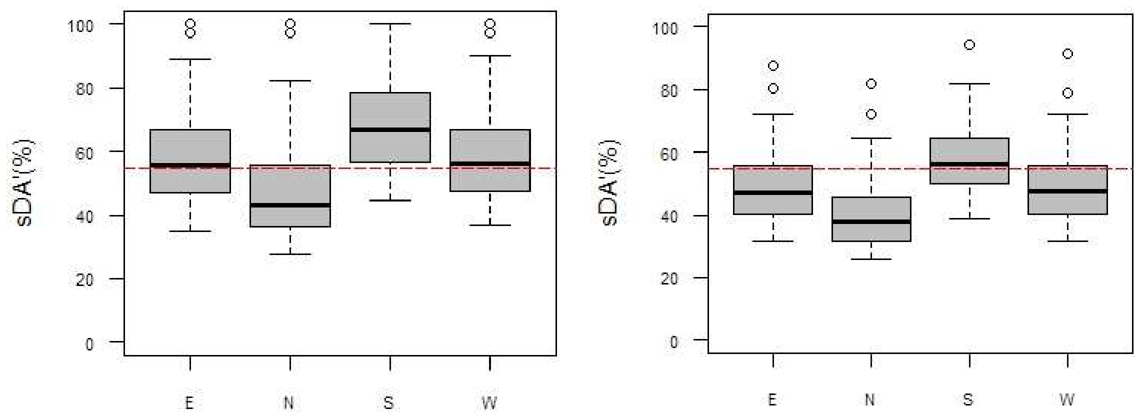
The boxplots show in all cases an ascending pattern in the results for street width: the higher the value of the width, the higher the result of indoor daylight performance. This can be explained, considering that the sky view from the window is amplified, increasing the amount of daylight indoors. However, the increased performance seems not to be linear: there might be a limit in which the increase in the street level is not that beneficial anymore. Further simulations with streets >20m, for instance, 25-30-35m could clarify this point.

Regarding solar orientation, no such pattern was observed. But it can be seen that in both cases the performance between the east and west is alike, with the window towards the south is higher and the north is lower.

The opposite occurs concerning room depth and height of frontal obstruction: their average values form a descending pattern. As anticipated, the higher the value of these parameters, the lower is the indoor daylight performance. The differences between the averages are more prominent for room depth in the baseline as well in its version with fewer bounces.

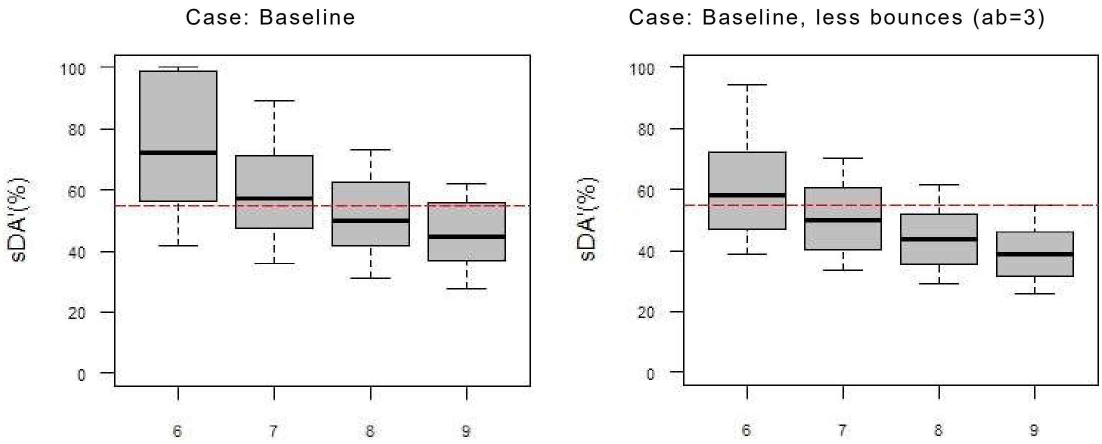


(a) Street width

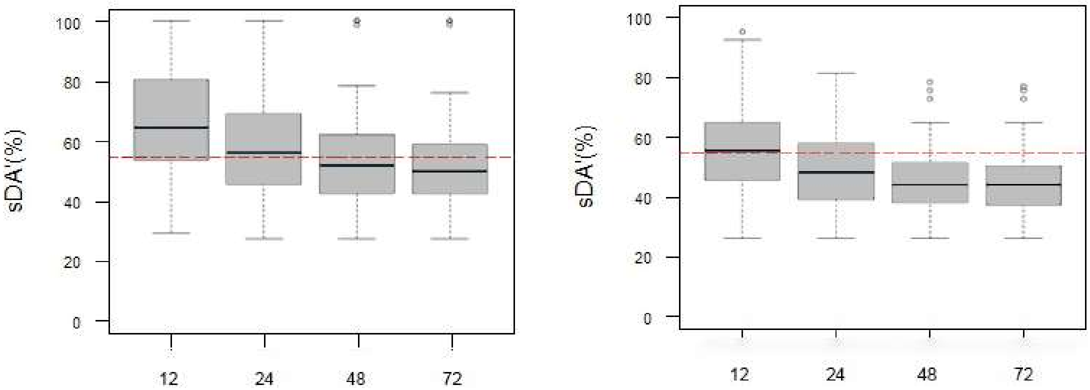


(b) Solar orientation

Figure 40: Descriptive analysis of the results of Phase 1 per case and for each parameter (Part ‘a’). Source: own author.



(c) Room depth



(d) Height of frontal obstruction

Figure 41: Descriptive analysis of results of Phase 1 per case and for each parameter (Part ‘b’). Source: own author.

These overall results remind that the frontal ‘obstruction’ can act like a ‘reflector’ of daylight for indoor spaces. Valid to recall the observation by Ng (2003) for a case study in Hong Kong, that “*for windows of residential units of lower floors of a building block surrounded by high buildings, daylight is achieved primarily through reflected light from the opposite buildings”.* Because of that, the selection of number of bounces and reflectances of surfaces are relevant.

From the cases evaluated in Phase 1, the following conditions were selected to experience variations in Phase 2: room depth of 6m and 9m (minimum and maximum), 6 bounces (insisting on exploring inter-reflections), and street width of 15m (often sufficient with higher bounces, and the same value chosen by Sattrup and Strømann-Andersen, 2013, in similar simulation studies for European cities).

Phase 2

The simulations in this phase occurred for a street width of 15m, room depths of 6m and 9m, and solar orientations of N-S-E, as previously mentioned.

The main results are shown in Figure 42. The WWR of 15% did not provide minimum daylight conditions in the tested cases. The performance towards South were better and with lower internal differences when compared to North and East.

For the room depth of 6m, the WWR of 60% and 90% were above the minimum sDA' in almost all of the tested H/W scenarios; the lower ratio, however, failed to reach the minimum for higher frontal obstructions at the North. The WWR of 30% was sufficient only at the South.

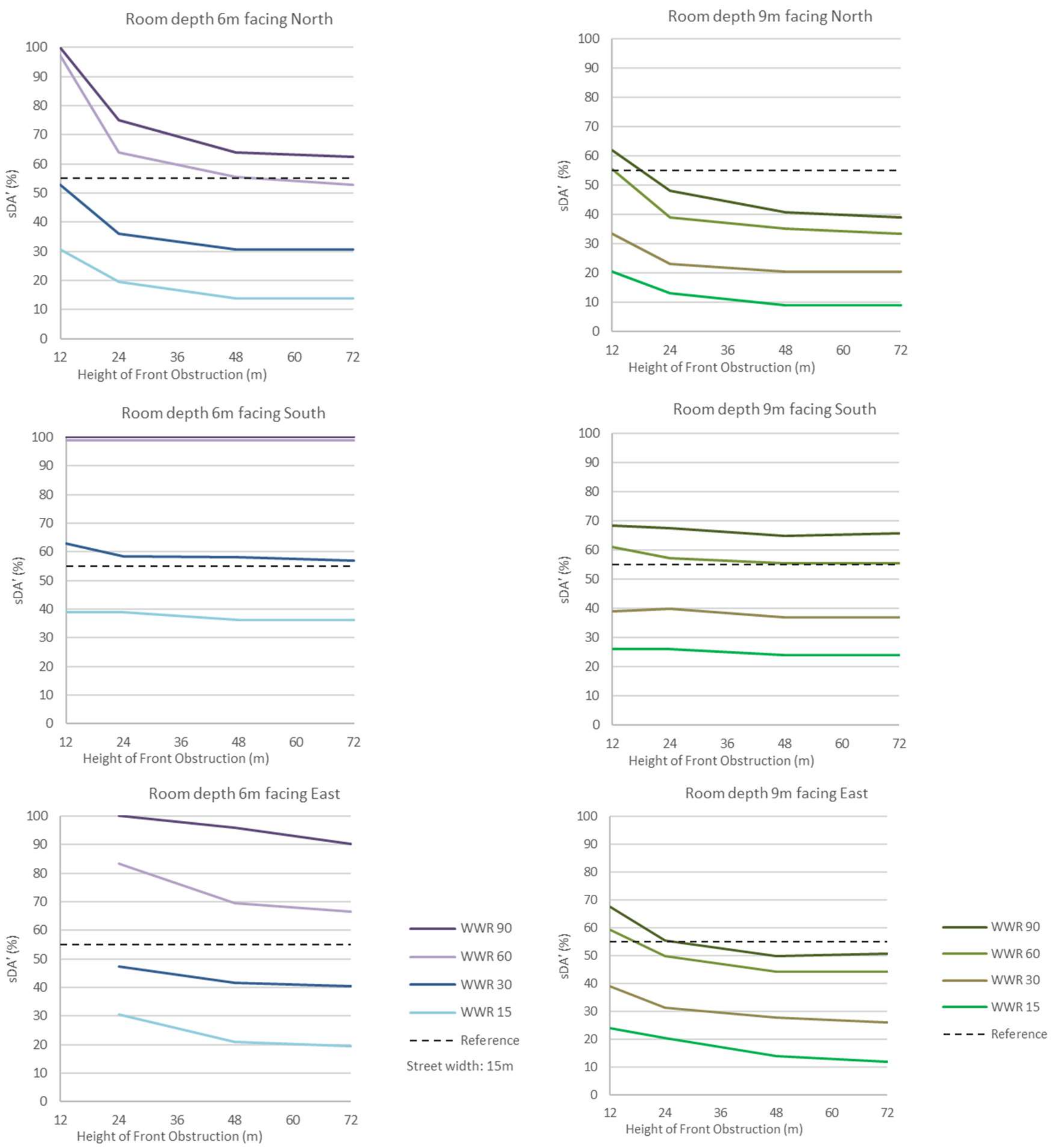
For the room depth of 9m, the WWR of 60% and 90% were above the minimum only in the case of window oriented towards South. At the East and North, bigger windows were not sufficient to provide minimum daylight levels, except for very low frontal obstructions. The WWR of 30% and 15% combined with this 9m depth were insufficient for all tested orientations.

Taking into account the variations in façade reflectances, the differences in results were mostly considerable. This indicates how sensitive the results are to the definition of reflectance quantities. As expected, the reflectance of 60% achieved the higher levels of sDA', followed by 40%, and then 20%. Taking into consideration the variation in reflectances of façade of 20-40-60% with Tvis of 88%, and the reflectance of 40% with Tvis of 30%, the South also outperformed. Reflectances of 40% with this 'dirty' glazing represented by the low Tvis were insufficient in all cases, thus highlighting the importance of the glazing settings. Reflectance of 20% rarely succeeded. In general, the higher the frontal obstruction, the lower the differences in sDA'. Once more, the room depth of 6m exhibited the best results.

For the room depth of 6m, reflectances of both 40% and 60% met the minimum levels in almost all cases when the glazing was clear; the reflectance of 40% failed to achieve the minimum in front of higher obstructions at the North. Façade reflectance of 20% achieved acceptable level of sDA' for South; the same would happen for East only if frontal obstructions were low, under ca. 24m height. Reflectances of 60% for East and South achieved sDA' of 100%, the maximum percentage, in face of almost all obstruction heights. This maximum sDA' was achieved by the reflectance of 40% only at the South.

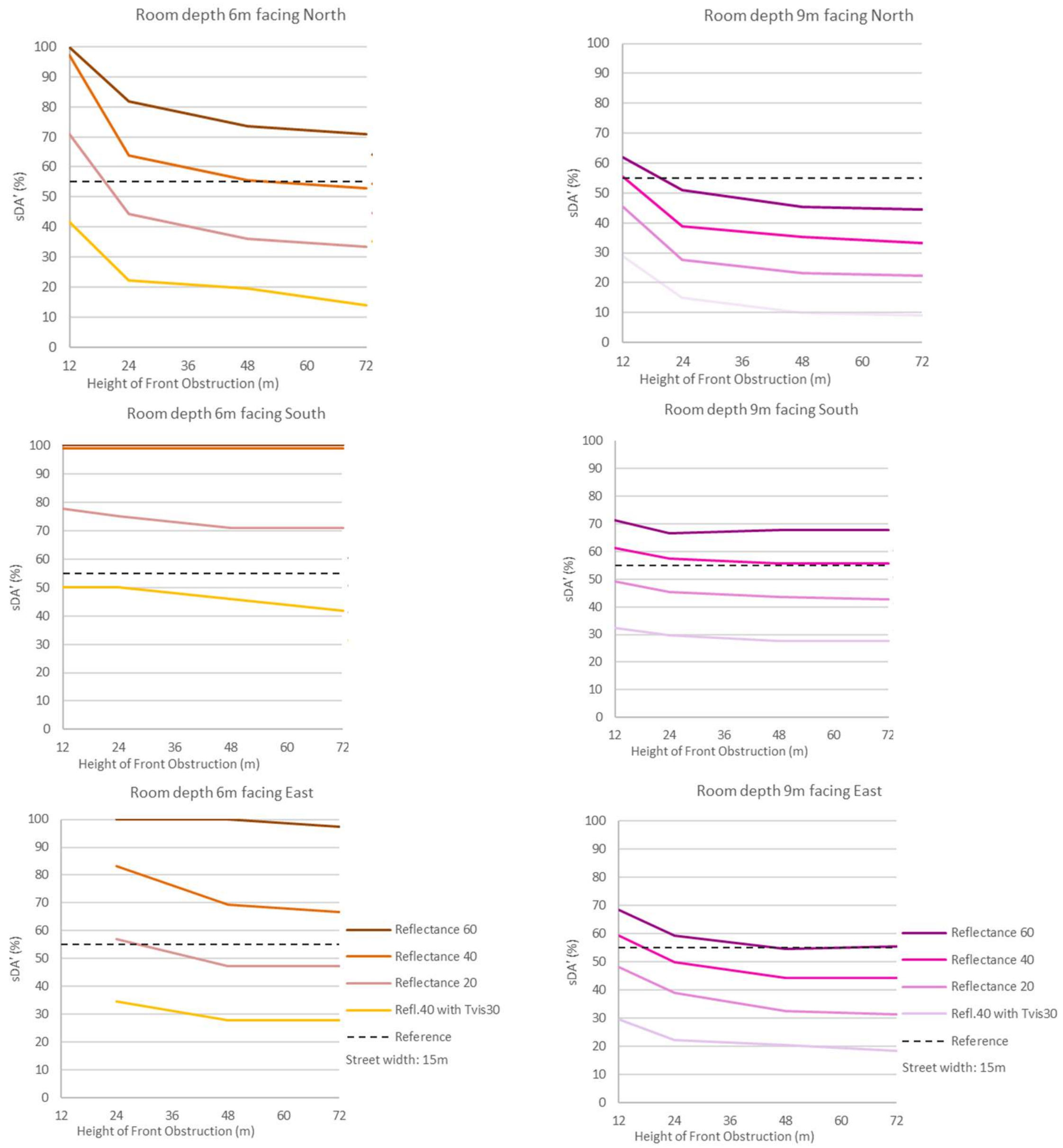
For the room depth of 9m, the sDA' maximum of 100% was never achieved. At the South and East, the reflectance of 60% exceeded the minimum in face of obstruction variations. At the North and East, the reflectance of 40% achieved the sDA' minimum only when combined with the lower frontal obstructions; the same was observed for reflectance of 60% at the North. At the South, the reflectance of 40% was slightly above the minimum despite the variations in frontal obstructions. The reflectance of 20% and the reflectance of 40% with low Tvis did not meet the minimum sDA’ level in the tested cases.

The eight results pertaining to the frontal obstruction of 12m height at the East were not computed due to an unexpected interruption in the simulation. The simulation of these four cases separately could generate results with slight differences within the set due to the stochastic configurations of the software, as previously explained. Therefore, assuming that the missing results would be equal to or higher than the ones for the obstruction of 24m height, which would not substantially interfere in the selection of values for the next simulation, these missing data were not replaced.



(a) Variations in window-to-wall ratio (WWR, %).

Figure 42 (continued on the next page)



(b) Variations in façade reflection (%).
Figure 42: Results of experimental simulation of a test room within continuous canyon.
Note: city of Rio de Janeiro. Comparison of different WWR and façade reflectances for the baseline case, considering room depths of 6m or 9m.Source: own author.

Appraisal

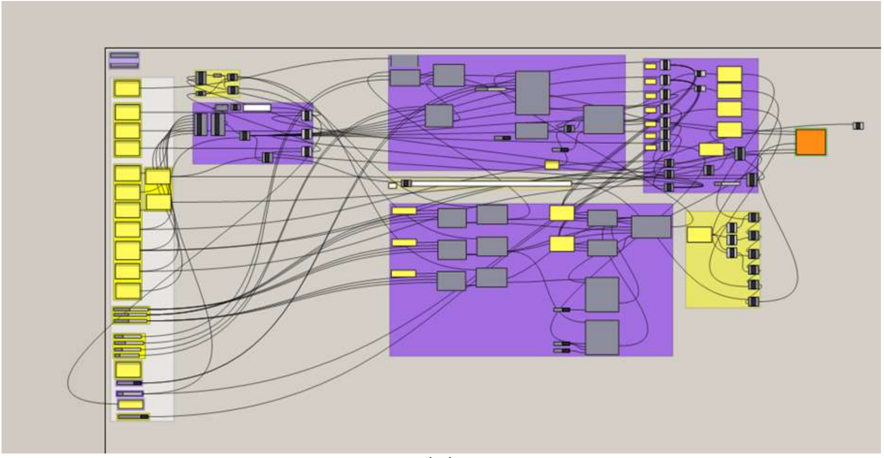
From the results of simulated indoor daylight performance of a canyon, for only one city, conducted in Phases 1 and 2, parameters and values that satisfied minimum daylight sufficiency levels were considered as an indicative value to be included in the final model: a more complex urban geometry, altered in diverse parameters, considering multiple cities.

Some of those results corroborated the data appearing in literature review. For instance, as previously mentioned, rules of thumb recommend the depth of a sidelit space of 1 to 2.5 times the window head height. Here, the depth closer to this recommendation (6m) was found potentially satisfactory for daylight, considering the metric and simulated conditions. This depth is going to be further simulated in the next stage, as well as the street width of 15m, and façade reflectance of 40%. The decision to choose this reflectance is mostly based on studies such as Givoni (2006) and Dornelles and Roriz (2008), whose conclusions indicate that higher reflectances are difficult to achieve in urban centers, especially due to accumulation of dust and dirt, and study by Ng (2001b) relative to errors in simulations. The higher performance of south orientation for Rio de Janeiro was similar to the results found in Santos et al. (2017) for Cuiabá. The ab=6 proved to be influential in the performance results when compared to ab=3, as discussed in Mardaljevic (1999), but also time consuming; therefore, it was chosen to use an intermediate value in the final simulation: ab=4, like Saratsis (2015).

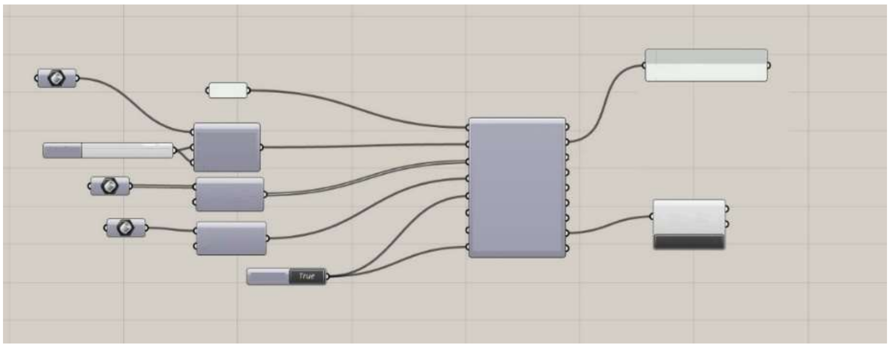
This overall process of conducting exploratory simulations with inputs based on critical literature and analysis of current building technology aimed pragmatism. Thus, acquired data from simulations might more useful than those arising from faster processes in which inputs are selected statistically, disregarding their feasibility or relevance in construction applications.

The exploratory simulations were conducted using the open source interface for Radiance/DAYSIM built in Grasshopper, the plugins LB/HB, due to their parametrical features. However, the level of flexibility offered by the combinations of components, the requirements for programming skills, the frequent updates with sometimes unclear adjustments made by developers, and the type of visualization render the system more complex and difficult to use, requiring extended time for checking the correctness of multiple inputs. Because of that, the simulations of the planning phase had been completed, it was decided to continue the process in the final step using interfaces that make parametric simulations straightforward, simpler and faster: DIVA-for-Rhino combined with DIVA-for-Grasshopper, developed by Solemma. As mentioned, DIVA-for-Grasshopper became available during the course of this research, incorporating the advantage of allowing parametrization. DIVA uses the Radiance-based program DAYSIM for daylight simulations; all daylight simulations found in "*Daylight Handbook I*" (Reinhart, 2014) were conducted in DIVA-for-Rhino v2.1.

Figure 43 compares a segment of the visual programing done in the environment of (a) Grasshopper using Ladybug/Honeybee and other elements of Python language, which was used for the Exploratory simulation in this research, and of (b) DIVA-for-Rhino, used in the final urban simulation to be presented in the next sections. This figure aims to illustrate the difference of complexity for setting the models and obtaining the performance results using the resources available in these different tools. This decision privileged the fast processing of the next step, but reduced the possibility of comparison between the canyon simulated in this stage and the grid of the final simulation. In any case, comparisons between the results of simulations also need to consider variations in the stochastic process within the software, the correspondence between input and output configurations, complexity of geometry, resolution of settings, research goals, etc.



(a)



(b)

Figure 43: Difference of complexity of setting the model for simulation.
(a) Grasshopper with Ladybug/ Honeybee. (b) Grasshopper with DIVA. Source: own author.

4.3.3. Results of the final simulation

The final simulation of indoor daylight performance comprises eight cases of urban and/or architectural variations (Figure 44). As previously explained in the Methodology, Case A is the baseline case: a grid of buildings with homogeneous with 35m height each, separated by distances of 15m to each other, with outdoor reflectance of 40%. The measurements were taken in the ground floor of three central buildings: test rooms of 6m depth for favor daylight indoors, open floor plans, one window that occupies 100% of the main façade, oriented towards North or South. From baseline (Case A), variations were tested in terms of vertical and horizontal densification (Cases B, E, G and H), as well as of WWR (Cases C, D, and F). Case B represents an urban configuration of heterogeneous height. Cases C and D are copies of baseline, but with reduced windows (60% and 30%, respectively). Case E is baseline with higher building heights (70m), from wich case F has windows reduced to 60%. Case G is the case of tallest buildings (100m), and G is the unique case of urban canyon.

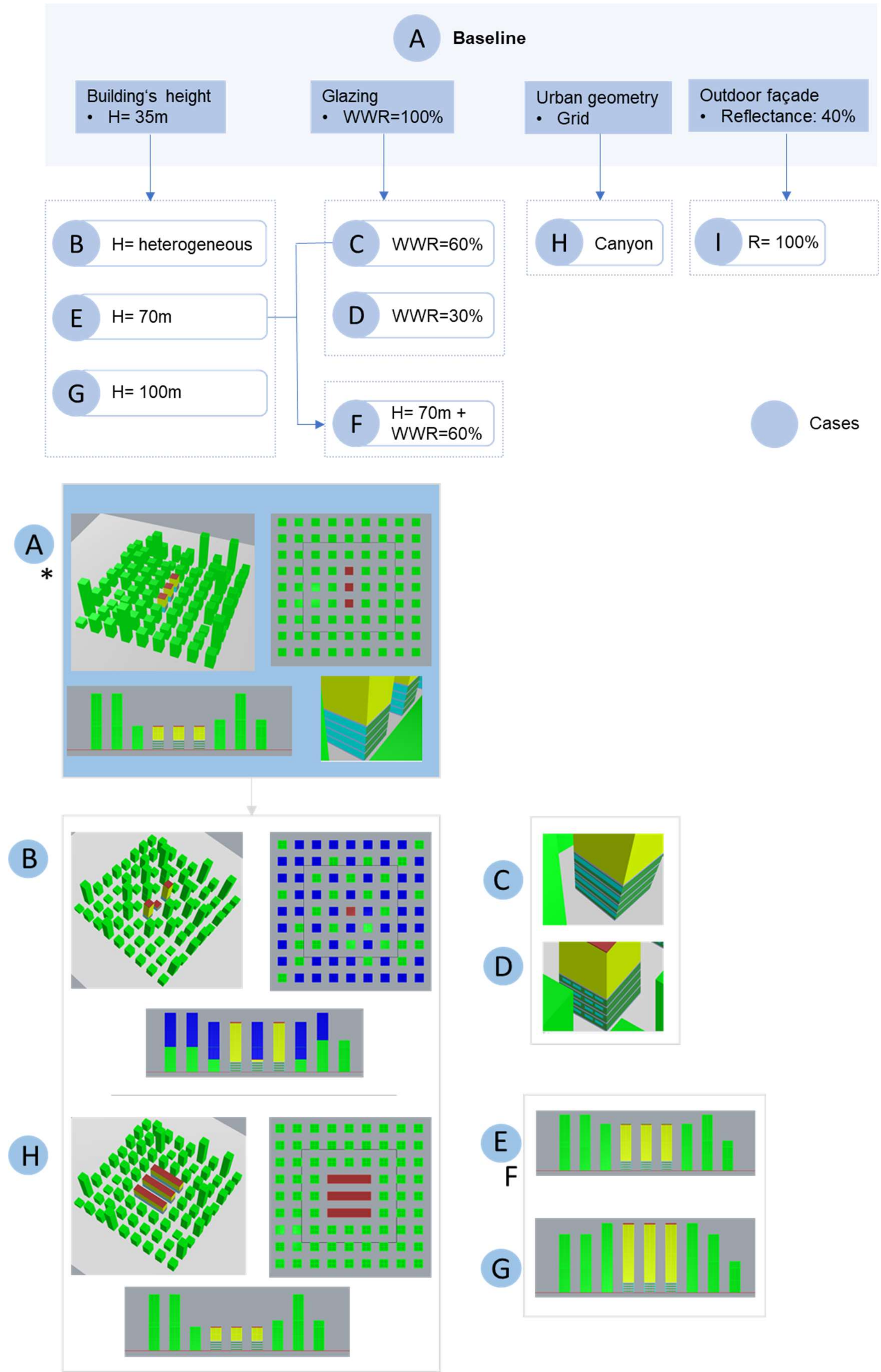


Figure 44: Simulated urban cases: baseline (Case A) and its variations.
Source: own author.

The FAR and building coverage of the 5 x 5 matrix is varied for testing effects of the urban densification (see previous Table 20). The results of the final simulations of the urban grid named ‘baseline’ and their variations for each city were taken from the three central buildings of the urban matrix, as previously mentioned. Tables containing results that are presented in this section are presented in Appendix F.

Daylight performance: annual results

Annual results of sDA’ are represented by dots in Figure 45, which were then summarized in Table 28. The horizontal axis presents each one of the nine tested cities. The vertical axis shows the average sDA’ of open floor plans on the ground floor of three central buildings in the matrix (ab=4), colored according to each variation. The dashed horizontal line is set to sDA’=55%, adopted here as the minimum daylight sufficiency level.

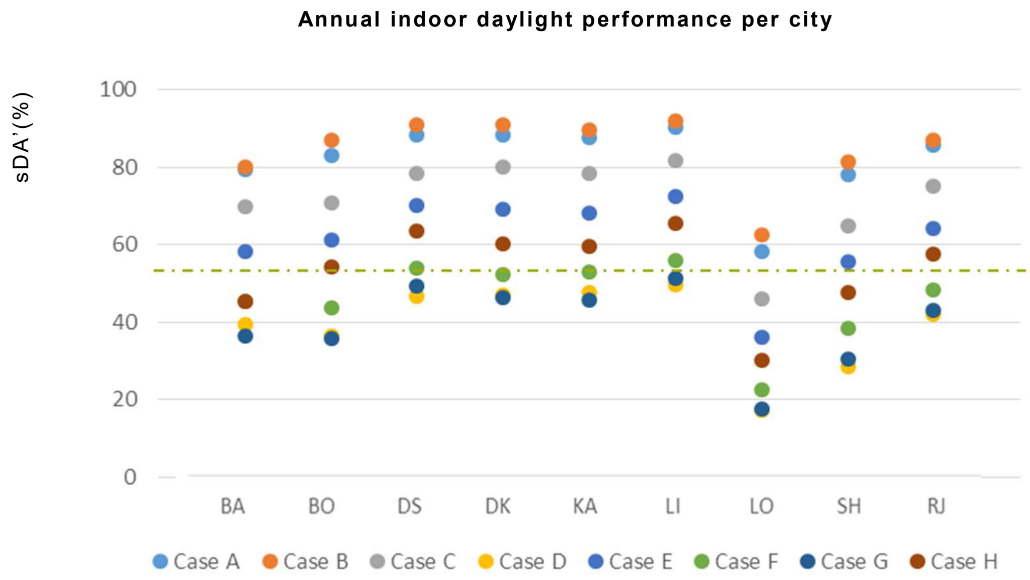


Figure 45: Results of simulation of annual indoor daylight performance, sDA’ (%). Note: measured in ground floors of central buildings within a theoretical urban block, per simulated case, by city. Source: own author.

These results indicated that the selection of values and parameters based on the previous exploratory simulation and literature review achieved its goal: there is substantial variation of sDA’, necessary for a visual and numerical comparison, and most of the proposed design strategies resulted in daylight levels surpassing the pursued minimum in the urban context.

In most cases, the tested variations resulted in satisfactory indoor daylight levels. The simulation of façade reflectance set as a mirror generated sDA’= 100% in all cities; in other words, it did not result into differences among cities. Because of that, it was not presented in the above graph. In simulating the same model baseline with reflectance of 40% (Case A), all cities also outperformed (Figure 45); however, there is a difference: all cities could be grouped under the "*preferred performance*" (sDA≥75%) classification as per the IES LM 83-12, except for London, whose result is only "*nominally acceptable*" (55% ≤ sDA < 75%).

Table 28:

Summary of results extracted from Figure 45.

Case	Description	*Result: sDA'≥55%
A (Baseline)	Baseline (Grid, H=35m, WWR=100%, solar orientation N/S, ab=4)	Yes, for all cities.
B	Baseline+ vertical density as heterogeneous height	Yes, for all cities.
C	Baseline smaller windows (WWR=60%)	Yes, except for London.
D	Baseline smallest windows (WWR=30%)	No, it underperformed for all cities.
E	Baseline taller (H=70m, WWR=100%)	Yes, except for London.
F	Baseline higher small windows (H=70, WWR=60%)	Varied. Underperformed in several cities**
G	Baseline tallest (H=100m, WWR=100%)	No. Underperformed in all cities**
H	Baseline+ horizontal density as canyon	Varied. Underperformed in 3 cities***

*Annual average, simulated and measured in the ground floor of 3 central buildings.
Note: ** Results close to the threshold in Dar es Salaam, Dhaka, Karachi, and Lima. ***London, Buenos Aires and Shanghai. Source: own author.

In the descending order of performance, the results were as follow: heterogeneous height, baseline, baseline with WWR=60%, homogeneous height of 70m, densification as canyon, height of 70m and WWR=60%, and, finally, overlapping/alternating positions pertaining to the height of 100m and the baseline with WWR=30%, respectively.

In other words, based on the simulated conditions, densification with heterogeneous height tends to show better results in terms of indoor daylight performance than the lower built area with homogeneous height. This result reaffirms what was found in literature for static metrics, i.e. Cheng et al. (2006b), Scalco and Pereira (2016), and for dynamic metrics like in Sattrup and Strømann-Andersen (2013). It should be noted that the results obtained in this research are a function of the choices of urban layout and densification level; other vertical heterogeneous layouts could produce different results. Additionally, because the results are obtained as the annual average of ground floors in central buildings, some information is lost. More specifically, the case of heterogeneous height tends to generate different results of daylight performance per floor; lower values can be hidden by the resulting average of the block. Although due to the output format of the software it is possible to assess whether a particular floor underperformed during a certain interval of the year, or maybe during a specific season, or towards a defined solar orientation, this was not presented here since these specificities are not scope of this work. However, they are relevant for ensuring daylight sufficiency, quality of life indoors, for all the targeted floors in an urban distribution. This simplification of obtaining the average of a group of buildings might be interesting for cases in which achieving overall sufficient performance of an area is the goal of designers, in deprivation of underperformance in particular cases.

As a general result, the sDA' performance of baseline declines by ca. 10% when the WWR is decreased from 100% to 60%. The gap is notable for WWR=30% (Case D), with a difference of ca. 40% in sDA' performance relative to the baseline, resulting in insufficient levels. This is important to note from the urbanistic perspective. On one hand, among the tested cases, minimum required performance is achieved in all cities, given certain geometry and height of buildings, only if the architectural design facilitates performance. This includes façades of generous openings (WWR=100% are preferred), adopting narrow depths of rooms, clear glazing, and certain conditions of reflective ceilings and walls. On the other hand, the consulted guidelines of diverse countries referred to WWR up to 40% or 60%; or limited the WFR up to 10%, 12.5% and 16.7%; or required a minimum sill height that might restrict the size of the translucent window. These results serve as evidence that guidelines for window dimensions, if established disregarding urban context, might create poor indoor daylight conditions.

Considering the threshold of sDA'≥55%, some design strategies worked for all cities, e.g. baseline and densification through heterogeneous height. Others did not work for any city, such as the case of baseline with 'small' windows and the 'very tall' buildings of homogeneous 100m height. Other strategies proved successful in some cities, but not in others. In fact, the taller buildings and smaller windows of Case F satisfied only Lima, maybe due to the higher illuminance level of this city, albeit for a small margin of error (sDA'=55,79%). One might conclude that this design option is not recommendable for cities in the sample; however, in the Case F, other three cities were close to be satisfied with levels between 50% and 55% (DS, DK, KA), reminding of the importance of the threshold for any classification, comparison and grouping of cities. Case H (canyon) is also interesting: 55.6% of the cities in the sample outperformed under this geometry; this calculus included Bogotá, despite its slightly inferior percentage (sDA'=54.23%). This could indicate that this urban typology is more recommendable for some sites than for others from the daylight perspective. Especially because the canyon underperformed mostly in the cities located far from the Equator (Buenos Aires, Shanghai and London), it is assumed that densification through the canyon typology should be carefully recommended for higher latitudes minding daylight conditions, when considered this annual metric. London demonstrated very different results from other cities: only two cases outperformed, Case A (baseline) and Case B (heterogeneous height), although those results were close to the threshold of sDA'=55%. In other words, under the conditions tested in this research, increasing density or reducing the WWR of the baseline model of urban grid was problematic for daylight sufficiency in London.

It is important to note that the finishing of high reflectance for the façades (100%) would contribute to substantially improving the performance, including in London. This result does not consider aspects such as the risk of disturbance in urban visual comfort, depreciation of reflectance due to pollution, or the potential transmission (trap) of beams through openings of higher floor levels.

The results for London call attention to cities of higher latitudes, reinforcing the proposals such as the ones by Bauer and Wittkopf (2015) and by Dogan and Park (2018), referring to breaking of the annual performance assessment respectively into months and seasons, eventually with the review of thresholds by city. Such flexible systems might offer better conditions to represent performance in those cities, especially because their daylight conditions vary notably through the year, as discussed previously.

Overall, the urban canyon exhibited lower daylight performance than the grid typology; this result was found previously in the researches such as in Sattrup and Strømann-Andersen (2013). The result of sDA' for the canyon in the selected cities seems to reinforce the importance of the sky openness and latitude for daylight sufficiency indoors according this metric, despite their sky condition.

With regard to heterogeneous heights, it is important to note that this geometry is neither common nor incentivized by urban zoning systems, maybe because it might interfere with aspects such as the dynamics of real state and the local mobility system flow. The mentioned "*cap and trade*" concept is one rare exception. The vertical heterogeneity was already indicated in other studies as interesting for promoting daylight, like in Cheng et al. (2006b), and here it exhibited satisfactory performance. Thus, this is an urban option to be further explored and presented to designers as an alternative to current predominant models.

The performance of the canyon simulated here could also benefit from horizontal heterogeneity of the grid (Figure 46), since the portion of the sky seen from the measured points would increase. Indeed, horizontal heterogeneity in the grid could improve daylight in various situations. And since higher reflectance of frontal buildings can substantially improve the performance indoors, as demonstrated here, the gain in performance due to a higher visibility of the sky can be compromised by a decrease in the contribution from outdoor reflectance due to the absence of frontal walls in such rearrangement of the buildings. Investigation into this duality of sky visibility and frontal reflectance considering dynamic metrics in the urban context might be an interesting topic for research. Additionally, the quantitative benefit can vary depending upon the urban daylight climate of the city.

(a) (b)

Figure 46: Sketch of urban design with examples of horizontal distribution of buildings. Note: (a) homogeneous grid, and (b) heterogeneous one. No scale. Source: own author.

At this point, it is interesting to observe that three cities have the predominant annual sky type overcast: Bogotá, London and Shanghai (see previous Figure 36). This similarity of sky type did not correspond to a higher similarity of performance among these cities within the sample: although London and Shanghai presented the worst performance, Bogotá outperformed Buenos Aires in several cases. Buenos Aires has mixed sky types along the year, and together with London and Shanghai, have a higher latitude in the sample. These results are indicative that, alone, the parameter sky type might not be representative to indicate sufficiency conditions among cities: a city with overcast sky not necessarily has better performance than other with a clear sky, and vice-versa.

Dhaka and Karachi present similar annual sky cover percentages (37% and 35%, respectively, representing a difference of 2%; for details, see previous Table 24).They also presented similar results of performance as per sDA' in each simulated case. In one hand, their performance similarity is higher than the one between Dar es Salaam and Rio de Janeiro, which have sky cover of 65% and 66%, respectively, which corresponds to a difference of only 1%. In other hand, Buenos Aires and Shanghai, with sky cover of 56% and 69% (difference of 13%), did not present a noteworthy difference of performance between them. This result also indicate that sky cover alone is probably not a good indicator of differences in performance among cities.

However, when the parameter illuminance is considered, a certain association between the levels of illuminance of cities and their resulting performance can be observed. There is a pattern for annual data that become more evident when the profile of two previous graphics is overlapped: the graphic of illuminance per year and the one of performance (Figure 47). This image combines the graphs of Figure 35 and Figure 45, with one alteration: the dots of values for each city are connected only as a strategy to visualize the correspondence of pattern between annual illuminance and annual performance (there is no physical meaning). The same connection of dots was done to the graphic of sky cover from Figure 36b, and no similarity of pattern was found, indicating that its relation to performance is weaker than illuminance. The same graphical comparison was not possible to be made with the parameter sky type, once it is a categorical parameter.

One observation: Bogotá has annual illuminance level slightly lower than Buenos Aires. However, each case simulated for Bogotá presented better daylight performance than its correspondent simulated for Buenos Aires, except in Cases D and G. In other words, illuminance alone seems to be a good indicator of performance, rather than the other two daylight climate parameters, but not always. At this point, it was considered that the combination of two or of all three parameters (illuminance, sky cover and sky type) might be a better indicator of performance than each of the parameters observed separately.

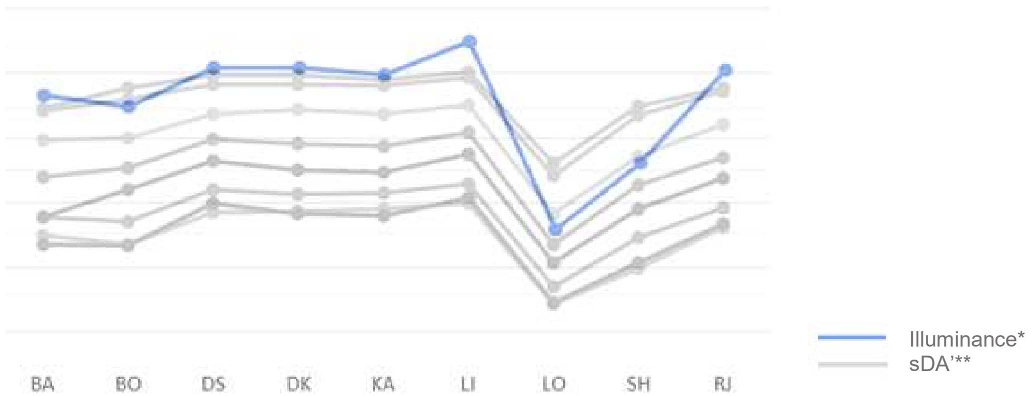


Figure 47: Overlapped graphs of illuminance and indoor daylight performance, all cities. Note:*Annual global horizontal illuminance (lx); **indoor daylight performance as per sDA'(%). Dots connected by lines for better visualization and comparison of the profiles.No scale.Source: own author.

Another comment regarding the performance of typologies is easier to observe in Figure 48. A curious response is observed in the two cases of worst performance: cases D and G. Case D is baseline with buildings of 35m height with WWR=30%, and G is the tallest baseline with heights of 100m. The performances of D and G almost overlap in some cities (i.e., Bogotá and London). Case D is better than G in Buenos Aires and Karachi, while D is worse than G in Dar es Salaam and Lima. This result highlights the concept that one typology is not necessarily always better for daylight performance than the other for all cities: other factors should also be considered. Here, the resulting difference between D and G is probably due to the fact that, beside daylight climate parameter, factors such as latitude might play an important role in performance.

An additional curiosity about typologies is demonstrated by cases D and F (which has height of 70m and WWR=60%). All typologies performed better in Bogotá than in Buenos Aires, except in these two cases. This can be observed in the negative slope of the two lines of comparison between these cities. Similar phenomenon occurs between Dar es Salaam and Dhaka: cases C/D generate the only two positive slopes (yellow and gray lines) between these two cities.

For a more comprehensive understanding of differences between cases, they should all be further investigated in detailed simulation under different, varied conditions. This is especially valid for cases like the mentioned D and G, or D and F, in which the pattern gets altered for no clear reason.

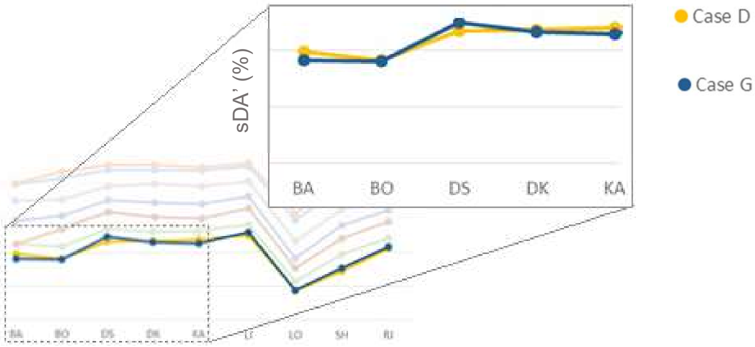
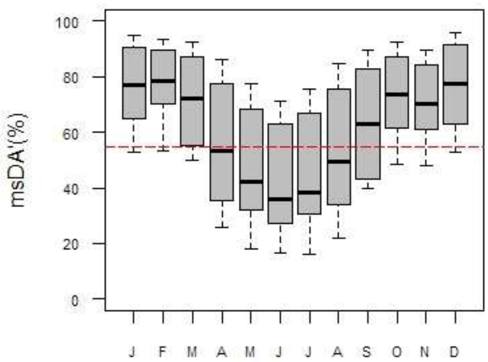


Figure 48: Detail in result of performances of Figure 47a. Comparision of annual sDA' of Cases D and G. Note: dots connected here by lines for better visualization and comparison of the profiles; no scale. Source: own author.

Daylight performance: monthly results

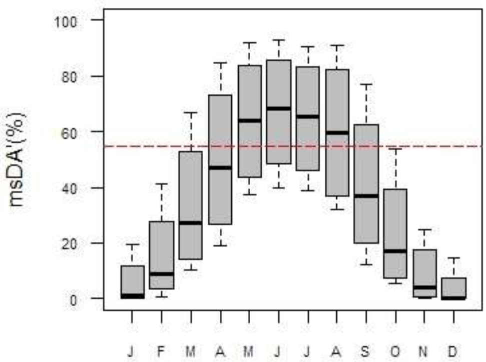
Monthly indoor daylight performance within a year was analyzed by case and by city. Relevant comparative aspects are presented in this section.

The analysis by city, considering all simulated cases, resulted in the monthly performance shown in Figure 49. Interestingly, the ascending profile of the curves is exhibited in four cities: London, Shanghai, Dhaka and Karachi. These cities are located in the northern hemisphere, and the peak of performance tends to occur towards the middle of the year, within the summer season. Bogotá is the unique city located in the northern hemisphere that does not show an ascending profile, probably because it is located close to the Equator.

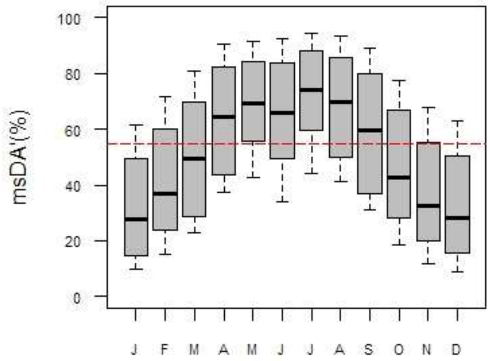


Rio de Janeiro

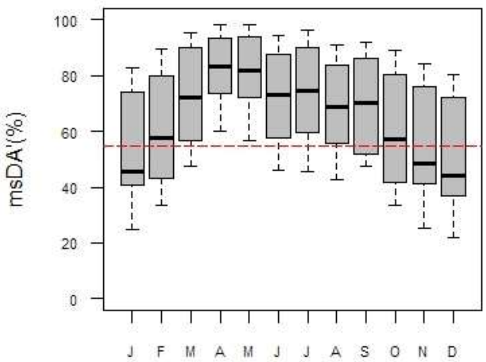
Figure 49 (continued on the next page)



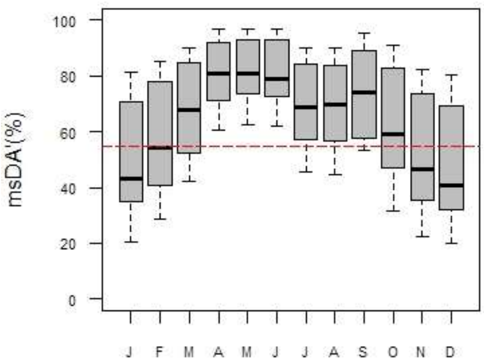
London



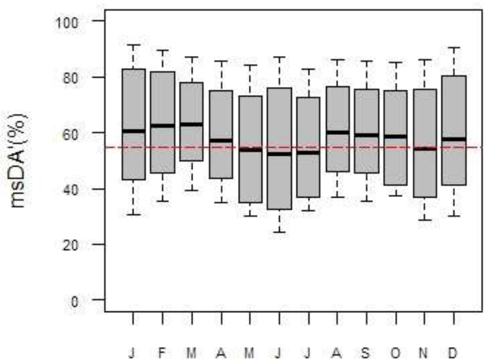
Shanghai



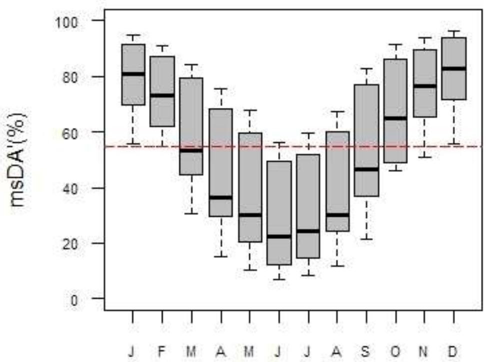
Dhaka



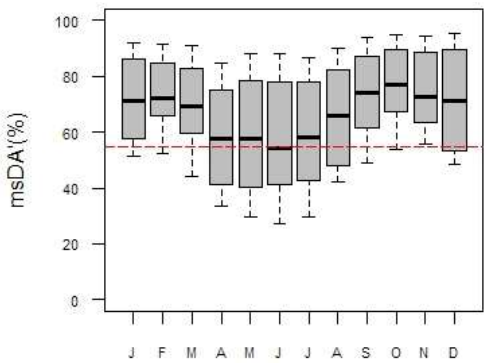
Karachi



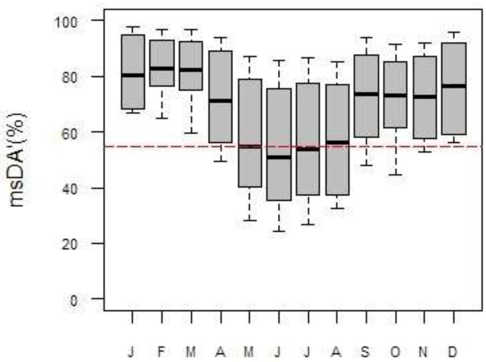
Bogotá



Buenos Aires



Dar es Salaam



Lima

Figure 49: Variation of msDA' (%), 12 months of the year, per city, Cases A to H.
Source: own author.

In general, it was found that the resulting profiles of the boxplots of msDA' (Figure 49) reflect the global horizontal monthly illuminance by city (Figure 34a). Indeed, the resemblance of their profiles becomes more evident when the graphs corresponding to these two figures, illuminance and msDA', are set side by side (Figure 50).

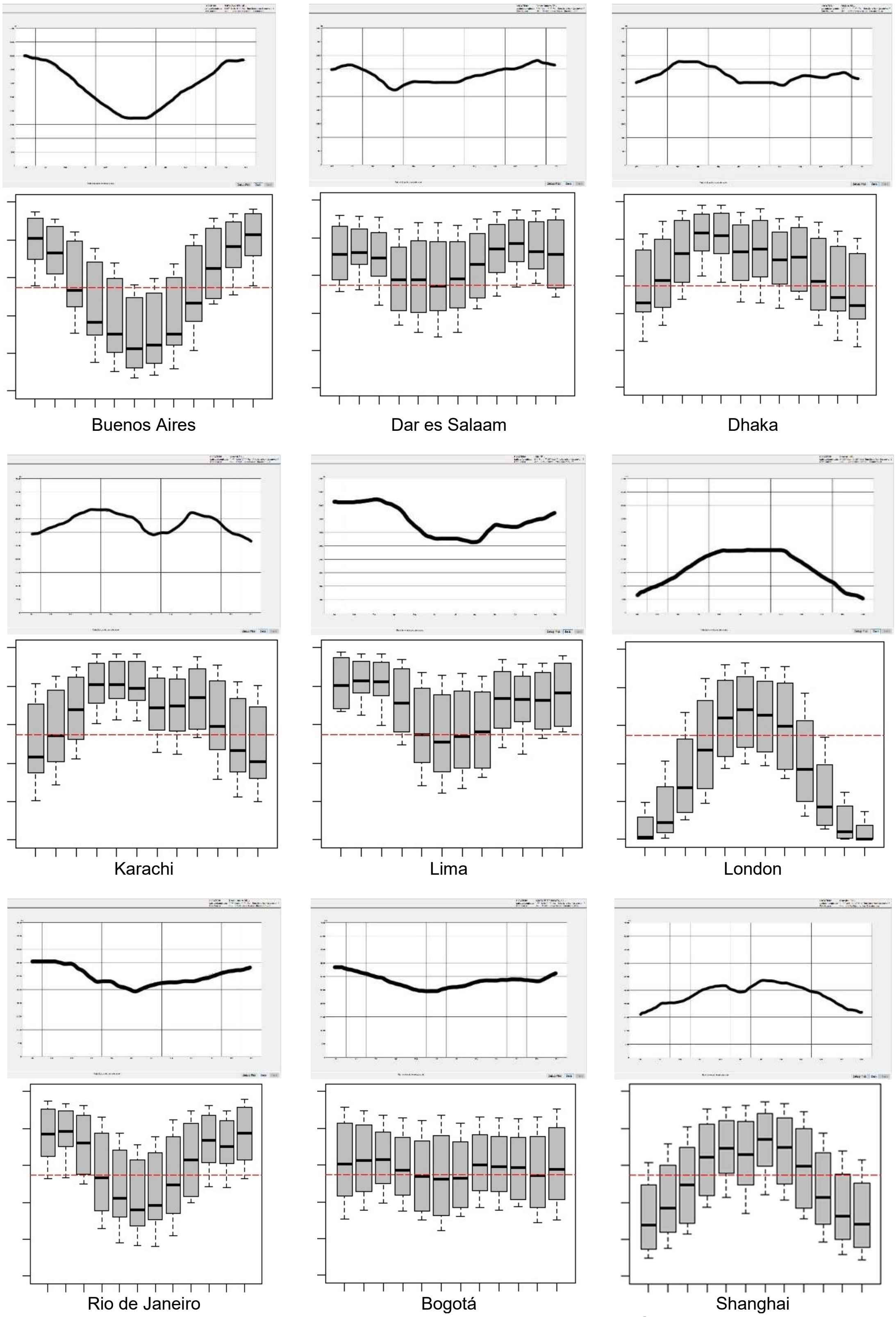


Figure 50: Monthly illuminance *vs.* msDA' per city. No scale. Source: own author.

This indicates that illuminance is very relevant for msDA’, considering this study of urban variations. Nonetheless, the patterns of the graphs are not identical in all cases; this indicates that latitude is not the only determining parameter for msDA’ performance.

Another approach is to compare the msDA’ of the cases with variation in urban geometry (Figure 51). They illustrate how each urban configuration can generate different daylight results throughout the year considering the sample of all cities together.

Comparatively, baseline (Case A) and its version with heterogeneous height (Case B) result in higher percentages of msDA’, with smaller variations during the months within cities than the other cases. The differences among the two cases were not considerable, although in Case B the FAR of the model was increased by 20%.

When the height of the buildings is doubled, increasing from 35m of baseline to 70m (Case E), the variation of performance among the cities along the year also increases. In other words, when Case E is compared among the cities of the sample, the differences in performance due to location are higher than in Cases A and B, and the average of E is lower than these two cases. Despite that, satisfactory sufficiency prevails in the three Cases: A, B, and E.

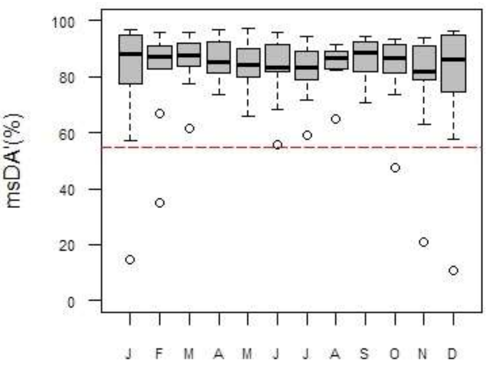
The profile of the plotted results of Case E is similar to Case H (canyon). However, in Case H the mean of performance in all boxplots is lower than in Case E in all months.

One aspect is relevant to remember: the urban density of Case E is the double of baseline, while in Case H it is only 20% higher than baseline (see FAR, previous Table 20). This means that increasing the urban density twice by using buildings with heterogeneous heights resulted in a higher performance than by increasing density horizontally in 20% using canyons in the tested cases.

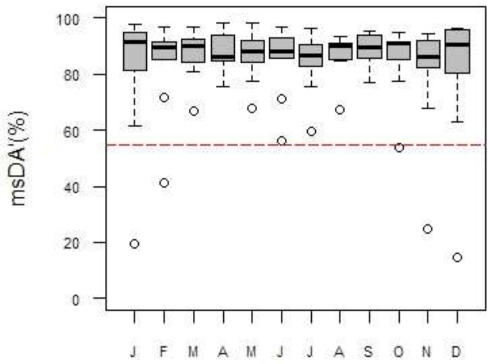
In Case G, the height of the buildings of the baseline is increased from 35m to 100m. Its variation in performance throughout the year and also among the cities was the highest in all cases. Its performance was rarely above the threshold of minimum sufficiency.

Overall, the urban configuration in Cases A (baseline) and B (heterogeneous height) tend to favor indoor daylight in all cities tested in the sample, while the performance of the urban designs of Case G and H are more vulnerable to the climate of the city.

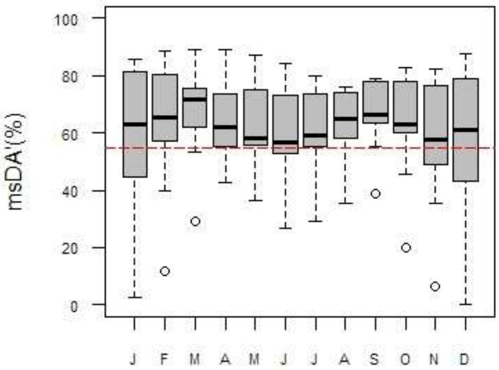
One note regarding the dots representing outliers in these graphs of Figure 51. Based on the peaks of the graphs in the previous Figure 49, the outliers in the beginning and/or end of the year are results probably from London and/or Shanghai. Outliers in the middle of the year are probably from Buenos Aires and/or Rio de Janeiro, two cities that present quite low performance between June and July.



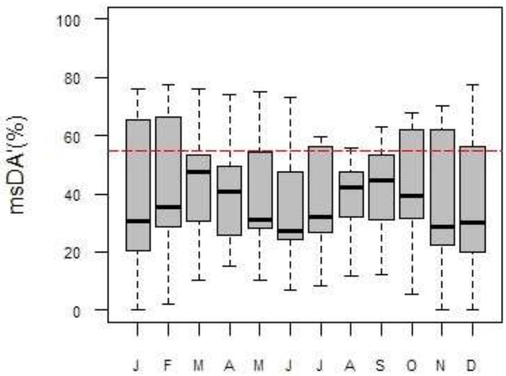
Case A: Baseline (H=35m)



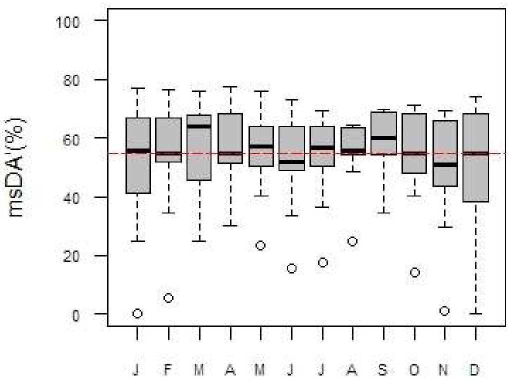
Case B: Heterogeneous height



Case E: Baseline taller (H=70m)



Case G: Baseline, tallest (H=100m)



Baseline H: Baseline as canyon

Figure 51: Variation of msDA' (%) within the 12 months of the year, considering all cities of the sample and only the cases with variation in urban geometry.
Source: own author.

Appraisal

The process presented in this study is here described in a structured sequence for enhancing clarity, but it was not always linear.

Decisions made in this stage interfered in decisions taken in the previous section and vice-versa. For instance, the crucial decision regarding the output of performance was the metric to be adopted. This decision was consolidated after preparatory simulations and the literature review. The metric influenced the choice of the data format of climate parameters (annual and monthly data), presented in the previous section for didactic reasons, as well as the choice of the software for performance evaluation. The software, in turn, affected the definition of the urban model, from the size of the measured area, through settings, to the input characteristics. In this context, some strategies helped to decide and to build the final framework of the study. One of the most relevant was to run fast, non-detailed simulation tests; this is highly recommended for future studies.

A quantitative comparison of the results of performance using different software in Phases I (Ladybug/Honeybee) and II (DIVA) was not the scope here. A note: such comparisons should be treated with caution, not only due to script differences among software. This is also because daylight calculations in the software adopted here rely on stochastic models that might retrieve different results for each run, as the user's manual of DIVA informs. The methodology for such analysis can be found in Ng (2001b) that focused on Radiance, and in a review provided by Jones (2017). But one comparison between the tools in terms of the process is valid to notice: the complexity of the simulation using DIVA was lower, and the achieved results were faster than using Ladybug/Honeybee under the conditions of this study.

Regarding the 3D model, there are additional advantages of the choice for the baseline. As mentioned, the final baseline model presented characteristics of high density according to an existing classification system by Oke and Stewart (2012) that is being used in urban studies related to climate. Because of that, the model might serve to other studies in the urban climate field, contributing for a potential interchange of information regarding interferences of climatic parameters.

Regarding the choice for specific design elements and their impact on the results, other aspects of the model are valid to be discussed. For instance, the simulation of architectural elements that could alter the indoor daylight performance results found here can be further explored. In the final urban simulation, the measured area was open floor plans, but the inclusion of internal partitions in the models could improve the results. As Dogan and Park (2018) pointed out, rooms with internal partitions tend to have higher daylight performance than open floors due to the contribution of inter-reflections. The effect of the design and position of windows in the façade, as well as the interference of different pollution levels, are also topics for investigation since they can alter the results. The effect of light shelves, fins, or overhangs on performance is a topic for future studies.

It is important to have in mind that it is not possible to have access to detailed information on architectural design in the stage of urban design and planning, unless mandatory mechanisms antecipate architectural decisions. Examples of that are the limits of WWR defined in different locations (see previous Table 12), or the minimum values of façades' reflectance that certain instruments propose or request, or the definition of the function of the building by conventional urban zonings.

The selected urban baseline model in the grid and its variations combined non-theoretical and theoretical approaches. Through them, it was achieved one of the objectives of this study: they served to better understand aspects of daylight indoors for multiple cities, generating results that can be used from a pragmatic perspective for real applications.

In fact, on one hand, diverse non-theoretical elements were incorporated into the models. This includes the adoption of settings from the IES LM-8312. This standard was partially developed considering indoor daylight conditions in existing buildings. The models were also based on input parameters selected from literature combined with the analysis of the urban morphology of some of the global megacities. This was done using tridimensional digital databases such as Google Earth (illustrated in Figure 12), although Samuelson et al. (2016) noted that past urban design might not be appropriate for new cities.

On other hand, the building and urban concepts in the 3D model were in part also theoretical. It is unlikely that in real urban configurations all buildings would have an equal quadratic base, narrow floor plan depth, same height or similar pattern of heterogeneous height variations, uniform outdoor reflectance, positioned in a regular grid. And most probably, urban models would not be replicated in several cities without adaptations. However, by using the same 3D models in different cities, this study explores the possibility that those locations with a growing population and potential demand for new spaces could adopt any design. Additionally, the use of the same models in various cities favored the comparative approach on the same basis, which was relevant for this research.

From the literature review and from the simulations conducted here another point is reinforced. The use of simplified or 'worst case' conditions, like the undistinctive building function, facilitates and/or make feasible studies on indoor daylight performance in the scale of urban design. This is especially necessary not only due to the mentioned unavailability of information on architectural design but also due to the current conditions of software and hardware.

However, considering the accelerated development in computer technology, the necessary time for conducting such simulations is going to decrease in a near future. This will expand the possibilities for exploring more diverse, accurate simulation conditions.

Noticeable, the decision of replicating the model in diverse locations does not mean that this author recommends or endorses the incorporation of the same urban design models in different cities without the proper understanding and attention to local culture, constructive tradition, landscape, urban development goals, and other principles of sustainable urbanism. This is an important aim, but it is also a very complex task that should be conducted with experts in the peculiarities of each city and region to avoid oversimplifications or biased analysis. Thus, the development of urban models for each city that represented or reflected past conditions or specific interests for the future was not a scope of this work.

4.4. Classification of parameters and daylight performance

This section presents the results of the classification of parameters of cities, which supported the test of the hypothesis. Summarizing the entire section, as previously detailed in the Chapter on Methodology, the results between daylight climate and indoor daylight performance of cities were compared separately, and then they were contrasted against each other.

4.4.1. Part 1: results of the comparison per data type

In this section, cities are grouped based on the similarity of their ‘raw’ data. These are organized into tables or plotted in graphs. The goal was to keep the groups in a number inferior to three, especially considering the number of cities, as previously detailed. There are several possibilities for grouping; the results presented here are not exhaustive.

4.4.1.1. Daylight climate parameters

Firstly, the parameter global horizontal illuminance (klx) for each city is considered. For annual data, the previous Figure 35 is used to facilitate the analysis. One possibility is to generate two groups (Figure 52, Option 1), one of them composed of London and Shanghai, the cities characterized by the lowest illuminance values. Another possibility generates three groups, by complementary isolating the city with the highest performance in one group: Lima (Option 2). Another alternative generates four groups (Option 3). In this case, results are obtained by separating cities considering arbitrary ranges. Lima and London, the cities with respectively maximum and minimum values, are separated in one group each. Another group is composed by Dar es Salaam, Dhaka, Karachi, and Rio de Janeiro, cities with very similar illuminance values. The remaining cities compose the last group: Shanghai, Bogotá and Buenos Aires. As explained, the number of four groups is considered excessive for the purposes of this research; it was used here only to exemplify how complex it might be to define a group since the criteria can vary in different directions.

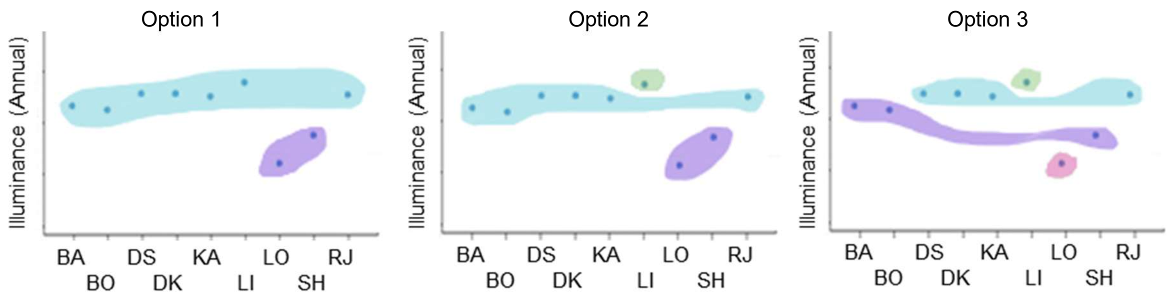


Figure 52: Illuminance, annual data: exploring possibilities for grouping cities.
Source: own author.

By taking the previous Figure 34, which refers to monthly illuminance, several options for grouping the cities also arise. One possibility is to group them by the similarity of their amplitude and levels along the year (Figure 53, Option 1), which could generate three groups: one with London, the other with Bogotá, Dhaka, Dar es Salaam, and the third group composed of the remaining cities. Bogotá could also compose a fourth group alone, because of its small amplitude. Another possibility is to group the cities considering the proximity of their medians (Option 2). This generates one group formed by London and Shanghai and the other group formed by the remaining cities. Another possibility is to isolate in one group the unique city with very different levels of illuminance, London (Option 3).

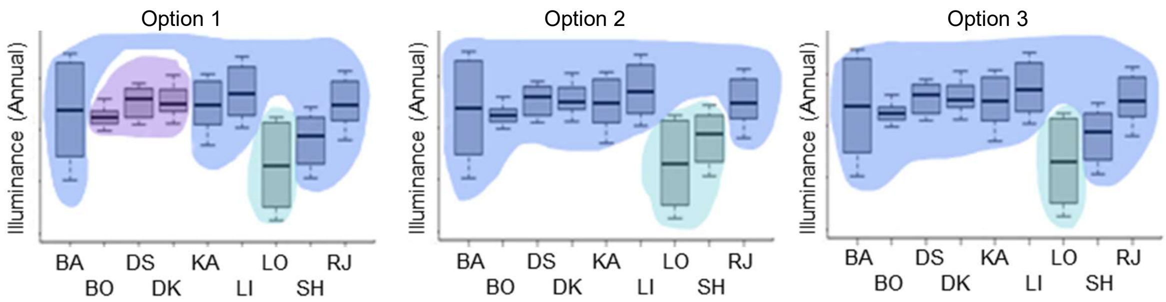


Figure 53: Illuminance, monthly data: exploring possibilities for grouping cities.
Source: own author.

Secondly, it is considered the parameter sky cover (%) for each city.

Over the graph of annual sky cover data of previous Figure 36, three suggestions were developed (Figure 54). In Option 1, two groups emerge. One of them is composed of Karachi and Dar es Salaam, cities with lower percentages. However, it is also coherent to that a third group, composed by cities of higher percentages of sky cover: Bogotá and London (Option 2). Depending upon the criteria, Shanghai could be grouped with London and Bogotá (Option 3).

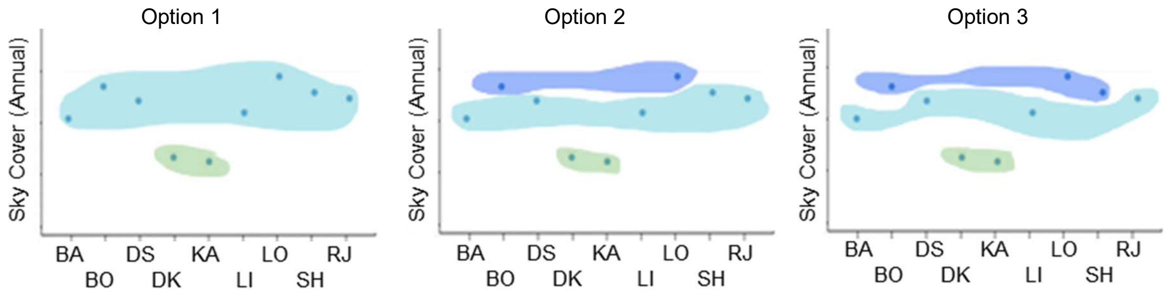


Figure 54: Sky cover, annual data: exploring possibilities for grouping cities.
Source: own author.

For monthly data of sky cover, the situation is more complex to obtain from the previous Figure 36 (a). One option is to group cities considering the amplitude of their curves throughout the year. Karachi and Dhaka present higher amplitudes when compared to the other cities, but the amplitude of Lima is also noticeable and they could all form a group. These three cities present a curve with a peak around July. In opposite, Bogotá presents fewer variations throughout the year and could compose a group with London. In any case, however, it is not easy to propose groups based on this type of graph neither the tables containing their raw data. In this situation, boxplots could facilitate the analysis. This example demonstrates that the type of graph matters in the investigation, and should also be defined carefully.

The last analysis of a climate parameter considers the sky type for each city. The annual analysis is based on Table 25. Karachi and Lima form one group, since both present annual predominance of the sky type 14. Buenos Aires composes another group, because it is the only city in which the type 13 prevails. The remaining cities compose the last third group; all of them have the sky type 1 as the most frequent.

The monthly analysis of sky type is based on the graph of Figure 37. One alternative is to separate the cities into two groups, one of them containing all cities with the predominance of the same sky type along the year: London, Bogotá, and Shanghai (Figure 55, Option 1). An alternative is to repeat this situation and add a third group, formed by the unique city that does not demonstrate sky type 1 in the year, Buenos Aires (Option 2). Another option is to add a fourth group, consisted of Dar es Salaam and Lima, cities in which two sky types prevail throughout the year (Option 3).

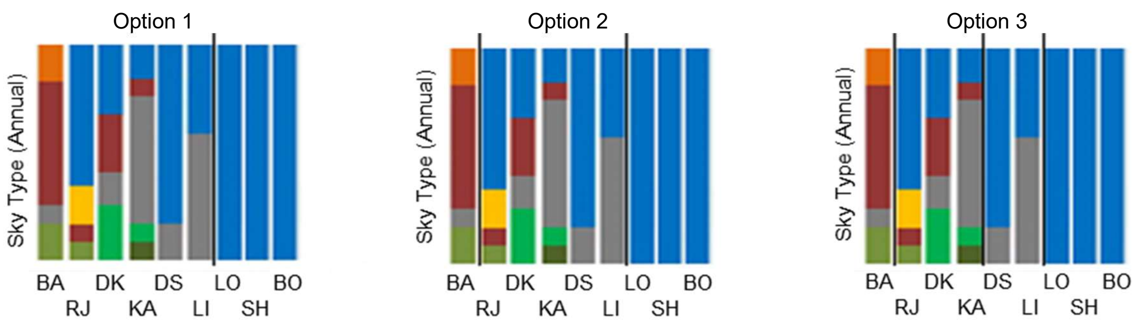


Figure 55: Sky type, annual data: exploring possibilities for grouping cities.
Source: own author.

4.4.1.2. Daylight performance indoors

In the case of indoor daylight performance (sDA', %) for each city, the annual results plotted in Figure 45 were reviewed. Three options were retrieved (Figure 56). In Option 1, three groups based on the similarity of upper and lower levels can be formed: one group by London; the other by Shanghai, Buenos Aires, and Bogotá together; and the third composed of the remaining cities. The distance of the lowest values from the threshold of minimum performance generates three groups (Option 2). This time, London and Shanghai are unified in one group. A possibility is to separate these two cities due to their peculiarities. London is visually different in the graph from all cities, but Shanghai is also in a midterm between London and the other cities (Option 3).

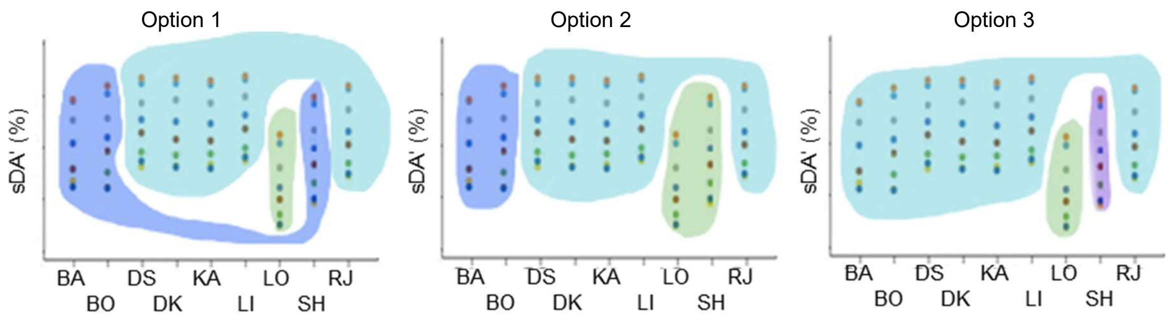


Figure 56: Annual indoor daylight performance: possibilities for grouping cities.
Source: own author.

In the analysis of the monthly data (msDA', %), the boxplots of Figure 49 were used as a reference. If the shape of the profile of each graph is considered as a criterion, two groups could be formed visually. One group formed by London, Shanghai, Buenos Aires, and Rio de Janeiro, that present a more accentuated sinusoidal shape.

If the direction of the curve (convex or not) is a criterion, two groups can be considered: one with London, Shanghai, Dhaka, Karachi, and the other group containing the remaining cities. These groups are related to the position in the hemisphere of the globe.

If the variability of the median along the year is a criterion, Bogotá calls attention and could form a unique group, while the other cities could be grouped in another one.

The criteria of the direction of the curve set call the attention for daylight variability throughout the year. However, considering absolute values, it is unlikely that London and Rio de Janeiro are similar in daylight performance. This observation exemplifies that the criteria for grouping shoud be aligned with the purposes of the research and reinforces the need for complementary analysis to support and debate the results.

4.4.1.3. Daylight climate *vs.* indoor performance

The results of the groups of daylight climate parameters of the previous sections were compared to those of indoor performance.

Taking as an example the annual case of climate parameters, some of the previous graphs were collected and reproduced in Figure 57. The previous graph of illuminance suggests that London and Shanghai composed a group of higher similarity among the cities (from Figure 52, Option 1). This option is partly endorsed by the alternative for sky cover in which a group is composed by London, Shanghai, and Bogotá (from Figure 54, Option 3). These three cities also formed a group as per monthly sky types (from Figure 55, Option 1), and also from the annual analysis. In other words, considering all three climate parameters, London and Shanghai are more similar to each other than to the other cities. Of course, this is a conclusion based on a set of alternatives for grouping.

In the case of annual indoor daylight performance, London and Shanghai could form a group (from Figure 56, Option 2).

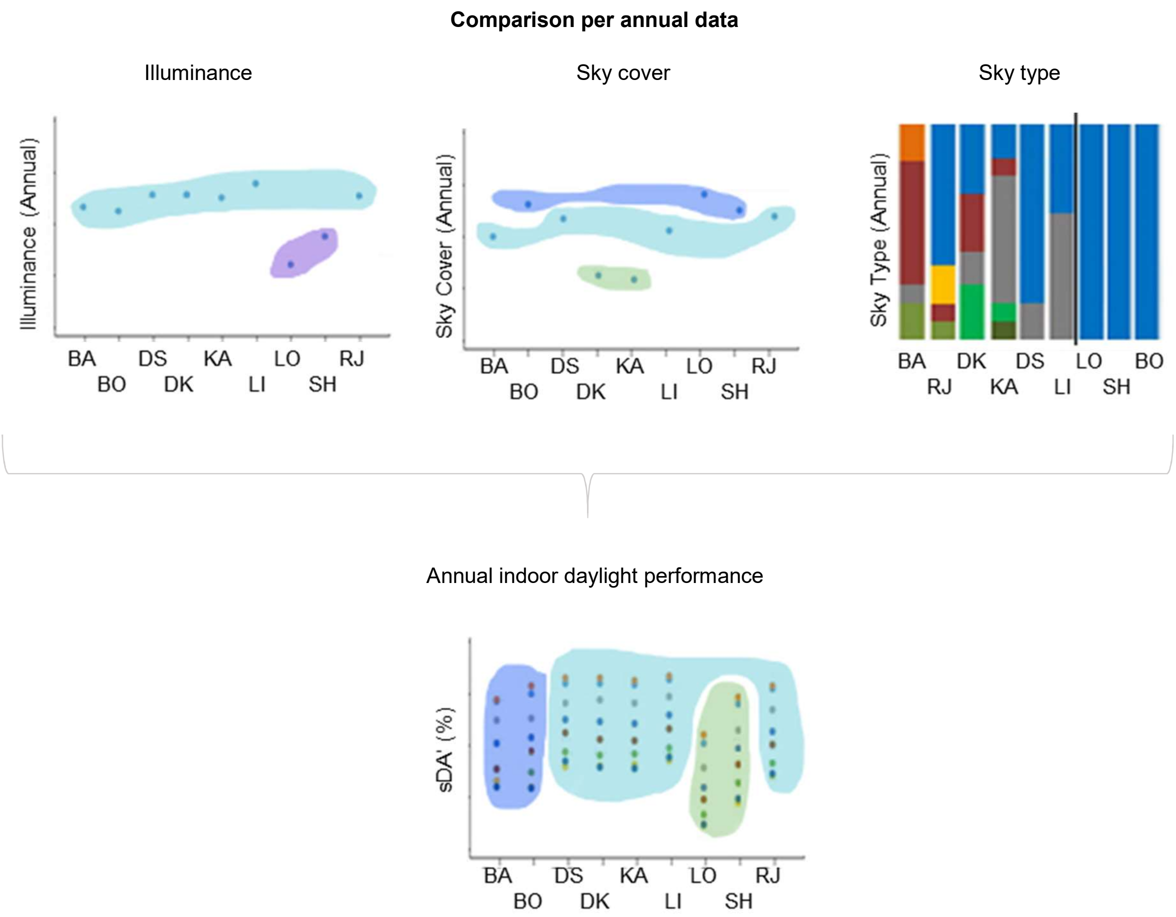


Figure 57: Comparison of annual data in a search for similarity between climate and performance. Source: own author.

By using this system, it was very difficult to find similarities between the groups due to the several possibilities of grouping and the different data types. And, considering the result of climate parameters *versus* daylight performance of the example, it remains unsure that by analyzing the similarity of the first, the similarity of the latter could be anticipated with precision. Any conclusion in this direction is debatable, since the criteria of grouping were diverse and subjective in some cases. Because of that, the analysis was not done for the monthly time frame, which is also more complex to be conducted using this method due to its larger amount of data.

Appraisal

In all cases presented in this section, the criteria for the selection of each group of cities based on similarity is demonstrated to be quali-quantitative, mostly supported by visual graphical perception. The results were vulnerable to decisions about thresholds adopted, which were not necessarily based on an accepted theory, but an exploratory system of trial and error. This does not invalidate the type of analysis. However, it makes the method of grouping difficult to be repeated by other researchers and its thresholds complex to justify.

As mentioned, there is also a difficulty to finally compare the groups of cities formed by similarity in terms of climate data *versus* those groups formed by indoor daylight performance. This is not only due to the complexity of translating data of different types into the same criteria but also by the high number of possibilities of groups that each data permits.

These problems are tackled in the next section, that present results of the application of methods integrated from advanced statistics: grouping by clustering.

4.4.2. Part 2: results of the comparison per combination of data type

In this section, cities were grouped using two consolidated statistical clustering methods, Ward d2*,* and k-means. This double assessment aimed to provide a more assertive quantitative investigation of the degree of similarity among the cities. Firstly, it is presented the results of clustering based on the daylight climate. Then, it is shown the results of indoor daylight performance. Finally, it is presented the comparison between these two results.

4.4.2.1. Daylight climate parameters

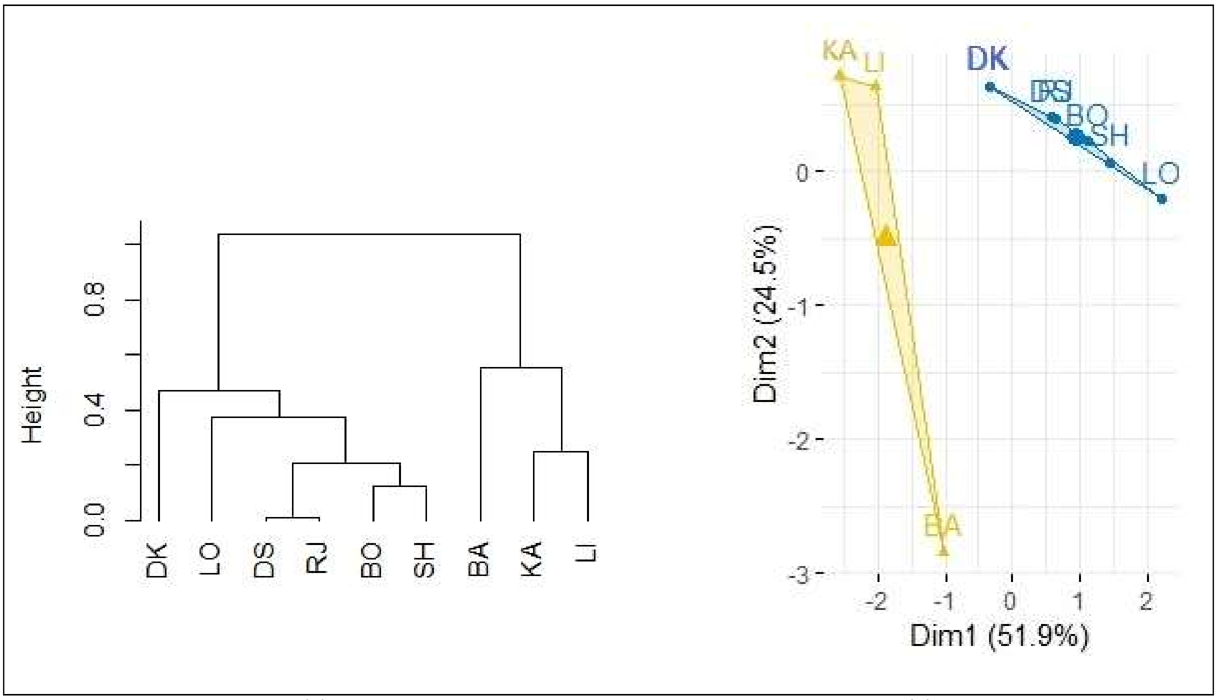
The cities within the sample were clustered by annual and monthly daylight climate.

It is important to note that daylight climate is here represented by three parameters (illuminance, sky cover and sky type), which were analyzed separately and represented in a combined mathematical form, visualized as a graph.

The generated clusters per Ward d2 and k-means methods are equal in terms of cities that compose each group. This occurred both for monthly and annual data. The comments below focus on the dendrogram, that are easier to visualize from the perspective of similarity.

The results of the cluster for annual climate data shows that the distribution of cities generated two groups (Figure 58). One of them is composed by 3 cities (Lima, Karachi and Buenos Aires). With respect to daylight climate, Dar es Salaam and Rio de Janeiro have a degree of dissimilarity close to zero - in other words, these two cities have almost equal daylight climate when the 3 parameters are analyzed in a combined way. Dar es Salaam and Rio de Janeiro are also similar in terms of performance, albeit belonging to distinct subgroups in which Dar es Salaam is closer to Lima, while Rio de Janeiro is closer to Dhaka and Karachi. Bogotá and Shanghai are close both in terms of sDA' and daylight climate, and Buenos Aires is far from the two cities with respect to daylight climate.

Cluster by annual daylight climate data:



(a) (b)

Figure 58: Cities clustered by annual daylight climate, (a) Ward d2 and (b) k-means.
Source: own author.

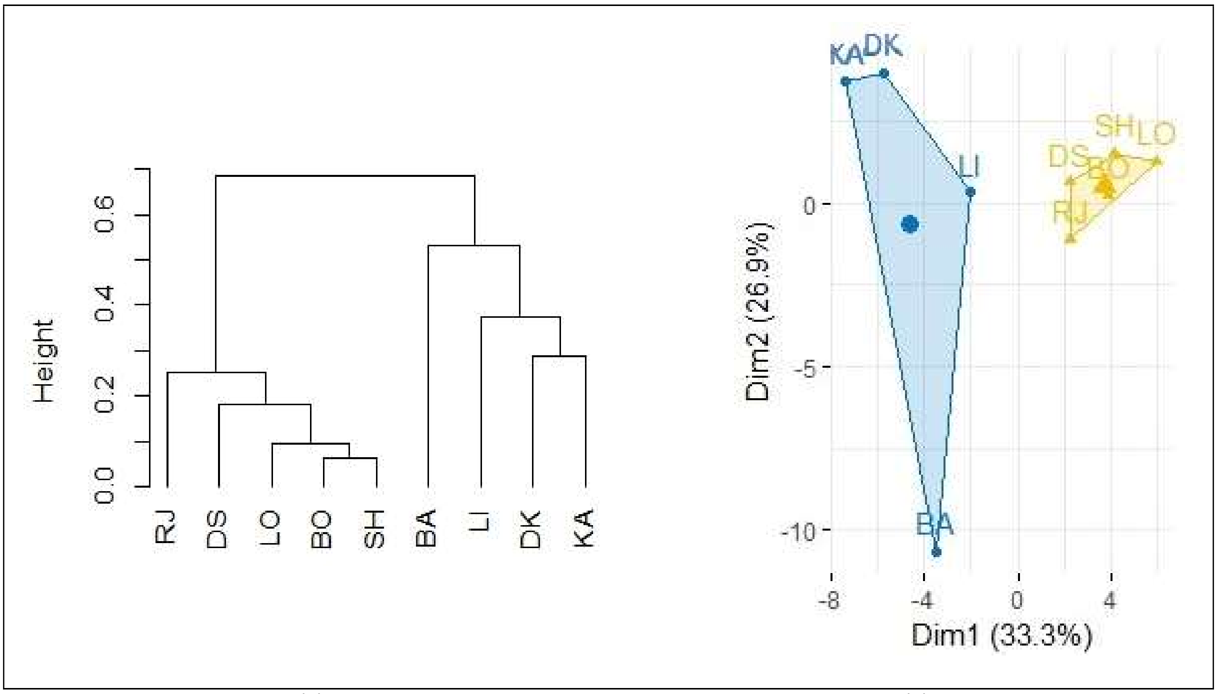
The clusters generated with monthly climate data were different from the annual ones (Figure 59). Two groups in the Ward d2 were formed as well. Four cities compose one of the clusters: Karachi, Dhaka, Lima and Buenos Aires are similar both in terms of daylight climate.

The remaining cities composed the other group. In one group, Karachi and Dhaka are the most similar to each other. In the other group, Bogotá and Shanghai are more similar.

However, in the k-means cluster, Buenos Aires is more distant form the members of its group, while the group formed by Bogotá and the remaining cities is more compact.

As expected, all cities exhibited a certain degree of difference to each other (dissimilarity ≠ 0).

Cluster by monthly daylight climate data:



(a) (b)

Figure 59: Cities clustered by monthly daylight climate with (a) Ward d2 and (b) k-means. Source: own author.

4.4.2.2. Daylight indoor performance

The cities of the sample were clustered using the indoor daylight performance data. These data were taken as sDA’ and msDA’ only from the geometry variations (Cases A, B, E, G, H). This strategy focused on the comparison of cities in terms of only one element of design at the time (in this case, urban morphology), avoiding misleading conclusions that the inclusion of other architectural variations could lead to.

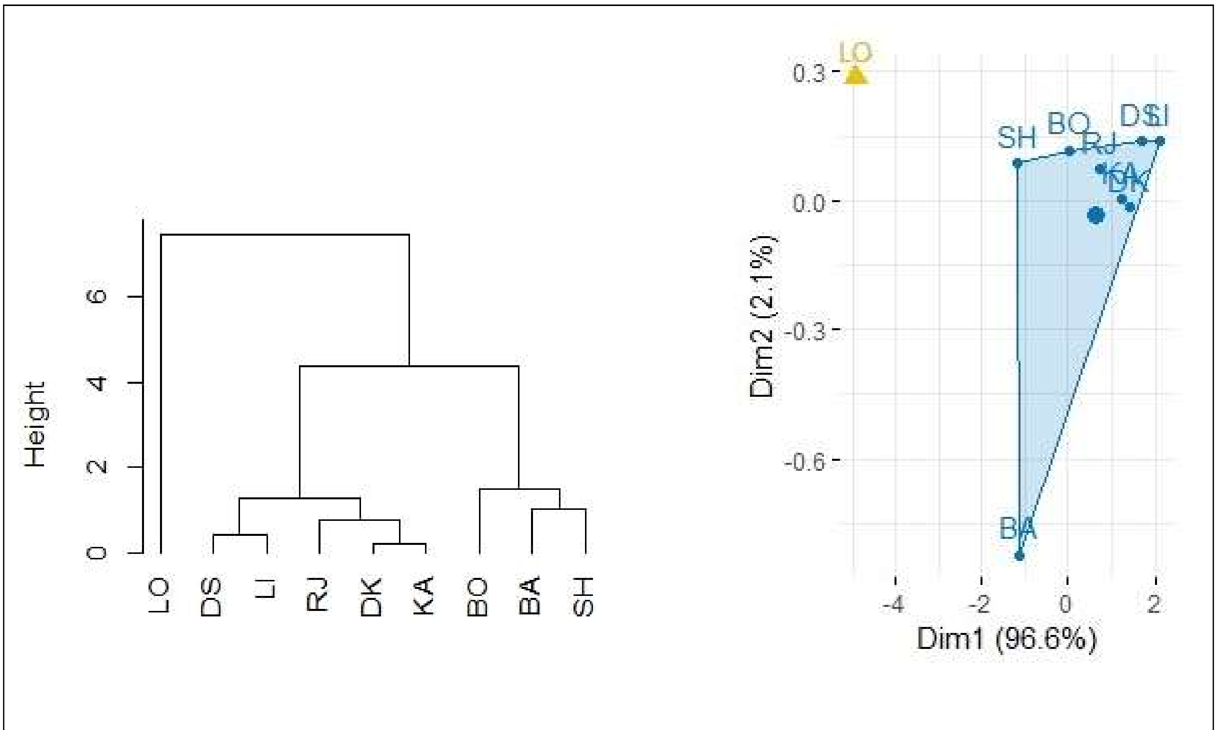
The results of clustering per Ward d2 and k-means methods resulted in the same cities composing each group, both for monthly and annual data. Thus, the comments focus on the dendrogram.

The dendrogram pertaining to sDA' resulted in one group comprising only one city (London), while all the other cities composed another group, which can be subdivided by similarity into different levels (Figure 60). These levels indicate that Buenos Aires has performance more similar to Shanghai, and that the performance of Bogotá tends to be closer to these two cities.

In another subgroup, Dhaka is more similar to Karachi, with Rio de Janeiro also tending to be similar to these two cities. Dar es Salaam exhibits performance behavior similar to Lima.

The distinctiveness of London from other cities could already be anticipated from the results shown in previous Figure 45, and from the statistical descriptive analysis done a priori. This analysis showed that the median of daylight performance (sDA'≥55%), considering all simulated variations of geometry, was below the minimum only in London; all the other cities surpassed the threshold of sufficiency.

Cluster by annual indoor daylight performance data:



(a) (b)

Figure 60: Cities clustered by annual indoor daylight performance, using (a) Ward d2 and (b) k-means. Source: own author.

Additionally, the annual performance data generated groups similar to the ones formed using the visual method illustrated in previous Figure 56. The higher similarity was found in Option 1, then reproduced as Figure 61 to highlight this aspect. By looking especially to the lowest values of performance for each city, London is really differentiated, and compose one group alone. In the cluster, the remaining cities that on average outperformed formed the other group, from which three cities that are more similar to each other formed a subgroup: Shanghai, Bogotá, and Buenos Aires. In other words, their indoor daylight performance levels are closer to the ones of the other cities rather than the performance of London. One difference is noticed: in Option 1 cities were separated as an additional group, not as a subgroup.

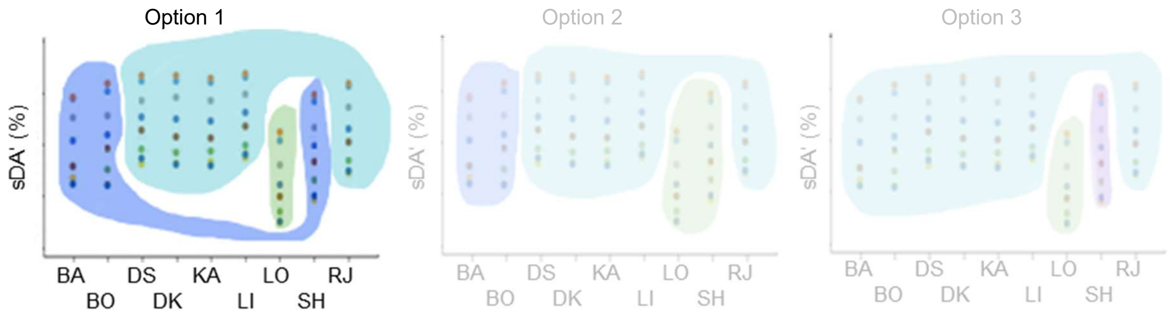
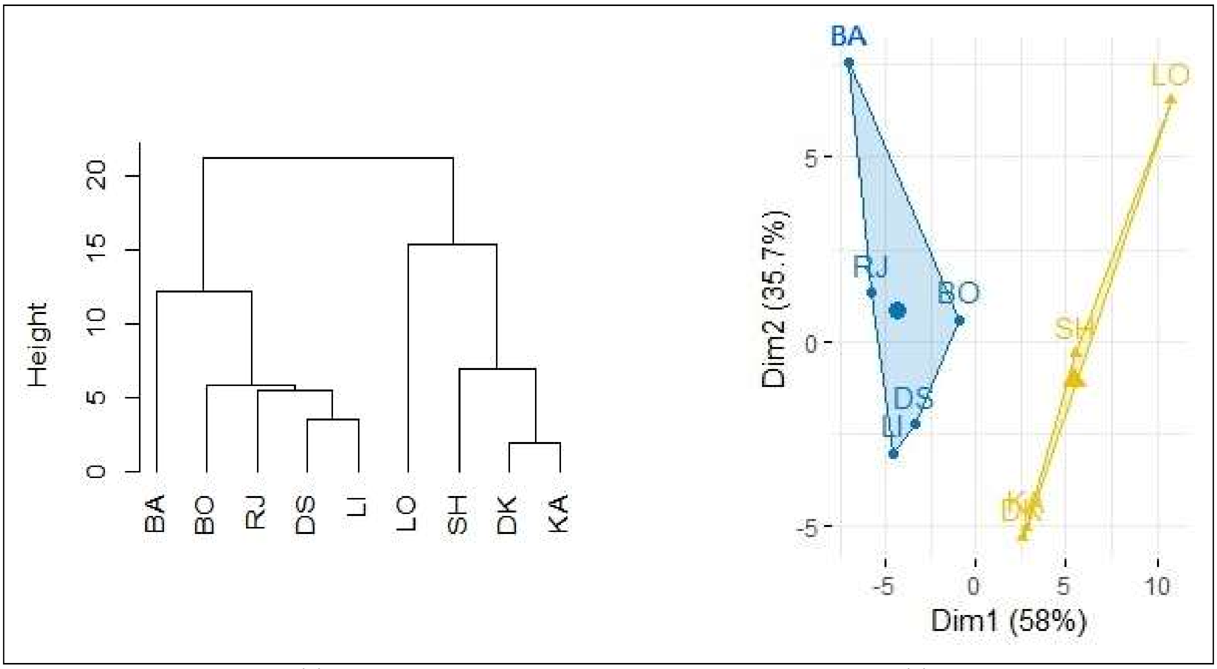


Figure 61: Option 1, highlight of the previous figure “Annual indoor daylight performance: exploring possibilities for grouping cities” is similar to the results of cluster analysis. Source: own author.

The clusters emerging from monthly indoor daylight performance data formed also two groups Figure 62. Nonetheless, the distribution of cities between the groups is more balanced than in sDA': four cities formed one group, and five formed the other one.

More specifically, in the clustering by msDA', one group comprises London, Shanghai, Dhaka and Karachi. Karachi is more similar to Dhaka, and both are more similar to Shanghai than to London. In the other group, Buenos Aires is the most dissimilar city, while Lima is more similar to Dar es Salaam.

Cluster by monthly indoor daylight performance data:



(a) (b)

Figure 62: Cities clustered by monthly indoor daylight performance, using (a) Ward d2 and (b) k-means. Source: own author.

The result of the cluster by msDA’ reflects characteristics observed during the analysis of the boxplots of the monthly performance shown in previous Figure 51. They are here reorganized in Figure 63 to highlight another aspect: these four cities (LO, SH, DK, KA) presented a similar ascending profile with higher performance in summer, reflecting their distance from the Equator and their location in the North Hemisphere. In other words, these two conditions related to latitude appeared to be a relevant criterion for the results of the clustering of monthly daylight performance.

At this topic, the case of Bogotá is peculiar. Among the sample, this is the closest city to the Equator. Although it is located in the northern hemisphere, the profile of its msDA’ is slightly similar to those in the southern hemisphere, with lower average in the middle of the year. Coincidently, it is also around June that this city presents lower monthly values of illuminance (see previous Figure 33).

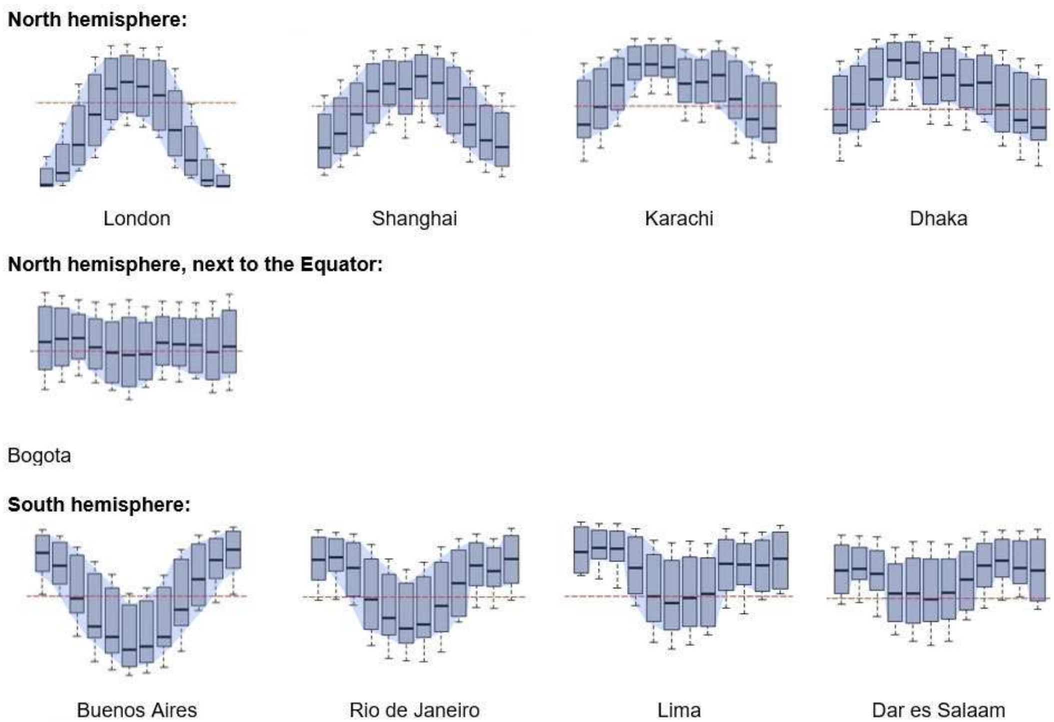


Figure 63: Graphs of msDA’ reorganized according to cities’ location in the globe highlights the similarities of their concave or convex profiles in terms of monthly indoor daylight performance. No scale. Source: own author.

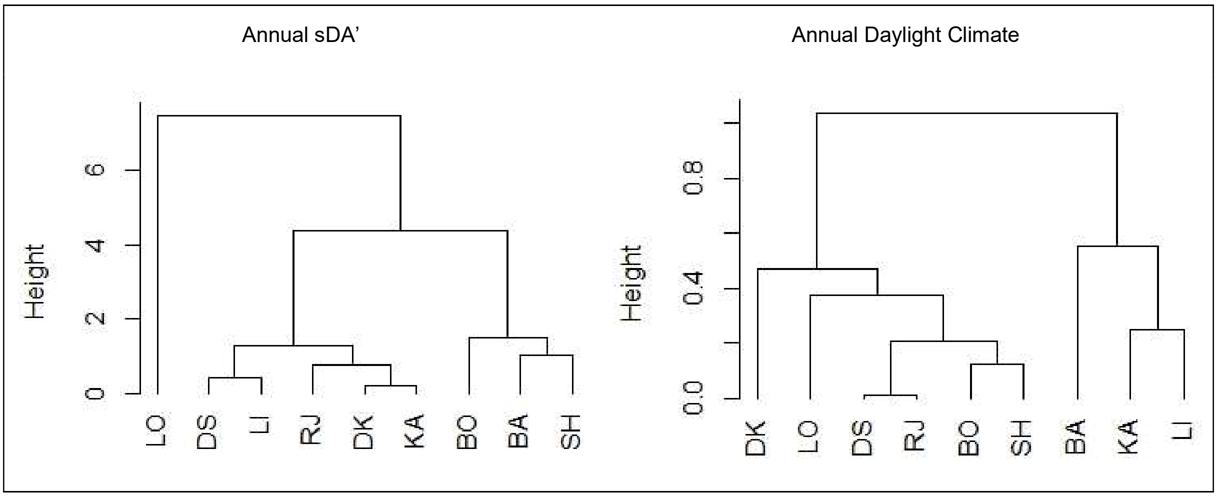
4.4.2.3. Daylight climate *vs.* indoor performance

The results between daylight climate and indoor daylight performance of cities were compared, aiming to identify a potential correspondence among them.

Again, regarding performance, only results obtained from variations in geometry were compared to the climate data. The comparison was based on only one of the clustering methods, Ward d2, but it can also be conducted for k-means.

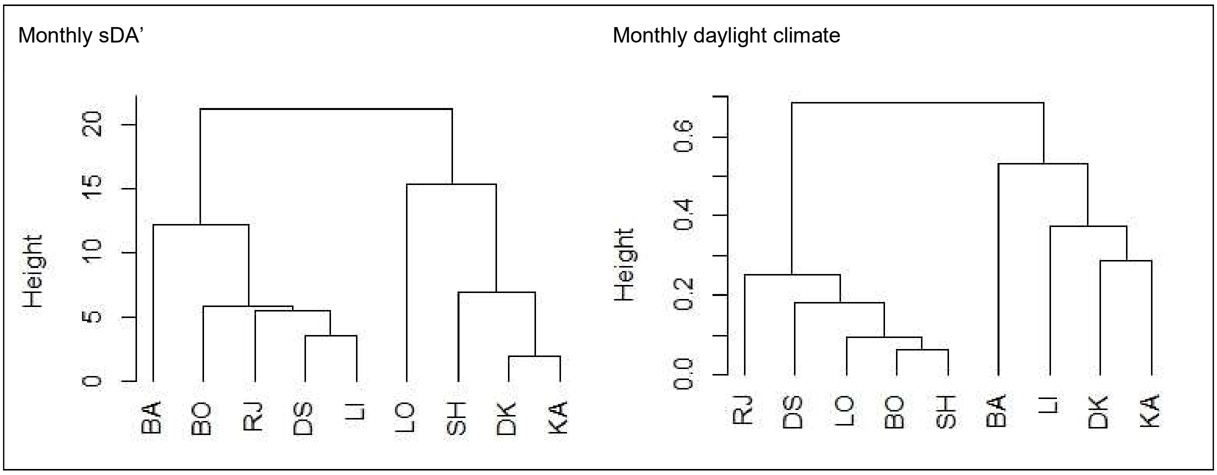
For facilitating the comparison, all dendrograms were reorganized and are shown in Figure 64.

Cluster by annual data:



(a)

Cluster by monthly data:



(b)

Figure 64: Dendrogram of cities clustered by sDA' and daylight climate, using the Ward d2 method. Source: own author.

Cities were compared in terms of sDA' and daylight climate, respectively, in annual (a) and monthly (b) timeframes. As a main result of this step, it can be observed that, although climate and performance were clustered into two groups each, there is a clear distinction between the dendrograms pertaining to daylight climate and sDA' in annual and in monthly terms. In other words, no evident correspondence was found among the clusters.

Table 29 compiles the results extracted from the clustering. Indeed, observing the generated groups and subgroups of the analysis, cities similar in terms of daylight climate are not necessarily similar in terms of indoor daylight performance. One cannot straightforwardly associate daylight climate similarity with indoor daylight performance considering the three selected parameters of daylight combined (illuminance, sky cover and sky type). This conclusion is valid for both annual (sDA') and monthly data (msDA'), under the simulated urban cases, using the conditions and selections defined through the application of the proposed general framework of analysis, limited to the conditions selected within the study.

Table 29:

Generated groups resulting from the cluster analysis using Ward d2 and k-means.

Cluster	Cities with similar daylight climate		Cities with similar indoor daylight performance		Result of similarity between clusters
	Cluster 1	Cluster 2	Cluster 1	Cluster 2	
Annual data	DK, LO, DS, RJ, BO, SH	BA, KA, LI	DS, LI, RJ, DK, KA, BA, BO, SH	LO	Daylight climate and indoor performance is not equivalent.
Monthly data	RJ, DS, LO, BO, SH	BA, KA, LI, DK	BA, BO, RJ, DS, LI	LO, SH, DK, KA	Daylight climate and indoor performance is not equivalent.

Source: own author.

These data, results and conclusions are further explored in the next sections through a series of complementary analysis. As mentioned, this process was supported by ABG (comments and details in Appendix G).

4.4.2.4. Complementary analysis

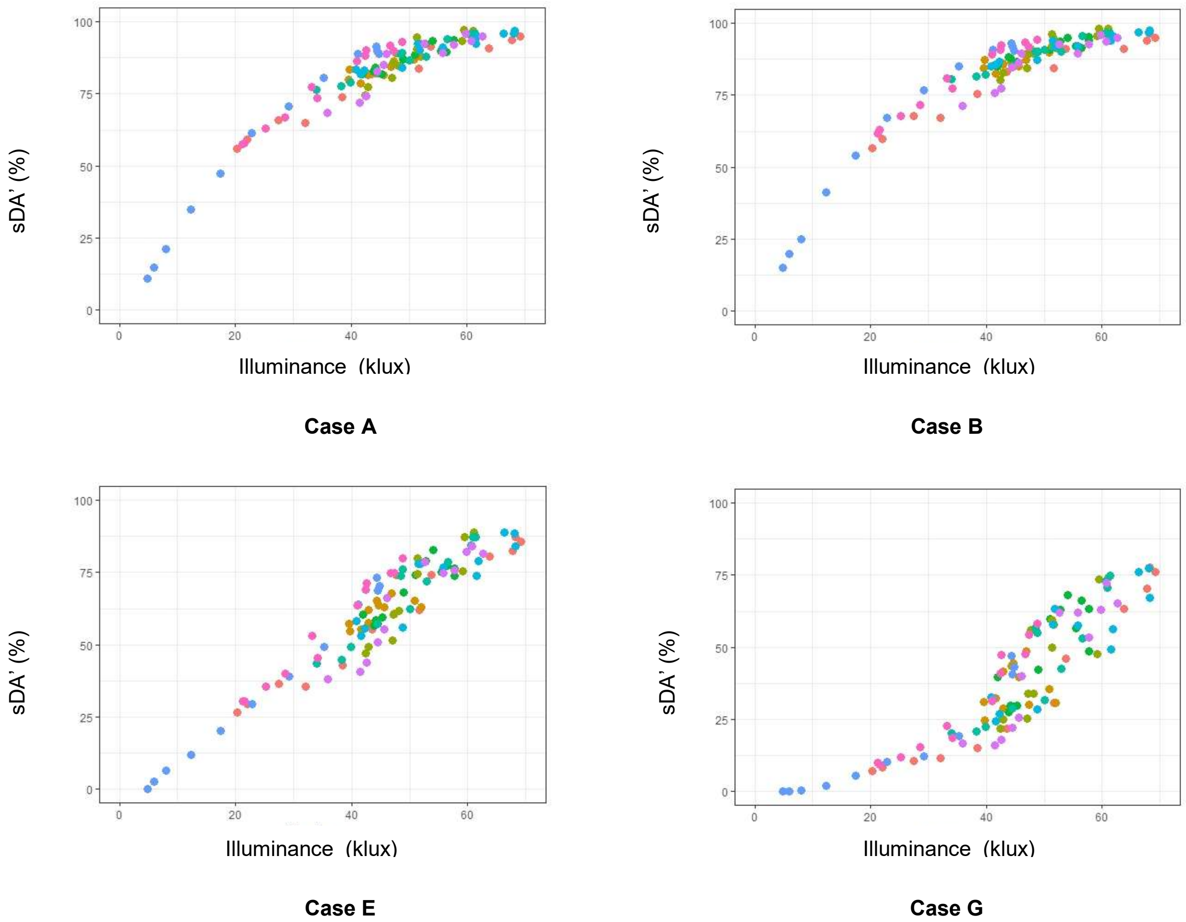
In the search for a better understanding of the results of the clusters, a series of complementary analysis were conducted. Considering the generated dendrograms, answers were pursued to the following questions: "*Why these results? Which parameters might have been responsible for these results*?".

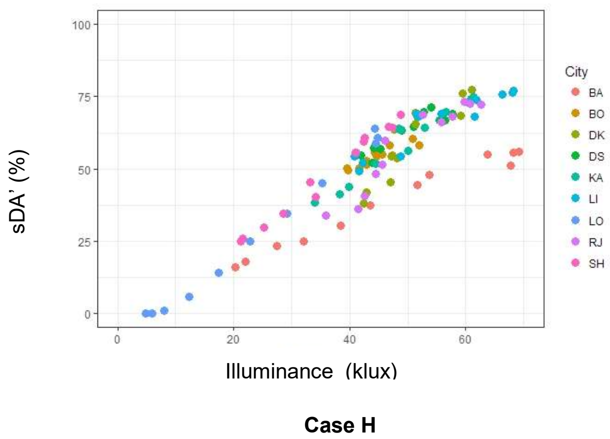
For the quantitative parameters, complementary statistical analysis was conducted to test the association between each climatic parameter and the results of indoor daylight performance using Pearson's correlation for the quantitative parameters illuminance and sky cover. Only monthly inputs were analyzed because their higher amount of data tends to produce more robust results.

As expected, these tests confirmed that by increasing illuminance levels, indoor daylight performance increases, while by increasing sky cover, performance decreases.

When monthly illuminance *vs.* msDA' of each city is plotted (Figure 65), indicative of those patterns can be observed, especially in geometries of lower heights where dots appear more aligned and concentrated. When monthly sky cover *vs.* msDA' is plotted (Figure 66), points appear more distributed, anticipating a weaker association in comparison to illuminance.

Taking the graphics related to illuminance, it is possible to observe that the association is stronger in cases A and B (Figure 65).





Case	Description
A	Baseline
B	Baseline, heterogeneous height
E	Baseline taller (H=70m)
G	Baseline tallest (H=100m)
H	Baseline as canyon

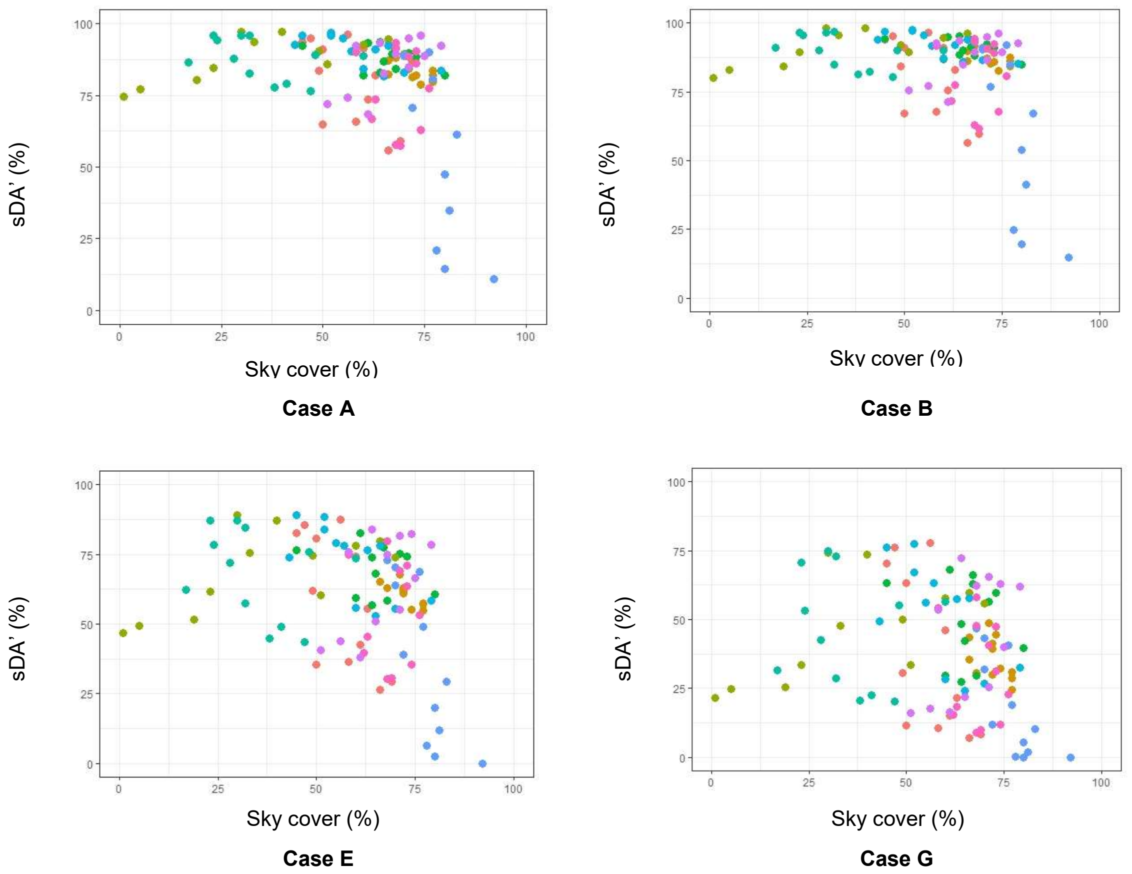
Figure 65: Scattter plot of monthly illuminance *vs.* msDA' of each city in a year. Source: own author.

In Figure 65, Case A represents the baseline, a grid of buildings with uniform height of 35m; Case B, the grid of heterogeneous height. The curves in Cases A and B tend to be exponential, with values of sDA' concentrated above 75% for illuminances close or superior to 40 klx. The association in Case E seems to be linear, indicating that there is a demand for higher illuminance levels to achieve higher sDA' percentages when the height of the buildings in the baseline is doubled (70m). The same linear behavior is observed in Case H (canyon). The association in Case G, baseline with building height of 100m, is weaker than in the other cases.

After illuminance *vs.* daylight performance, the statistical association assessment was done for the parameter sky cover *versus* monthly indoor daylight performance (Figure 66). This figure shows more disperse dots in each of the graphics in coparison to Figure 65. In other words, inferring any association between sky cover and performance is more difficult than in the case of illuminance. In Cases A and B there is a concentration of dots in higher levels of sDA', except for London, indicating better performance of these two urban geometries despite the diversity of sky cover percentages among the cities. However, in none of the cases a stronger association in comparison to illuminance could be observed.

This sort of statistical association assessment was not done for the sky type, a non-quantitative parameter, but the overview of illuminance and sky cover confirms that the choice of the input parameter plays an important role when it comes to finding a stronger correspondence between the dendrograms pertaining to daylight climate and performance. Namely, in the tested conditions it was found that global horizontal illuminance has a strong relation with resulting indoor daylight performance, while this relation is weaker for sky cover, especially when the urban morphology was denser

Additionally, considering the overall results of clusters, sky type might be making the correspondence between dendrograms weaker. In fact, when the annual clustering by daylight climate was contrasted with the weather data for each of the three composing parameters, an interesting point emerged. Lima, Karachi and Buenos Aires, which are the cities of the sample with predominant annual sky type different from 1-Overcast, were clustered together as one group. In other words, the clustering results indicate that sky type was a decisive parameter for grouping the cities. This can be due to the categorical characteristic of the parameter. At this point, it is important to recall some aspects regarding this parameter. Sky type is the only non-quantitative parameter of the clustering, for which criteria for clustering are more complex or, at least, not so evident as the treatment of numerical parameters. Its annual data was retrieved based on hourly and monthly absolute frequency (mode), limitations of which were already discussed in the section pertaining to weather data analysis. For instance, the decision on which type would represent annual conditions in Lima was convoluted by equal percentages among two types, while the relatively balanced sky type variation in Dhaka was not possible to be represented when one of the types had to be selected.



Case	Description
A	Baseline
B	Baseline, heterogeneous height
E	Baseline taller (H=70m)
G	Baseline tallest (H=100m)
H	Baseline as canyon

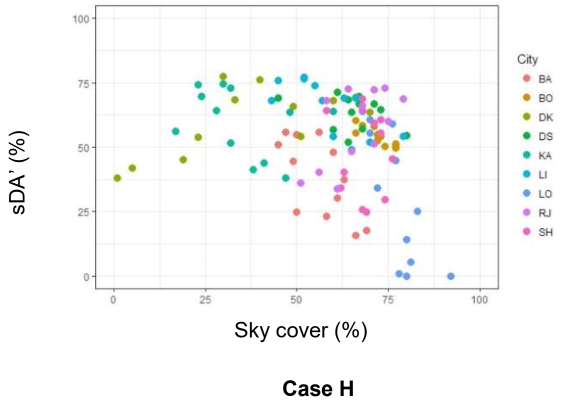


Figure 66: Scattter plot of monthly sky cover *vs.* msDA' of each city in a year.
Source: own author.

Considering all these aspects and the clustering results in which cities with diverse daylight climate characteristics were grouped together, a recommendation must be made for future studies: the inclusion of non-quantitative parameters should be carefully considered and, depending upon the case, anticipated by detailed studies. In case of sky type, further variations of calculi are incentivized, for instance, by using relative frequency instead of absolute. Plus, for future studies, the complexity of the analysis could be reduced by using the more traditional three sky types (clear, partly cloudy, and overcast). This might induce interesting, different grouping results. Nonetheless, this would also reduce the quality of characterization of the sky of each city, a simplification that this study avoided in favor of a more precise classification.

Ranking

The use of input parameters that have stronger association with performance could change the result of the dendrogram, achieving a higher similarity between daylight climate and performance. In other words, if other input parameters were selected, there is the possibility that the two generated dendrograms could be more similar to each other.

In this context, daylight related parameters that could have a stronger association with the results of performance among cities were shortlisted, reviewed, reorganized, and ranked. This ranking was built under the structure of the generated dendrogram of sDA' and msDA', from which a potential correspondence of each parameter to the results of indoor daylight performance were pursued.

Parameters primarily defined in this work were shortlisted: illuminance, sky cover and sky type. Data on irradiance was not included since an analysis confirmed its correspondence to illuminance data in the weather files here adopted. Latitude, which was indirectly considered in the analysis through the differenciation of cities per macroclimate (KGC), was now added directly as an input parameter, since in a preliminar analysis it appeared to correspond to the results of the dendrograms.

Those parameters were scrutinized according to different levels of information, including an overview of multiple facets of the same data. Firstly, global horizontal illuminance was analyzed in terms of average of the year, accumulated in the year; distribution over the year considering the standard deviation; hourly data organized in ascending order (Appendix E). Secondly, location of each city was observed: Southern or Northern Hemisphere; within the tropical, subtropical or temperate region (<23.5°, 23.5°-35.5°, 35.5°– 66.5°); between (sub)tropical or temperate region; distance from the Equator (random intervals); distance from the Equator within three intervals (maximum-medium-minimum). Thirdly, sky cover was approached in terms of average of the year and standard deviation. Finally, sky type was investigated in terms of yearly mode; by subdivision in three subgroups (overcast, partly cloudy and clear); by degree of variability along the year (low, medium, high >50%); and by hourly data (Appendix C3).

The final complementary ranking analysis was done considering the results of the previous dendrogram of annual and monthly sDA', organized into tables, where the above-mentioned parameters were listed. The quantitative or non-quantitative attributes of these parameters were described, distinguished by colors. The result of this process is presented in Figure 67. Noteworthy, this approach of analyzing and ranking each parameter was possible because the number of parameters was relatively small. For bigger amount of data, statistical analysis would be necessary a priori to reduce the number of parameters to the most relevant ones.

Taking these ranking results, when it comes to contrasting the Cluster 1 *vs.* Cluster 2 (Figure 67a), attention should be directed to the parameters or conditions that might explain the results regarding similarity among cities in terms of sDA'. The strongest equivalence is found when cities are compared in terms of their location in the temperate region. This might reveal that the location in higher latitude might influence or even define the result of the clustering. Illuminance accumulated in the year is also probably an indicator: the city with the highest value of annual accumulated illuminance, London (65.8 klx), became one separate group. Other potential correspondence is found by comparison of annual average illuminance of the cities; however, Shanghai could maybe be grouped together with London, since both have the lowest illuminance average. No clear relation was found with respect to other criteria. When the cities were compared within the subgroups, in this case only within the subgroups 2.1 and 2.2 of Cluster 2, relations were more difficult to identify. Only in terms of average illuminance a condition might be related to the result of sub-clustering: cities with levels between 36.0 klx and 44.8 klx composed one subgroup, while cities with average illuminance above 49.7 klx composed another subgroup.

When comparing Cluster 1 *vs.* Cluster 2 presented in Figure 67b, referring to the cities divided in the dendrogram pertaining to monthly sDA', three cases attract attention. Evidence of potential relation between parameter/condition and the result of clustering was found in the analysis of hourly illuminance data, in the differentiation by location in the Northern or Southern Hemisphere, and in the location by tropical/subtropical/temperate latitude. Like in the case of annual assessment, illuminance and latitude seem to play a role in the result of cities pertaining to similarity of indoor performance. Also, no clear relation was found when the other criteria were assessed. There was no relation observed among the subgroups within respective Clusters.

The findings of this additional analysis showed that the clearest evidence of relation between the result pertaining to similarity of performance and input parameter was found for illuminance (corroborating the results of statistical analysis as expected) and the latitude parameter. More specifically, in the case of msDA', the higher correspondence was found for hourly illuminance and latitude organized per hemisphere.

CLUSTER PER ANNUAL DATA	CLUSTER 1	CLUSTER 2								Relation*
	No subgroups	Subgroup 2.1.					Subgroup 2.2			
Cities	LO	DS	LI	RJ	DK	KA	BO	BA	SH	
Illuminance (lux) - Yearly, Average	25892,9	50790,4	54890,0	50478,9	50784,2	49709,3	44898,5	46507,9	36077,4	Partial
Illuminance (lux) - Yearly, Accumulated	658679,5	609409,9	596511,0	609484,4	432929,2	605747,3	538781,6	558095,3	310714,7	Partial
Illuminance (lux) - Monthly, Std. Dev.	4600,5	1665,8	2966,5	2556,2	1798,0	2667,6	1134,2	5328,1	2925,4	No
Illuminance - Hourly (1)										No
Latitude (S/N Hemisphere)	51,5	-6,8	-12	-22,9	23,7	24,8	4,2	-34,6	31,1	No
Tropical/Subtropical/Temperate (2)										No
(Sub)tropical vs. Temperate										Yes
Distance from Equator (3)										No
Distance from Equator (max, min, ave.)										No
Sky Cover (%) - Yearly	77,3	65,4	58,9	66,1	37,3	35,0	72,1	56,2	68,6	No
Sky Cover - Monthly, Std. Deviation	6,5	8,1	10,0	8,1	21,8	11,8	3,8	7,6	5,1	No
Sky type (yearly mode)	1	1	14	1	1	14	1	13	1	No
Sky type variability along the year (4)	low	low	low	medium	high	high	low	medium	low	No
Sky type - Hourly, graph radar chart										No

*Is there any evidence of relation between values of parameters and the resulting clusters of similarity?
(1) Organized in ascending order, visual assessment.
(2) Tropical/Subtropical/Temperado (latitude <23.5°, 23°- 35°, 35°- 66.5°)
(3) Latitude <10°, 10°-23°, >23°
(4) Low <25%, medium 25-50%, high >50%

(a) Basis: annual sDA'

CLUSTER PER MONTHLY DATA	CLUSTER 1					CLUSTER 2				Relation*
	Sub.1.1	Subgroup 1.2				Sub.2.1	Subgroup 2.2			
Cities	BA	BO	RJ	DS	LI	LO	SH	DK	KA	
Illuminance (lux) - Yearly, Average	46507,9	44898,5	50478,9	50790,4	54890,0	25892,9	36077,4	50784,2	49709,3	No
Illuminance (lux) - Yearly, Accumulated	558095,3	538781,6	609484,4	609409,9	596511,0	658679,5	310714,7	432929,2	605747,3	No
Illuminance (lux) - Monthly, Std. Dev.	5328,1	1134,2	2556,2	1665,8	2966,5	4600,5	2925,4	1798,0	2667,6	No
Illuminance - Hourly, ascending order										Yes, except for Dk.
Latitude (S/N Hemisphere)	-34,6	4,2	-22,9	-6,8	-12	51,5	31,1	23,7	24,8	Yes, except for BO.
Tropical/Subtropical/Temperate										Yes, except for BA.
(Sub)tropical vs. Temperate										No
Distance from Equator										Partial
Distance from Equator (max, min, ave.)										Partial
Sky Cover (%) - Yearly	56,2	72,1	66,1	65,4	58,9	77,3	68,6	37,3	35,0	No
Sky Cover - Monthly, Standard Deviation	7,6	3,8	8,1	8,1	10,0	6,5	5,1	21,8	11,8	No
Sky type (yearly, mode)	13	1	1	1	14	1	1	1	14	No
Sky type variability along the year	medium	low	medium	low	low	low	low	high	high	No
Sky type - Hourly, graph radar chart										No

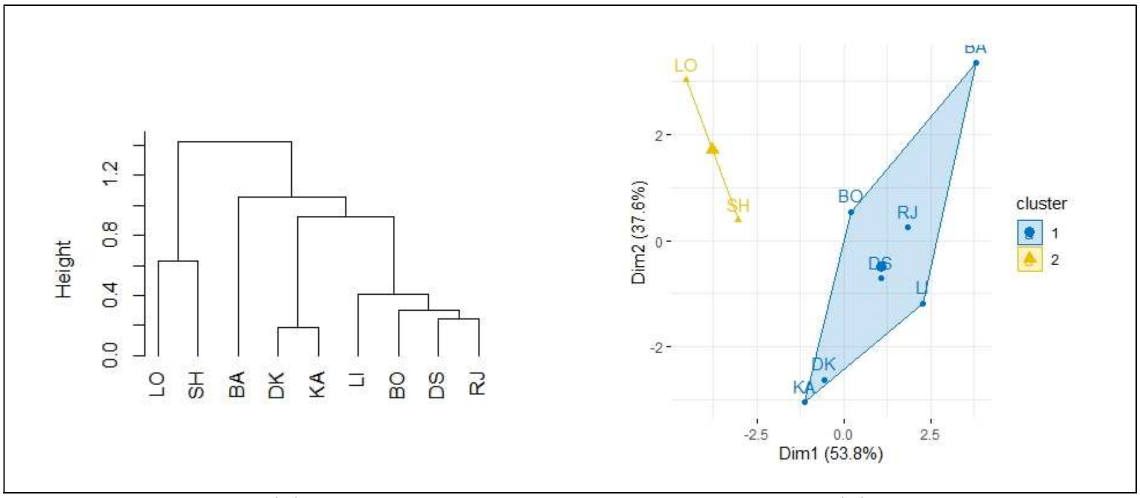
(b) Basis: monthly msDA'

Figure 67: Analysis of the dendrogram pertaining to sDA'.
Source: own author.

4.4.2.5. Cluster review: other parameters *vs.* indoor performance

Given these overall results, the agglomerative clustering produced using the three daylight climate parameters was reviewed. A new dendrogram was built to replace it, using two parameters that appeared to have a stronger relation to the results pertaining to performance in the previous analysis.

The two parameters were global horizontal illuminance and latitude. More specifically, monthly values of illuminance served as input, considering that their amount of data favor more robust results. Figure 68 shows this reviewed dendrogram (a) and the graph resulting from the repeated cluster analysis using k-means (b).



(a) (b)

Figure 68: Graphs of monthly illuminance data combined with attributes of latitude using (a) Ward d2 and (b) k-means method. Source: own author.

This new dendrogram based on monthly illuminance and latitude also resulted in two groups, one of them composed of London and Shanghai. Again, the result using k-means method corroborated to those from Ward d2, an important step to evaluate the cluster results.

On one hand, the new dendrogram of latitude and illuminance did not correspond precisely to the dendrogram of monthly indoor daylight performance of Figure 62. In the dendrogram of msDA'. The group of London and Shanghai is also composed by Dhaka and Karachi, two cities that are also in the Northern hemisphere.

On other hand, this new dendrogram reached a higher degree of similarity to the one of performance than the three daylight climate parameters combined. This is specially observed towards msDA', in which the similarity among Lima, Dar es Salaam, Rio de Janeiro and Bogotá turned then closer in their group. This result signals that the similarities of illuminance and latitude data of cities, organized under certain conditions, could be an indicator of their similarity in terms of monthly sDA', measured on the ground floor of simulated buildings in dense urban context, with limitations that are exposed in the next section.

4.4.2.6. Implications of the results for other cities

The classification of cities using as criteria the similarity of indoor daylight performance repeated in part the classification using the similarity of latitude and illuminance. This result is especially valid for the analysis of monthly data conducted in the last stage of the research, considering both clustering methods: the hierarchical Ward d2, and the non-hierarchical k-means. Indeed, from the nine cities of the sample, seven (77.8%) were grouped in the same clusters when the two corresponding dendrograms were compared. The remaining 22.2% of cities that were positioned in a different group point out that other parameters influence the classification by indoor daylight performance: the urban morphology, the selected metric, and/or other climatic parameters.

Although an exact correspondence between the dendrograms was not found, this better result considering latitude and illuminance *versus* indoor daylight performance permits to consider the application of this specific result to other cities that do not compose the sample. Expressly, cities worldwide can be grouped based on the monthly data of latitude and illuminance, as a way to potentially anticipate their similarity in terms of monthly indoor daylight performance. More than that, in order to achieve sufficient daylight indoors, the results pointed out that attention should be given to cities located in high latitude that present relativelly low values of illuminance. This concept is not a novelty, but the results of the applied method provide a path to a further step: the identification of cases of reference for additional analysis.

Considering the clustering results of latitude and illuminance for the nine cities of the sample (Figure 68), and data of latitude and irradiance for all 41 megacities (Table 22), an example can be given. Noticeable, illuminance is not provided in this table, but it can be explored in terms of its direct correspondence to irradiance, according to the equation Eq. 1 (Treado and Kusuda, 1981). Taking one of the megacities of the sample as a reference, comments can be addressed about the other ones around the globe.

The city of Shanghai serves as a reference. Figure 68 (a and b) shows that Shanghai pertains to Group 1, and it is almost in a position to 'migrate' to the other group. In fact, this city is closer to Group 2 than London, and has a latitude of 31.17° and GHI of 1327 KWh/m^2. As follows, it can be inferred that all cities that present higher values of latitude and lower values of GHI than those of Shanghai would tend to require more attention to promote indoor daylight performance under dense urban context. This can also apply to the cities with values approximated to these thresholds.

Following these criteria, examples of megacities of this list that could be at risk of insufficient performance under intense densification and should be deeper investigated are (Table 30):

Chengdu, Chongqing, Beijing and Tianjin (China); London (UK, already analyzed); Tokyo and Osaka-Kobe (Japan); Istanbul (Turkey); New York (USA); Paris (France); Moscow (Russia). These 12 megacities account for almost 30% of future urban agglomerations with more than 10 million inhabitants.

Table 30:

Megacities with potential worst conditions for indoor daylight performance.

#	City	Country	GHI (KWh/m^2)	Latitude (°)
1	Istanbul	Turkey	1492	41.00
2	Osaka-Kobe (Osaka)	Japan	1476	34.63
3	Tokyo	Japan	1457	35.55
4	Tianjin	China	1412	39.15
5	Beijing	China	1392	39.90
6	New York-Newark (NY)	USA	1354	43.05
7	Shanghai*	China	1327	31.17
8	Paris	France	1145	48.86
9	Moskva (Moscow)	Russian Federation	1046	55.76
10	Chongqing	China	1023	29.55
11	London	United Kingdom	1017	51.50
12	Chengdu	China	918	30.66

*Reference. Source: own author.

Following the findings, a map of the 41 megacities and their potential classification of indoor daylight performance as per msDA' is illustrated in Figure 69.

Figure 69: Megacities identified by potential similarity per indoor daylight sufficiency.
Note: Group 1 (green dots); Group 2 (orange dots).
Source: adapted from world map of megacities in 2030 by UNESCO (2018).

In this Figure 69, the dots in green color indicates the evaluated cities: those that have a high potential of achieving minimum necessary levels in terms of daylight sufficiency if the urban conditions are not too dense. The dots in orange characterize cities that are potentially vulnerable to urban densification, tending to achieve intermediate or insufficient daylight performance levels. The gray dots represent the remaining megacities by 2030 that would tend to present sufficient conditions to daylight indoors, like the green ones. Reinforcing, these results were based on monthly sDA'. Additionally, the classification in this map suggests a tendency of similarity, which is not necessarily 100% precise.

At this point, comments can be described for urban design.

One could infer from the map above or the cluster analysis that, since the cities would be divided into two groups, they could also compose two groups of different demands for an urban design for indoor daylight. However, this is not the case. The resulting number of two groups calculated through the Ward d2 method is not necessarily an indicator that two groups of urban design strategies for densification should be made to make cities meet minimum daylight performance levels as per the selected metric of this study.

This aspect can be discussed using Figure 45: there were urban cases that achieved the goal of minimum levels in all cities, like the baseline or the heterogeneous skyline. And there were urban cases that underperformed in all cities: for instance, when the height of the buildings in baseline was almost tripled. An advantage of this approach through dendrograms is that a detailed investigation targeting the cities with a higher similarity within subgroups in the clusters could clarify, quantify and/or characterize the necessary differences in design strategies among the groups to promote indoor daylight.

Appraisal

General observations of the methods used in this last phase of the research can be done.

The adopted advanced statistical techniques had a relevant role since the early stages of the research, influencing the definition of the number of input and output parameters. Therefore, for future studies that aim to adopt statistical analysis, it is recommended to incorporate the guidance of this science in the entire process, including for the detailed definition of the experiment. In this study, due to the higher number of inputs for analysis, the assessment per month is considered more robust from a statistical perspective.

Given the amount of data generated in the process, the use of computer tools combined with sophisticated statistical analysis proved beneficial for generating results with enhanced accuracy. However, given the characteristics of this research, some of the results could be (and were) anticipated, with a certain degree of accuracy, without the use of statistics.

Overall, the clustering method Ward d2 was valuable, since it allows combining different parameters in one visual tool. From a graphic standpoint, the dendrogram might offer designers a useful perspective of the results due to its simplicity and visual organization. Complementarily, the k-means graph reproduces the results of a deeper analysis, in which the comparison is conducted under a series of intermediate rules.

It is relevant to note that only two cases of performance would be sufficient for the clustering, but more cases were included to increase the robustness of the results.

Here, the study of cluster combined with ranking was feasible because the number of parameters was intentionally and carefully restricted. In future studies that use more parameters and variables, an inversion of the methodological sequence might be interesting. Before the conduction of the clustering technique, an extensive analysis of the correlation between performance and daylight-related parameters could be conducted to a) reduce the number of parameters to serve as input to create the clusters, b) increase the potential of correspondence between the cluster of performance *versus* the cluster of multiple weather-related parameters. In this case, the intensive use of specific programming languages for producing scripts and statistical tools might be necessary.

The results of the clustering using the k-means method were equivalent to the ones generated by the Ward d2 for the main purpose of comparison in this work: both yielded the same cities in each group, and this happened for annual and monthly data on performance (sDA') and climate. Because of that, the comparison could be continued using only one of the methods to avoid redundancies. The Ward d2 method visualized through dendrograms was selected as the main tool for conducting all the rest of the analysis. It demonstrated to be simpler to comprehend in the case of this research since the number of elements for analysis was not excessive. Indeed, for instance, in comparison to the k-means graphs, the dendrogram facilitated the observation of cities that are most similar to each other in a way that is suitable for non-experts in statistics, being simultaneously able to communicate complex information for designers[42]. Additionally, from its nature of an interconnected 'tree', it presents the 'history' of internal subdivisions within the generated groups, which is an informative advantage when compared to the k-means graphic. In future studies, other clustering methods could be applied to verify if the tendency discussed here is repeated.

The results of clustering for annual and monthly time frames for the selected metric for indoor

[42] Indication from an activity in which these graphics were discussed with a small sample of designers and students of architecture and urbanism.

daylight performance differed. This divergence was expected, reinforcing the need for sensibility studies towards climate variability and the evaluation of urban daylight performance. Future investigations that also take climate seasonality into account should be considered, especially concerning the results of the cluster by performance data organized by month. In future studies, the clustering of monthly data organized by season could also generate interesting results to be explored in the comparison among cities. At this point, the concept of the recently developed metric RDA (Dogan and Park, 2018) might be an alternative to consider. It was not applied here because it is oriented towards residences in high latitudes; adaptations might be required for application in other conditions. The map of megacities that was generated by the combination of illuminance and latitude data corroborates with these authors in terms of the potential need for a differentiated metric for higher latitudes. A higher number of urban design strategies might be also needed in comparison to regions closer to the Equator.

Additionally, the method of comparison of clusters here exposed can serve to review the concept of zoning territories based solely on climate conditions, by reinforcing the focus on simulated data of performance. After all, these are more relevant for design. For instance, the bioclimatic daylight zoning of Brazil, developed by Fonseca et al. (2017) targeting building performance optimization, included in the classification the parameter sky cover as a key criterion. This parameter might be important for studies on daylight under certain conditions. However, if the proposed zoning is to be considered for the design of urban areas in Brazil, their criteria of classification might require a review. As this study found, considering the metric, geometries and other aspects here adopted, the parameter sky cover is not so relevant for indoor performance.

Finally, the correspondence between the groups of cities formed considering their data extracted from weather files *versus* their data from simulated indoor daylight performance achieved a better result in the last phase of classification and comparison. However, it was not completely analogous in none of the tested cases. Therefore, it was not possible to ensure that the analysis of a few parameters will indicate with 100% accuracy the similarity of cities in terms of indoor daylight performance. Therefore, considering the methods, conditions, and assumptions of this study, the evidence support that the hypothesis of this work is refuted.

5. Conclusion

5.1. Summary of the conclusion

The hypothesis that the *"classification of cities according to a few daylight-related parameters is enough to indicate daylight sufficiency conditions indoors in a dense, compact urban context"* was refuted. For achieving the results, the classification of cities was conducted using grouping and ranking techniques, as well as cluster analysis. Daylight-related parameters were established in terms of global horizontal illuminance, sky cover, sky type, and latitude. Daylight sufficiency indoors was obtained as annual and monthly Spatial Daylight Autonomy (sDA' and msDA'), on the ground floor of buildings simulated under diverse conditions.

The goals of this research were accomplished. Studies of indoor daylight performance through computer simulation, guidelines, metrics, and parameters were reviewed; methods for comparison of different data types were integrated; relevant inputs for daylight simulation were identified; variations in indoor daylight levels due to an increase in urban density under different climates were analyzed, and the hypothesis was evaluated.

Among the results, it was found that the classification of cities based on similarity considering few daylight-related parameters can be an indicator (not an assurance) of their potential similarity in terms of monthly indoor daylight performance. The potential to find similarity of performance (mSDA') among cities was higher by combining illuminance and latitude data rather than the other tested parameters combined. These general results can be used to filter cities by climate data for the further in-deep analysis of daylight performance.

Other broad results and comments can be pointed out. The increase of urban density does not necessarily degenerate indoor performance, as observed in one test using heterogeneous building heights. Low percentages of window-to-wall-ratio (WWR) in lower floors of simulated buildings undermine the achievement of minimum daylight performance. This is an alert to current prescriptive-based building guidelines that do not consider the urban context. Weather data for daylight analysis of cities shall be improved in terms of accuracy and availability. The variation of the time frame of a metric does alter the results of similarity among cities. Therefore, they should be carefully pre-selected. About the megacities grouped by similarity using cluster techniques, London was considered different from the rest of the sample in terms of sDA'; for msDA' London, Shanghai, Dhaka and Karachi comprised a group. Some of the urban models (under)performed in all cities simultaneously, others not. Further analysis of clusters by performance could also serve to indicate whether cities in the same subgroup would demand very different urban strategies for promoting indoor daylight on the assumption of densification. Given the characteristics of this sample, this is probably not the case.

The use of the same 3D models in various cities favored the comparative approach on the same basis, which was relevant for this research. However, in real conditions, the replication of the same urban design in different cities is not recommended. Adaptations based on detailed, case-by-case studies are needed, and for these tasks, the use of computer simulation tools like those adopted in this study are not only useful, but indispensible.

Highlights of this research include that a method for climate and performance comparison was developed and tested using advanced statistics for a sample of nine worldwide megacities expected to exist by the year 2030, following an innovative framework and adaptations in software for this study. From the results of the sample clustering and weather files, comments were extended to twelve megacities, therefore comprising for 51,2% of the total worldwide urban agglomerations above 10 million inhabitants.

In future studies, the methods applied in this research can be repeated and expanded, incorporating also advances in the fields of daylight for health, energy savings, the sustainability of the ecosystem, and beyond.

A detailed overview of the conclusion is exposed in the next section.

5.2. Detailed conclusion

Daylight is proven to be beneficial for human development and health, as well for energy savings by replacing artificial lighting. Its properties vary according to atmospheric conditions, and its characteristics and availability indoors can be affected by surrounding configurations, including urban ones. From this perspective, this study is oriented around the field of urban daylight climate. Its results aim to find application in urban design and planning, with the intent to provide relevant information for design. As to its values, it aspires to save resources through comparative studies before a further detailed city-by-city investigation and design proposal, and to indirectly propose a path for stimulating international interchange of knowledge among designers and academics for indoor daylight solutions in dense, compact, vertical urban agglomerations.

This study proposed a framework to identify whether cities with similar daylight related parameters would exhibit similar indoor daylight performance. A correspondence could serve as an indicator that cities could be pre-selected for deeper, complex studies of indoor daylight performance based on daylight parameters that are relatively easy to process, like the ones read directly from weather files.

The hypothesis was that "*classification of cities according to a few daylight-related parameters is enough to indicate daylight sufficiency conditions indoors in dense, compact urban context*".

Among daylight parameters, the initial focus was on the climate related ones. Three parameters extracted from weather files were selected from literature to characterize daylight climate: global horizontal illuminance, sky cover and sky type. Later, other parameters were analyzed, including latitude.

Performance was also selected based on consolidated literature on the topic of indoor daylight; it was restricted to its component daylight sufficiency, or minimum illuminance levels (lux), based on the concept of Spatial Daylight Autonomy (sDA') developed for architectural assessment. The indoor performance of each city was obtained through a theoretical urban context using computer simulations.

The comparison and analysis were supported by clustering methods using both dendrogram and k-means, as well as correlation and ranking techniques. During the process, the similarity of cities regarding daylight aspects was identified, observations about design characteristics that favor daylight were highlighted, necessary steps for daylight simulation were extracted, and initial design guidelines were set, among other aspects.

It is important to note that studies of comparison and grouping of cities based on weather data or by indoor daylight dynamic performance data (e.g., in U.S.A. and in Brazil) were used as main references. To the best of the author's knowledge, no other study proposed the comparison of daylight related parameters *versus* indoor daylight performance in the context of urban daylight climate using such a framework like the one proposed here.

5.2.1. The Main Contributions of the Study

5.2.1.1. The main results (general):

- Hypothesis: refuted, considering the methods, conditions and assumptions of this study.

- Clusters of illuminance combined with latitude, both organized under a specific format, exhibited a higher correspondence to the clusters generated by indoor daylight performance (mSDA') than the cluster composed of three daylight climate parameters combined initially (illuminance, sky cover and sky type). In other words, the potential to find similarity of performance among cities was higher by combining illuminance and latitude data than by using the other daylight-related data. In this case, 'less was more': the use of two parameters provided better results in the comparison than the use of a higher number, reinforcing that a critical assessment of parameters should be done before conducting the cluster process.

- Small percentages of WWR might not provide minimum conditions of indoor daylight performance (lux) on the lower floors of buildings under certain urban conditions, even if the indoor characteristics in terms of dimension and reflectance of surfaces favor daylight. These results reinforce that design guidelines shall take the urban context into account.

5.2.1.2. Answers to the research questions

- The similarity of cities considering a limited number of daylight related parameters can be an indicator (not an assurance) of their potential similarity in terms of indoor daylight performance in a dense, compact, verticalized urban context. Considering the three selected daylight climate parameters (illuminance, sky cover and sky type), organized in certain formats, combined and contrasted under the conditions tested here, the answer is negative. Tests with combined data of illuminance and latitude showed a better correspondence, but not equivalence.

- Cities with similar outdoor daylight climate do not necessarily have similar indoor daylight performance in a dense, verticalized urban context.

- Cities can be grouped by similarity in terms of daylight-related parameters and indoor daylight performance using clustering techniques. Other possibilities can be further explored.

- Different simulation variations do alter the results of daylight performance similarity among cities, depending upon the criteria of grouping, and considering the parametric tests conducted in the urban grid and selected cities.

- The variation of the time frame of a metric does alter the results of similarity among cities, as demonstrated here using sDA' and its derivate msDA' through clustering techniques. This difference reflects dynamic variations of daylight conditions throughout the year in the cities.

- In the sample of cities, London is different from the rest of the sample in terms of sDA'. In terms of msDA', the cities of London, Shanghai, Dhaka and Karachi comprised a group, while the remaining cities comprised another group according to the defined criteria of similarity.

- The increase in urban density (compactness) affected indoor daylight levels in different ways. Due to certain homogeneous building heights, indoor daylight levels started to be strongly compromised, independently of the tested location. The increase of density using heterogeneous heights has been confirmed as promising alternative to favor indoor daylight, and should be considered for application in guidelines for urban design.

5.2.1.3. Highlights

- Studies on computer simulation, classification systems, climate and design parameters, metrics, guidelines for design favoring indoor daylight were reviewed.

- A method for climate and performance comparison is developed and tested using advanced statistics and a sample of ca. 22% of worldwide megacities. To the author's knowledge, such comparison process was not proposed before.

- From the analysis of the sample, results were extended to all future megacities. These were also preliminary characterized in terms of daylight as a basis for urban design.

- Weather data were processed using software solutions in which new features were developed for the purpose of this study.

- Preliminary studies on indoor daylight performance using a representative dynamic metric[43] were conducted, considering the effect of design of dense urban sites, including shadowing and inter-reflectances in higher levels than those found in literature (ab=4 or 6).

- Limitations of the proposed approach and opportunities for future studies were discussed, as summarized in the next section.

5.2.2. Overall Discussion

For this investigation, a framework for the test of hypothesis was proposed based on literature review and a pilot computer simulation of daylight performance. Discussions regarding the framework itself, as well as its intermediate methods and results, are summarized as follows.

5.2.2.1. The Selection of Cities

Method:

Cities were selected using Geographic Information System (GIS) based on three criteria: 1) population above 10 million inhabitants by 2030, or megacities, distributed in the globe, for which densification might be considered in terms of design, 2) differences in general climate, for which the author of this study selected the Köppen-Geiger Climate, a well-known temperature-based classification, and 3) global horizontal irradiation (GHI), which is a parameter strongly related to daylight.

[43] According to Heschong (2012).

Main results:

Nine megacities were selected: Buenos Aires, Bogotá, Dhaka, Dar es Salaam, Karachi, Lima, London, Shanghai and Rio de Janeiro.

Discussion:

The use of GIS as a tool for pre-selection of the cities was valuable: it accelerated the process and required a priori criteria for the selection, favoring clearer and assertive choices. This step benefited from current technology, in which different maps are available for such use.

Of course, the selection of cities is dependent upon the databases and criteria of selection. For instance, the climate classification by city can vary across databases due to differences in algorithms, location of meteorological stations, period and regularity of measurements, standardization of reports, the impact of alterations in the landscape, and urbanization on the measured parameters, etc. The large area and landscape variety of megacities add complexity to the topic. It is hereby recommended that further evaluation of the climate classification by the city be performed in specific studies, having in mind these aspects. Following these investigations, the resulting cities used in this study could be altered. However, giving that the number of cities above 10 million inhabitants is higher closer to the tropics, the few numbers of cities in higher latitudes would prevail if the same criteria of selection are chosen.

In future studies, the selection criteria can be reviewed to include more megacities in higher latitudes for exploring potential differences in the comparison. Because they are few, cities of a smaller population could be considered – considering that, in these cases, densification by increasing compactness and verticality might not be appropriate urban design strategies.

Complementary information available through GIS could be included as layers in the selection of cities. Factors like the interest of cities in shared design solutions, or similarity by topography, street characteristics, vulnerability to phenomena such as the Urban Heat Island, 'bioclimatic' classification for thermal comfort, constructive techniques are examples.

5.2.2.2. The Assessment of Climate Data

Method:

Monthly and annual data on daylight climate, global horizontal illuminance, sky cover and sky type for each of the nine selected megacities were compared. Sky type was obtained as per CIE definition with a specific software for architectural indoor daylight assessment, APOLUX.

Main results:

In terms of global horizontal illuminance, the two cities of highest latitudes within the sample show also the highest variation throughout the year: London and Buenos Aires. London exhibits the lowest annual average, followed by Shanghai.

Considering sky cover, London shows the highest percentages, followed by Bogotá. Karachi shows the lowest percentage, followed by Dhaka.

As per sky type, in all cities the type 1-Standard overcast predominates, except in Buenos Aires, Karachi and Lima.

Discussion:

It was observed that some of the megacities did not have (enough) data available in the two climate databases initially considered for this study: Meteonorm, and the free one provided by EnergyPlus[44]. This fact represents a complication for studies that depend upon climate data, and the absence of data for urban population centers might cause concerns. The data availability was a determinant for the selection of the nine megacities for analysis.

On the topic of conversion models, some daylight parameters are currently based on radiation data. Measured data are necessary for improving the accuracy of assessments, especially within the tropical and subtropical regions. These regions are going to experience major urban growth in the upcoming decades, and that is where the highest number of megacities will be concentrated.

5.2.2.3. The Assessment of Indoor Performance

Method:

The dynamic metric spatial daylight autonomy (sDA) was selected based on studies summarized by Heshong (2012), which pointed sDA as a 'representative' metric among several analyzed. In order to investigate climate variability through the year, the metric monthly spatial daylight autonomy (sDA) (Bauer and Wittkopf, 2015) was adopted, since it is easily compatible with the available format of climatic data. Thresholds were established for sDA, disregarding function (residential, office, multi-purpose room), inspired by current studies on daylight performance in urban context, i.e., Saratsis (2015) and Nault et al. (2017). Once the concept of sDA is well stablished in literature, but the thresholds diverge, here the term was identified as sDA'. The selection of input parameters focused on the goal of providing minimum

[44] <https://energyplus.net/weather>, Acessed Nov/2017

daylight levels in cities that might have interest in combining densification and verticalization for achieving better designs in urban agglomerations. Indoor daylight performance (sufficiency) data, based on the concept of spatial daylight autonomy (sDA), were obtained in ground floors of urban models based on the LCZ 1-Compact High Rise classification scheme by Stewart and Oke (2012). Adopted software included DIVA-for-Rhino and Grasshopper Ladybug/Honeybee.

Main results:

From the exploratory simulation, it was clear that the inter-reflection between façades is a relevant aspect for indoor daylight in a dense urban context, as well as the percentage of WWR. The setting ‘ambient bounces’ (ab) was relevant for the quality of results, as well as the speed of the simulation, as other authors pointed out. It was observed that a decrease in the value of ab indicated also a decrease in the sensitivity of the results to variations in the model.

The input settings derived from the results of the exploratory simulation were confirmed to be useful for obtaining the necessary different outputs in the final simulation, without the need for exhaustive number of runs.

From the final simulation, several cities achieved minimum levels of sDA’ under the same simulated conditions of urban densification. London was a city that presented a bigger difference. This result reinforces the fact that latitude might be a very influential parameter when it comes to indoor daylight performance results using the chosen metric.

Some initial guidelines for daylight design in urban context were defined. The window-to-wall ratio should be defined taking into consideration the surroundings. Percentages of WWR close to 60%, which are higher than what some design guidelines recommend and higher than the mean of 30% found in a sample of residential buildings in the compact, verticalized city of Hong Kong (Lam, 2000), were not sufficient to allow minimum levels through the year under the conditions of this study. A solution might be to vary WWR according to the position of the floor in the building height, considering the fact that upper floors would have greater access to daylight. The reflectance of the walls, outdoors and indoors, should be as high as possible, having in mind comfort issues, like the potential of glare, as well as feasibility under real conditions, among other aspects. Referring to real conditions, the effect of pollution should be further investigated; here, a few tests simulated the reduction in the visible transmittance of glass due to pollution (Tvis=30%), but the simultaneous reduction of the reflectance of the surfaces, and its effects on the scattering of light itself were not experimented with, since it did not represent the focus of the study. On the other hand, a simulation of outdoor walls with high reflectance, tested as a mirror, generated the maximum result for all cities (sDA’=100%). This test, although very theoretical, together with the experiments involving lower reflectance, reinforces the importance of the finishing of surfaces in design for performance. Thus, the frontal obstructions of the windows that were tested in this study also act as reflectors, to a certain extent. As in Cheng et al. (2006a), it was observed that the built area can be increased while maintaining the similar level of performance if the urban morphology is arranged accordingly. In other words, it is possible to densify while keeping intended levels of daylight through proper design. Specifically, this was observed for one tested case: the grid with heterogeneous height. However, for the tested conditions, considering a homogeneous grid, the building height of 70m started to compromise indoor daylight, representing a limit to be considered. The typology of the canyon generated worst results in comparison to the model of urban grid with heterogeneous height, of same FAR. It is important to remember that an intermediate level of bounces was considered in the final simulations (ab=4), and this might have contributed to pessimistic results. In contrast, all the test rooms presented sizes that would favor daylight sufficiency, bringing optimistic results, assuming that the architectural design tends to promote daylight.

Discussion:

The indoor daylight simulation of a simplified model before the analysis of a more complex one was valuable for saving time and gaining sensibility of more important parameters.

The theoretical urban baseline model in the grid that was parametrically simulated generated useful results for applications in urban design. Because its characteristics are associated with an existing classification system developed for urban climate studies in general, the results here presented could serve for a dialogue with other fields. However, this does not mean that the real implementation of the same urban design model in different cities without the consideration of local peculiarities is endorsed. Aspects such as the analysis of local culture and urban development goals are fundamental.

The use of simplified or ‘worst case’ conditions contributes to the feasibility of studies on indoor daylight performance, especially considering that information regarding detailed architectural elements is not necessarily available during urban design and planning. The use of open floor plans in this study is an example of such simplifications; as a consequence of the absence of internal partitions in the model, the results obtained from the urban simulation here might be underestimated due to lower inter-reflections.

The accelerated development in computer technology will expand the possibilities for exploring other simulation conditions, as well to review the conditions tested in this study considering different levels of detail.

5.2.2.4. The Comparison of Climate and Indoor Daylight Performance

Method:

Climate and indoor daylight performance were compared using two different time frames: annual and monthly. Different performance results were compared considering results of variations in urban morphology. The comparison was done using a visual analysis of graphs and clustering analysis (Ward d2 and by k-means). Based on the results of this step, a broader group of parameters extracted directly or indirectly from weather files was reconsidered for clustering analysis: they were listed in a table, characterized and ranked according to quali-quantitative attributes. Two parameters were selected and composed a new dendrogram, which was contrasted to the correspondent one of daylight performance.

Main results:

For the conditions selected for the purpose of this work (input settings, parameters, metrics, software, urban model, etc.), there is more evidence in refuting the hypothesis.

In the first round of clustering using Ward d2, two groups were found to be optimal to separate the cities. This number of two groups served as input for the k-means, which then, interestingly, retrieved results of similarity among cities that, for the purpose of this research, were considered equivalent to those provided by the first method.

Considering the dendrogram of indoor daylight performance, results for sDA' and msDA' differed. In the dendrogram of sDA', London alone composed a group, highlighting its differences in performance; this resulting number of groups is coincidental with the one anticipated by graphs of annual performance in all simulated cases: London underperformed in the majority of cases, unlike the other megacities. In the dendrogram of msDA', cities in the North Hemisphere and distant from the Equator were grouped together, indicating that these two conditions related to latitude appeared to influence the results of the clustering.

The dendrogram of annual daylight climate (illuminance, sky cover and sky type combined) differed from the monthly one because of Dhaka. This city joined Karachi, Lima and Buenos Aires in the monthly analysis. This unexpected result of similarity by city indicated that the parameter sky type affected the clustering considerably.

From the analysis of correlation using monthly data, the more densified the model was, the less performance was related to the characteristics of sky cover of the tested cities. A strong correlation was found between illuminance of the cities and the simulated indoor daylight performance.

A final dendrogram of combined illuminance and latitude showed a better correspondence to the one of performance (msDA’) than the dendrogram of daylight climate, but not equivalence.

Discussion:

The clustering methods were more efficient to compare the cities than the visual method. The clustering allowed the comparison of different data types that contributed to the evaluation of the hypothesis. The results here presented are a consequence of the selection of the clustering method among the available options: Ward d2, visualized in a dendrogram. This tool demonstrated to be valuable due to its straight-forward visual organization as a ‘tree’, showing the cities that are more (dis)similar, a strategical ‘filter’ for selecting cases for other complementary studies. The results of the k-means supported the ones generated by the Ward d2.

The results for annual and monthly time frames for the metric sDA’ differed, reinforcing the need for attention to the climate/temporal variability for urban daylight performance.

Annual and monthly, the cities were grouped into only two clusters despite their diversity of irradiation levels and climate classification that served as criteria for their selection. This is not necessarily an indicator that two types of urban design strategies are required to make cities meet minimum daylight performance levels under the metric selected in this study. A detailed study of cities with higher similarity could contribute to clarify this point.

In the tested conditions it was found that global horizontal illuminance has a strong relation with resulting indoor daylight performance, while this relation is weaker for sky cover, especially when the simulated urban morphology was denser. For monthly data, variations in the urban geometry can substantially alter the resulting correlation between the tested parameters, namely illuminance and sky cover, *versus* indoor daylight performance.

The analysis of latitude and illuminance combined presented an interesting result of correspondence to the result of daylight indoor performance in terms of msDA’. From this point, an analysis considering daylight data of the other megacities was conducted. However, as the correspondence was not precise (100%), the main hypothesis of this work was refuted.

5.2.3. Challenges Overcome

- Research interface of different fields: urbanism, computer simulation, daylight climate and statistics.
- Collaboration of developers to adapt or include features in software necessary for the development of this research, e.g. software Climate Consultants and APOLUX.

- Relatively scarce literature on urban daylight climate.
- Resolving confusion of terms in literature, reinforcing the need for clarification of concepts and the borders of approaches. For instance, the use of the term 'sunlight' in studies without specifying the range of the spectrum or the scope (image or non-image forming), can compromise the accuracy of interpretation.
- Communication with experts in statistics during the process emphasized the need for careful distinction of concepts for conveying ideas, e.g.: terms such as simulation, parametric model, variable and parameter have different meanings than in urban computational modeling and assessment.

5.2.4. Opportunities for Future Study

As a continuation of this study, additional parameters could be evaluated. Among other parameters, sun hours, ground reflectance, presence of vegetation, irregularities in topography, glazing properties, could be included in future analysis. A larger number of urban morphology variations, and the comparison using another metrics could increment the level of information regarding daylight. At this point, complementary studies of whether the same metric and its thresholds are suitable for all cities are also needed, and might require a task force of experts to achieve a conclusion such as the one presented by Heschong (2012).

Investigations on seasonality in indoor daylight performance for cities can be explored using specific metrics like the one proposed by Dogan and Park (2018) for residences in high latitudes, considering the pertinence and eventual demand for adaptations for other conditions. Complementary statistical methods such as factorial analysis could be used for reducing the number of simulations, or Principle Component Analysis (PCA) to investigate interrelations among variables to map information - techniques adopted by different authors, e.g. by Martins et al. (2014). Regression methods could be tested to reduce complex parts of simulations through mathematical metamodels, as proposed by Nault et al. (2017). The use of simulations with higher levels of inter-reflections outdoor, as per Santos et al. (2017), could be continued. Aspects of daylight quality, such as variations in the spectrum, and comfort issues such as glare could be approached using recently developed tools such Alfa (Solemma, 2018) properly validated for the use in different conditions. The proposition of guidelines could advance with the use of automatic optimization process using specific software for that purpose. To what extent the differences in performance indicate that cities require different urban design strategies needs to be further investigated. The implementation of examples of guidelines based on these theoretical researches in practice could be tested. The effect of stochastic models on the differences of results in the selected software for daylight performance could be investigated and presented in detail. The potential of energy savings with daylight in the life cycle of buildings in the urban context could also be accounted economically.

Summarizing in topics, future opportunities for study include:

1) Application of alternative or complementary statistical methods for the selection of input parameters and their values, as well as for the sensitivity analysis of outputs.

2) Expansion of the number of parameters and urban design conditions simulated, as well as their levels of detail to support the development of guidelines.

3) Development of a classification system for the cities based on their common daylight characteristics.

4) Analysis of the pertinence of: the use of the same metric and thresholds for all cities, of the inclusion of upper limits of daylight levels with daylight barriers (blocking shading systems) for visual comfort, as well as the benefits of dynamic metrics that accounts for seasonal variability.

5) Expansion of the methods of analysis to combine image and non-image aspects through new metrics, software and systems.

6) Investigation of the applicability of resulting daylight guidelines for urban design in real conditions, and considering multiple actors and interests in urban development.

7) Comparison of the economics of energy savings in urban context by the adoption of proposed guidelines for daylight indoors *versus* those provided by existing guidelines or ‘built as usual’.

8) Investigate cities with a higher similarity within subgroups in the clusters, aiming to clarify the demand for different urban design of strategies among them.

5.2.5. Scientific Publications and Presentations Arising from this Study

SANTOS, I. G. dos; AUER, T.; SOUZA, R. V. G. de. Optimized indoor daylight for tropical dense urban environments. Ambiente Construído [Built Environment], v. 17, n. 3, p. 87-102, Jul. /Sep. 2017. ISSN 1678-8621. Open Access.
Note: Scientific peer-reviewed publication. This is considered "*the main national scientific journal covering the whole area of Built Environment Technology*"[45] in Brazil, lead by the academic, non-profit organization ANTAC[46].

SANTOS, Iara; SINGH, Shipra; MORAIS, Livia Miethke. Climate comparison of cities based on human comfort for applications in the urban design and planning. Oral presentation (selected by committee). 10th International Conference on Urban Climate/ 14th Symposium on the Urban Environment - ICUC 2018, New York.

SANTOS Iara, HAN Jing, LI Mohan, SHAO Rongdi, LIU Xiaotong, JI Yunzhu. Exploring indoor daylight variation in mega-tall building according to height. International workshop of scientific research proposals. The 2018 International Doctoral School of Future City and Architecture – College of Architecture and Urban Planning (CAUP), Tongji University, Shanghai, China. 2nd place, category Vertical Urbanism. Co-advisor: Dr. Peng Du.

SANTOS, Iara. Guidelines for urban design: promoting energy and environmental performance of buildings in dense context through daylight. Poster presentation and debate. 2nd Interdisciplinary Israel-TUM Winter School. Climate and Energy Policy in an Era of Technological Change, 2018. Academic lead: Prof. Dr. Miranda Schreurs.

[45] http://antac.pcc.usp.br/institucional/projetos-liderados, Accessed: Nov/2018. Original text: "A revista é o principal periódico científico nacional que abrange toda a área de Tecnologia do Ambiente Construído." Translation by this author.
[46] https://seer.ufrgs.br/index.php/ambienteconstruido, Accessed: Nov/2018.

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Appendices

Appendix A: Groups of climates

Table 31:

Climate classification groups according Köppen-Geiger.

Group	Description
A	**Equatorial climates**
	Af: Equatorial rainforest climate
	Am: Equatorial monsoon climate
	Aw/As: Equatorial savanna climate dry winter/summer
B	**Arid climates**
	BS: Steppe Climate
	BW: Desert Climate
C	**Warm temperate climates**
	Cw/Cs: Warm temperate climate with dry winter/summer
	Cf: Warm temperate climate, fully humid
D	**Snow climates**
	Dw/Ds: Snow climate with dry winter/summer
	Df: Snow climate, fully humid
E	**Polar climates**
	ET: Tundra climate
	EF: Frost climate

Source: adapted from Kottek et al. (2006).

Appendix B: Climate classification

Table 32:

KGC Climate Classification according alternative databases.

#	City	Climate	#	City	Climate
1	Tokyo	Cfa	22	Tianjin	*Dwa*
2	Delhi	BSh	23	Rio de Janeiro	Aw
3	Shanghai	Cfa	24	Chennai (Madras)	As
4	Mumbai (Bombay)	Aw	25	Jakarta	Am
5	Beijing	Dwa	26	Los Angeles-Long Beach	BSk
6	Dhaka	Aw	27	Lahore	BSh
7	Karachi	BWh	28	Hyderabad	BSh
8	Al-Qahirah (Cairo)	BWh	29	Shenzhen	Cwa
9	Lagos	Aw	30	Lima	BWh
10	Ciudad de México	Cwb	31	Moskva (Moscow)	Dfb
11	São Paulo	Cfa	32	Bogotá	Cfb
12	Kinshasa	Aw	33	Paris	Cfb
13	Osaka	Cfa	34	Johannesburg	BSk
14	New York-Newark	Dfb	35	Krung Thep (Bangkok)	Aw
15	Kolkata (Calcutta)	Aw	36	London	Cfb
16	Guangzhou	Cwa	37	Dar es Salaam	Aw
17	Chongqing	Cfa	38	Ahmadabad	BSh
18	Buenos Aires	Cfa	39	Luanda	BSh
19	Manila	Aw	40	Ho Chi Minh City	Aw
20	Istanbul	Csa	41	Chengdu	Cwa
21	Bangalore	Aw			

Note: details of the model that generate the Köppen-Geiger classification in the databases named climate-data.org and climatemps.com were not found. Source: own author.

Appendix C: Sky type data

Appendix C1: Obtaining the data in APOLUX

Example of Sky Type data generated by APOLUX for the city of Buenos Aires, 1 day of January, extension .stp, based on the weather file of Meteonorm:

- D:_PhD_IaraSantos(...)\BUENOS_AIRES_AR-hour.epw

BUENOS AIRES AR -
Latitude: ; -34.669998
Longitude: ; 58.500000
Altitude: ; 0.000000
Número de Steps: ; 8760

AzSol -> Azimute Solar
AltSol -> Altura Angular Solar
TV -> Turvamento da Atmosfera
MAOR -> Massa de Ar Ótica Relativa
TipoCéu -> Tipo de Céu ISO-CIE Escolhido (SE -1 NÃO HÁ DISTRIBUIÇÃO
IluGlb -> Iluminância Global Horizontal (lux)
IluDir -> Iluminância Direta HOrizontal (lux)
IluDif -> Iluminância Difusa Horizontal (lux)
LumZnt -> Luminância do Zenith (cd/m2)

Mês ; Dia ; Hora ; Min ; AzSol ; AltSol ; TV ; MAOR ; TipoCéu ; IluGlb ; IluDir ; IluDif ; LumZnt
1 ; 1 ; 1 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 2 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 3 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 4 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 5 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 6 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 7 ; 60 ; 109.01 ; 13.31 ; 20.60 ; 4.27 ; 1 ; 1512.10 ; 0.00 ; 1512.10 ; 617.18
1 ; 1 ; 8 ; 60 ; 101.59 ; 25.20 ; 39.95 ; 2.34 ; 1 ; 9385.99 ; 0.00 ; 9385.99 ; 3831.22
1 ; 1 ; 9 ; 60 ; 94.04 ; 37.41 ; 58.84 ; 1.64 ; 1 ; 12878.23 ; 0.00 ; 12878.23 ; 5256.72
1 ; 1 ; 10 ; 60 ; 85.42 ; 49.74 ; 58.32 ; 1.31 ; 1 ; 22230.91 ; 47.66 ; 22183.24 ; 9054.79
1 ; 1 ; 11 ; 60 ; 73.53 ; 61.86 ; 47.93 ; 1.13 ; 1 ; 33018.43 ; 501.96 ; 32516.46 ; 13272.21
1 ; 1 ; 12 ; 60 ; 51.16 ; 72.87 ; 59.31 ; 1.05 ; 1 ; 36719.73 ; 249.91 ; 36469.82 ; 14886.28
1 ; 1 ; 13 ; 60 ; 357.44 ; 78.38 ; 32.44 ; 1.02 ; 1 ; 54771.17 ; 4694.71 ; 50076.46 ; 20439.91
1 ; 1 ; 14 ; 60 ; 306.42 ; 72.14 ; 46.62 ; 1.05 ; 1 ; 39037.70 ; 927.20 ; 38110.51 ; 15555.22
1 ; 1 ; 15 ; 60 ; 285.37 ; 60.98 ; 52.74 ; 1.14 ; 1 ; 35275.25 ; 273.52 ; 35001.73 ; 14287.09
1 ; 1 ; 16 ; 60 ; 273.86 ; 48.82 ; 52.10 ; 1.33 ; 1 ; 28696.34 ; 96.91 ; 28599.43 ; 11673.92
1 ; 1 ; 17 ; 60 ; 265.37 ; 36.49 ; 57.49 ; 1.68 ; 1 ; 18307.36 ; 0.00 ; 18307.36 ; 7472.56
1 ; 1 ; 18 ; 60 ; 257.86 ; 24.30 ; 38.49 ; 2.42 ; 1 ; 7868.48 ; 0.00 ; 7868.48 ; 3211.78
1 ; 1 ; 19 ; 60 ; 250.42 ; 12.44 ; 19.20 ; 4.55 ; 3 ; 2632.65 ; 0.00 ; 2632.65 ; 950.23
1 ; 1 ; 20 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 21 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 22 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 23 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0
1 ; 1 ; 24 ; 60 ; ; ; ; ; -1 ; 0 ; 0 ; 0 ; 0

Appendix C2: Comparing sky types of cities considering different time intervals

In this step, the sky type data for each city was compared considering two intervals of time, in order to observe potential divergences in the results provided by APOLUX when the sun reaches low angles. Thus, the interval 8h - 18h (A) was contrasted to the conservative interval 9h - 17h (B) (see table below). These data were obtained from the mode of the sample of sky types for each month.

Table 33:

Predominant sky type based on frequency of occurrence, options A (8h-18h) and B (9h-17h), from January to December.

M	Buenos Aires		Bogotá		Dar es Salaam		Dhaka		Karachi		Lima		London		Shanghai		Rio de Janeiro	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	12	2	1	1	1	1	13	13	13	13	14	14	1	1	1	1	1	1
2	14	14	1	1	1	1	15	15	14	14	14	14	1	1	1	1	2	2
3	13	14	1	1	1	1	14	14	14	14	14	14	1	1	1	1	1	1
4	13	13	1	1	1	1	15	14	14	15	14	13	1	1	1	1	1	1
5	13	13	1	1	1	1	15	2	14	15	1	1	1	1	1	1	13	13
6	13	13	1	1	14	1	1	1	8	8	15	1	1	1	1	1	11	11
7	13	13	1	1	1	1	1	1	1	1	15	1	1	1	1	1	11	11
8	13	13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	13	13	1	1	1	1	1	1	15	15	1	1	1	1	1	1	1	1
10	2	2	1	1	1	1	14	14	14	14	1	1	1	1	1	1	1	1
11	12	12	1	1	14	1	13	13	14	14	1	1	1	1	1	1	1	1
12	2	2	1	1	1	1	13	13	14	14	14	14	1	1	1	1	1	1
A*	13	13	1	1	1	1	1	1	14	14	14	1	1	1	1	1	1	1
C	=		=		=		=		=		*		=		=		=	
F	**13**		**1**		**1**		**1**		**14**		**14**		**1**		**1**		**1**	

M: Month; A*: Annual mode in option A and B; C= comparison; Final choice. Source: own author, data obtained using APOLUX.

Considering the overall similarity between Intervals A and B, the interval 8h-18h (A) was chosen for the final analysis. In fact, the results when cases A and B were compared for each city were equal, except for Lima. This city presented a predominance of the sky type 14 in case A, while the sky type 1 occurred more often in case B.

Appendix C3: Example of sky type analysis

Complementary analyses of sky type were conducted through visualization of charts per city. Figure 70 is an example. It illustrates the number of hours within a year in which each sky type occurs in one city of the sample. In this example, CIE sky types ranges from 1 to 15; hourly values between 9h to 16h were plotted for the city of Rio de Janeiro. It is possible to observe that the occurrence of sky types 5, 7, and 9 is very low or null in this city.

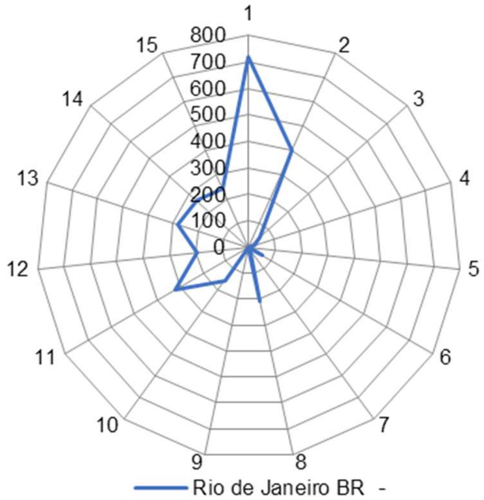
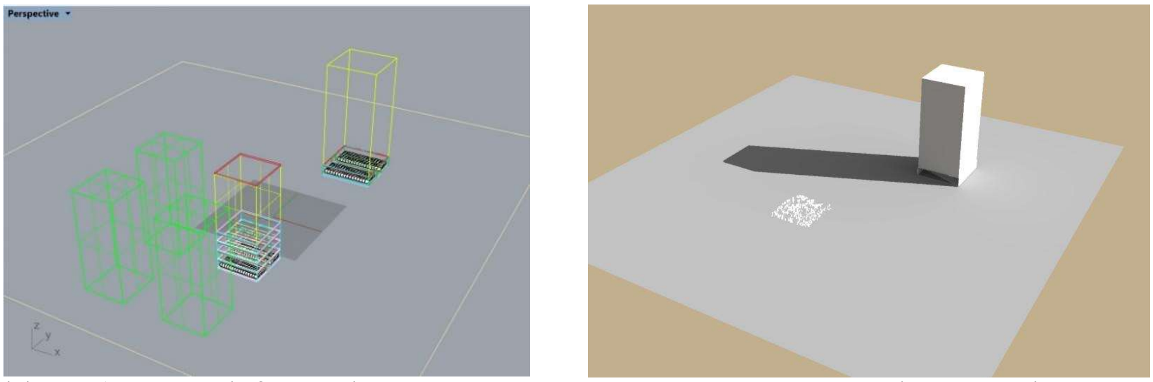


Figure 70: Sky types of Rio de Janeiro in the year.
Source: own author.

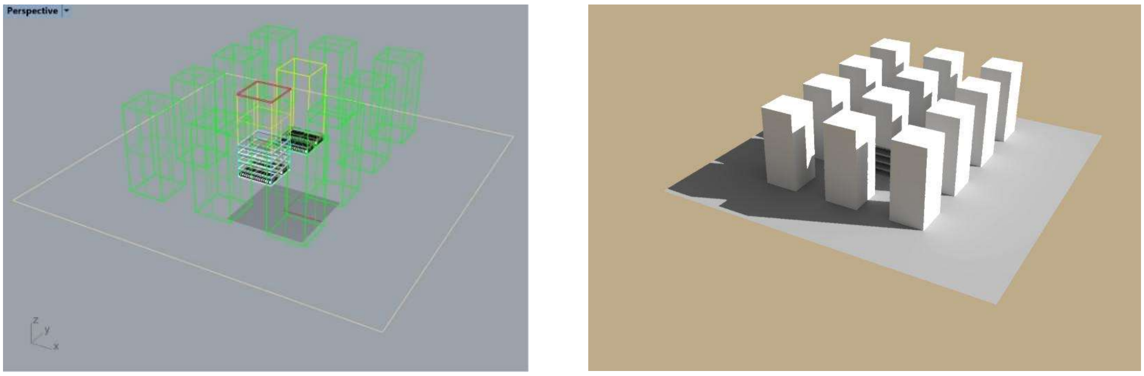
Appendix D: Software for daylight simulation

Appendix D1: Preparation of models in DIVA

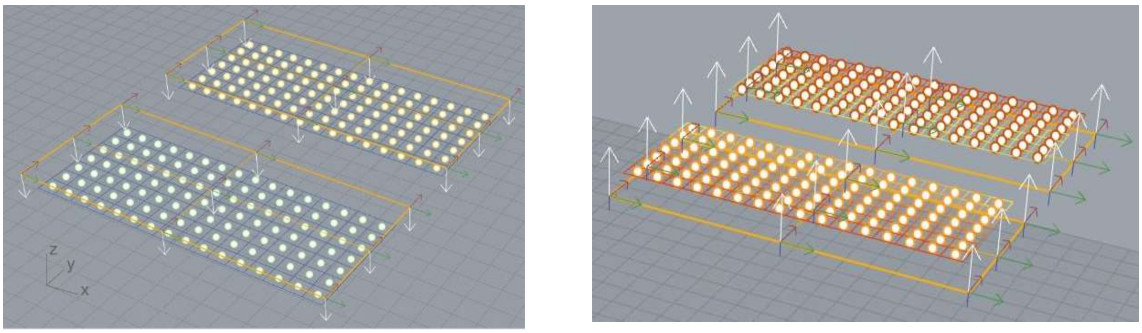
Exploratory tests were conducted for setting up the 3D models and control their visualization proccess using DIVA. Figure 71 shows some of them. The simulations were run in DIVA-for-Rhino, where materials were defined, and imported in DIVA-for-Grasshopper where settings were more carefully selected and several locations could run automatically, in a parametric proccess. Rhino v5 and v6 were adopted. In case of Rhino 5, the settings of exporting objects were defined according reccomendations of the User Guide (see next Appendix).



(a) Four ‘buildings’ (left corner) appear under the ground level when rendered (right image).



(b) Two measured central buildings surrounded by obstructions, test matrix 3 x 4.



(c) Vector inputs: Simulation of a test case produced odd results close to zero (left) due to the normal of reference surface wrongly oriented towards the ground, and problem corrected (right).

Figure 71: Tests for setting up the 3D models and control their visualization proccess using DIVA. Source: own author.

Appendix D2: Setting Rhino for DIVA

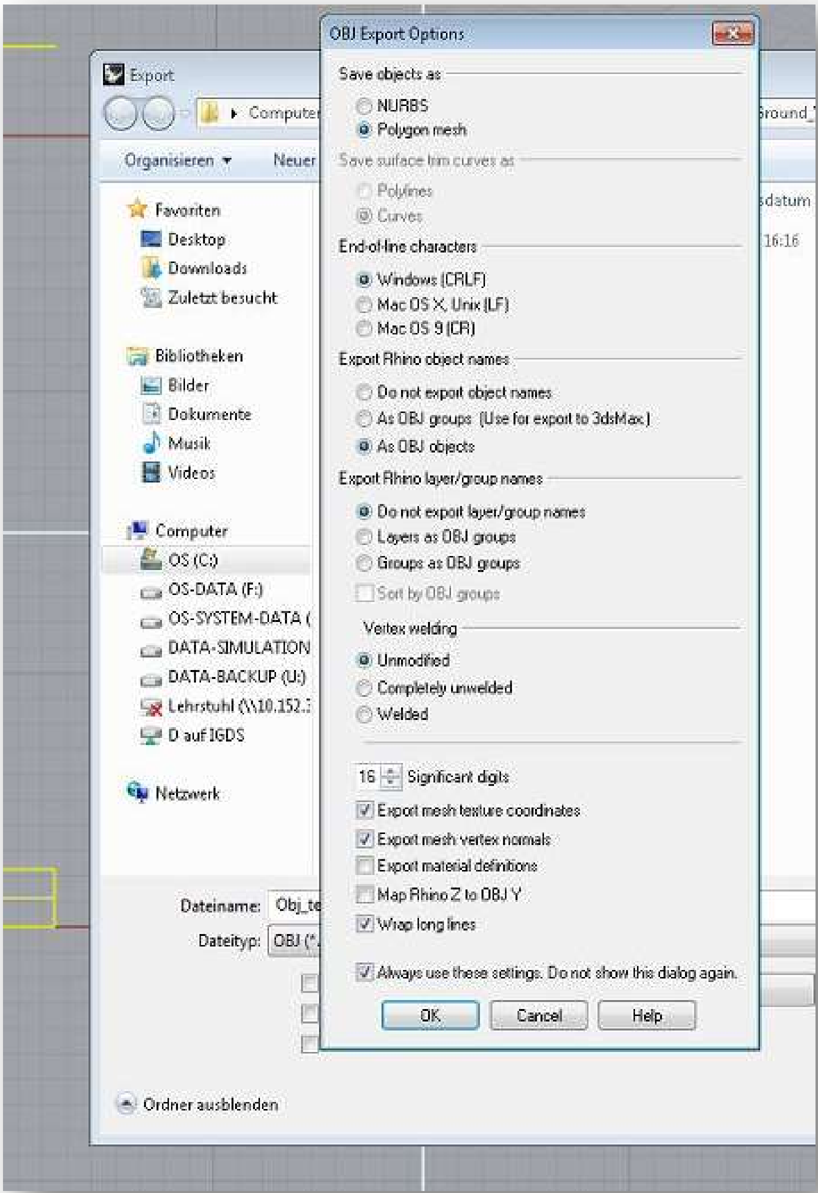
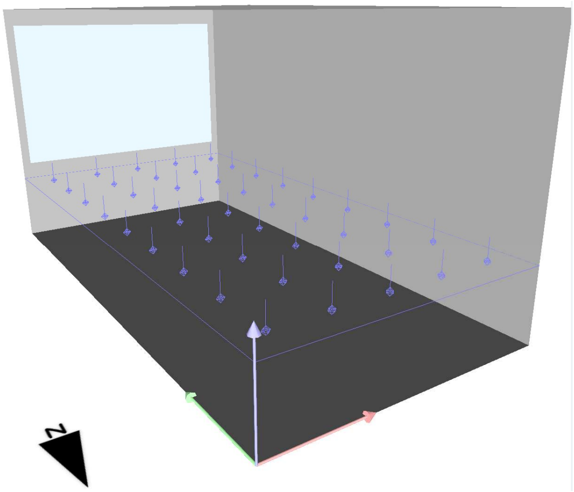


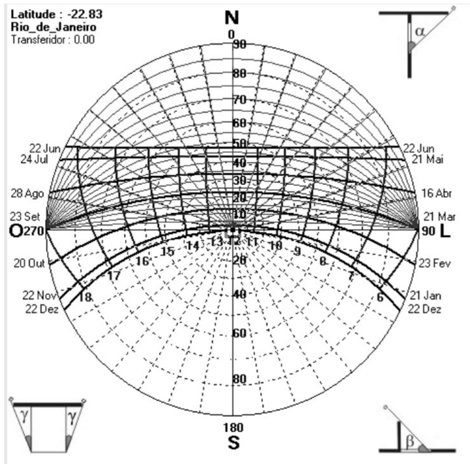
Figure 72: Print-screen of Setting OBJ Export Options in Rhino 5 for using DIVA.
Preparation of setting Rhino v.5 for using DIVA, following recommendations in the User Guide (http://diva4rhino.com/page/setting-obj-export-options-in-rhino-5, Accessed 2018).
Source: own author.

Appendix D3: tests with DIALux

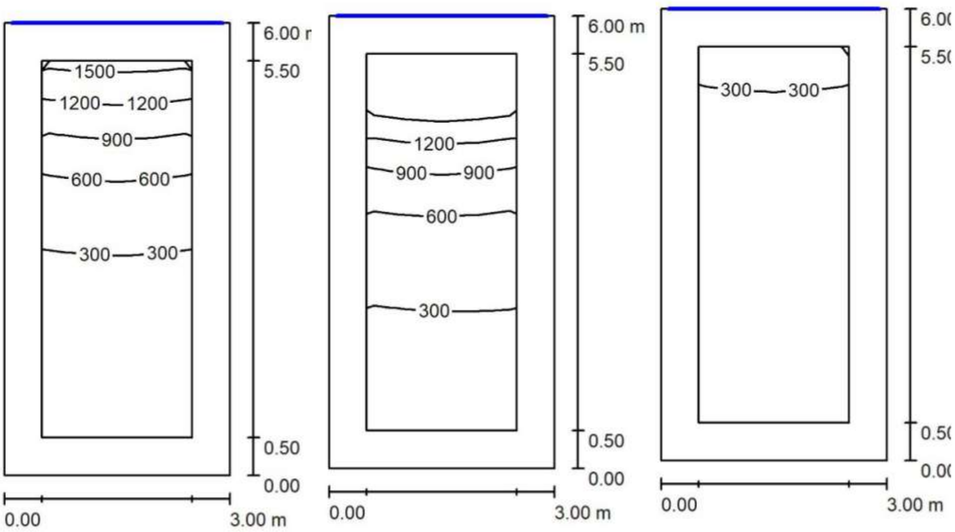
Complementary pre-tests in DIALux v.4.13 were conducted for one city of the sample, Rio de Janeiro. Results were analised with the support of solar charts, obtained for the desired city using the tool Sol-Ar v. 6.2 by UFSC. The results were compared to ones provided by other software to gain a deeper understanding of the daylight indoors phenomena according different tested conditions.



(a)



(b)



(c)

Figure 73: Pre-tests in DIALux v.4.13.
Note: (a) Interior of the 3-D model with measured points. (b) Solar charts for the city for the city of Rio de Janeiro. (c) Example of a point-in-time results with one sky condition for 8h, 10h and 18h. Source: own author.

Appendix E: Global horizontal illuminance

Hourly values of global horizontal illuminance were also reorganized using Excel for a better assessment of the similarity among cities. Only values greater than zero were compiled. The results highlight that London have the lowest values, followed by Shanghai (Figure 74).

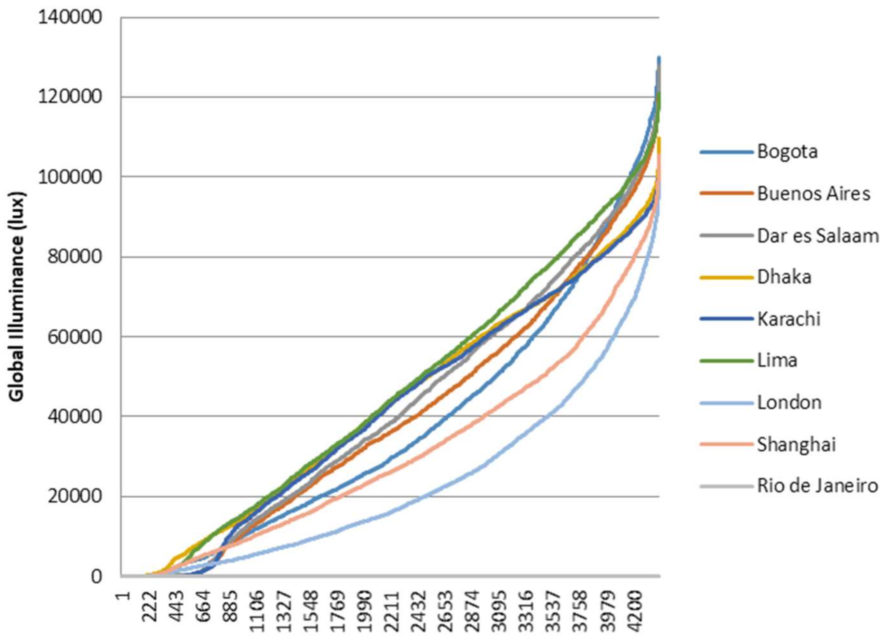


Figure 74: Hourly values of global horizontal illuminance (lux) organized in ascending order within a year. Source: own author.

Appendix F: Table of indoor daylight performance results

Compilation of indoor daylight performance results that served to the analysis in this study.

Table 34:

Results of annual indoor daylight performance (sDA') per city obtained through computer simulation.

City/Case	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
BA	79,37	80,13	69,88	39,50	58,20	45,28	36,51	38,31
BO	83,12	86,85	70,67	36,32	61,26	43,81	35,85	54,23
DS	88,13	90,94	78,50	46,65	70,20	53,96	49,48	63,39
DK	88,15	91,03	79,88	47,08	68,98	52,44	46,50	60,21
KA	87,52	89,68	78,43	47,78	68,01	52,97	45,78	59,56
LI	90,23	91,98	81,56	49,70	72,48	55,79	51,38	65,62
LO	58,41	62,50	46,20	17,32	36,22	22,73	17,62	30,32
SH	78,00	81,19	64,70	28,67	55,69	38,42	30,54	47,79
RJ	85,78	87,06	74,97	42,03	64,33	48,36	43,02	57,61

Source: own author.

Table 35: *Monthly indoor daylight performance (msDA') per city obtained through computer simulation.*

Case A

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	94,98	88,01	89,89	77,30	77,73	97,00	14,62	57,42	94,93
2	90,97	87,13	89,47	84,70	82,60	96,02	34,90	66,89	93,46
3	83,68	84,39	88,46	93,47	87,86	95,87	61,42	77,45	92,20
4	73,72	81,48	81,85	97,05	96,04	92,59	80,74	88,38	85,04
5	65,87	79,90	84,25	97,24	95,82	84,23	90,04	89,95	74,16
6	55,89	83,50	82,88	92,79	95,79	81,75	91,49	90,29	68,32
7	59,02	78,75	82,04	94,66	88,92	83,09	88,98	93,24	71,91
8	64,89	82,36	86,93	89,34	89,09	83,52	88,93	91,68	82,75
9	81,98	82,07	92,37	90,40	94,21	92,44	70,64	86,31	88,85
10	91,40	81,51	93,42	85,73	86,66	90,26	47,32	73,60	92,43
11	93,72	81,87	92,27	80,54	79,05	91,19	21,06	62,91	89,39
12	96,32	86,42	93,68	74,56	76,45	94,86	10,85	57,83	95,98

Case B

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	95,15	91,56	92,18	82,87	81,44	97,61	19,62	61,79	95,00
2	91,07	89,77	91,50	89,52	85,04	97,09	41,37	71,70	93,68
3	84,36	87,33	90,90	95,58	90,05	96,79	67,10	80,85	92,73
4	75,56	85,60	84,95	98,24	96,69	93,90	84,97	90,73	86,37
5	67,65	84,39	88,12	98,30	96,69	87,23	92,04	91,68	77,28
6	56,46	87,36	88,33	94,57	96,73	85,72	93,07	92,45	71,27
7	59,63	82,67	86,80	96,17	90,21	86,66	90,39	94,35	75,70
8	67,18	86,26	90,13	91,04	90,05	85,16	90,94	93,43	84,90
9	83,06	85,77	93,88	92,17	95,53	94,08	76,87	89,10	89,45
10	91,05	85,15	95,05	89,29	90,90	91,72	53,99	77,41	92,70
11	93,94	86,04	94,21	84,41	82,35	92,14	24,86	67,88	89,53
12	96,51	90,33	95,24	80,17	80,49	95,70	14,83	62,86	96,07

Case C

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	88,30	77,34	82,17	70,63	64,16	92,50	9,02	41,21	86,48
2	83,38	76,53	79,78	75,59	73,60	90,33	20,57	53,79	85,87
3	75,13	71,91	76,93	86,36	81,79	88,94	44,42	62,23	82,37
4	63,34	68,24	67,88	90,31	88,27	85,22	65,11	75,93	70,10
5	53,83	66,18	72,32	90,40	90,44	73,30	77,58	78,96	62,55
6	42,57	68,87	73,34	82,97	90,65	69,76	80,04	77,44	57,37
7	45,18	66,62	73,94	85,37	79,62	71,94	77,50	82,76	62,11
8	55,67	70,38	77,64	78,25	78,34	70,83	75,90	79,99	68,02
9	71,99	68,84	81,71	81,67	84,36	82,94	54,72	73,51	76,79
10	81,70	68,95	85,62	75,46	79,24	80,60	31,74	59,71	81,70
11	85,89	69,47	85,44	72,01	68,53	83,60	13,72	47,90	78,92
12	91,62	74,67	85,24	69,55	62,20	88,76	4,04	43,00	87,38

Case D

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	63,82	41,70	51,56	40,86	35,22	66,67	0,00	12,18	52,66
2	60,54	43,16	52,38	43,38	41,21	64,98	0,75	21,29	53,32
3	45,16	39,45	44,36	57,31	51,87	59,52	11,57	23,80	49,93
4	30,11	34,88	33,62	60,00	60,38	56,23	24,57	37,26	34,58
5	17,13	30,24	38,54	56,71	62,67	40,98	37,30	42,69	32,62
6	9,03	28,56	40,15	46,21	61,92	33,92	39,83	34,21	25,83
7	11,15	33,90	41,88	45,79	45,62	35,18	38,99	44,27	32,00
8	24,07	36,90	46,70	42,80	44,49	35,32	31,83	41,35	33,98
9	36,35	35,50	48,77	47,56	54,81	47,80	17,58	32,23	39,71
10	49,61	37,40	53,66	40,45	49,20	44,75	5,39	26,28	48,48
11	60,45	35,31	55,76	42,98	34,79	52,68	0,00	16,85	48,22
12	66,56	38,81	52,42	40,95	31,16	58,36	0,00	11,59	52,97

(Table 35 continued)

Case E

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	85,63	63,06	75,14	49,29	44,77	84,04	2,54	30,48	81,62
2	80,65	65,24	77,46	61,68	57,32	88,48	11,84	39,78	83,98
3	61,97	67,69	74,30	75,41	71,91	88,95	29,38	53,15	75,91
4	42,75	62,05	60,52	88,96	87,25	73,82	49,20	69,23	55,15
5	36,36	57,07	58,40	87,26	87,27	55,84	68,81	74,90	43,86
6	26,58	54,76	56,71	78,01	84,43	53,08	73,11	71,16	38,08
7	29,37	55,15	59,34	79,82	73,74	55,67	70,49	79,82	40,65
8	35,35	65,10	68,14	74,08	76,00	58,34	63,81	74,87	50,90
9	55,44	63,72	79,05	74,44	78,54	77,98	38,96	63,69	66,35
10	74,28	62,87	82,79	60,33	62,33	78,05	20,13	45,45	78,53
11	82,53	57,54	76,57	51,58	49,12	76,62	6,42	35,50	74,75
12	87,46	60,89	74,02	46,91	43,42	78,97	0,00	30,25	82,20

Case F

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	75,92	45,00	58,42	40,81	34,79	69,65	0,00	17,16	64,84
2	66,08	47,92	65,33	43,21	40,38	76,35	5,84	26,07	68,09
3	44,80	50,89	59,76	56,58	53,27	74,06	16,57	33,89	57,00
4	29,22	45,63	42,44	72,72	71,75	56,32	28,65	46,72	36,75
5	23,84	38,53	41,55	70,46	72,70	39,59	46,78	57,06	31,31
6	18,28	36,70	42,42	57,95	72,01	36,99	50,21	51,80	28,81
7	19,23	40,29	43,29	59,92	58,05	39,88	49,01	61,51	29,67
8	24,92	48,18	48,93	55,31	58,17	39,88	42,08	52,47	34,20
9	37,90	46,93	60,28	54,39	60,33	58,64	22,08	41,57	46,09
10	55,26	43,11	67,06	43,04	45,06	59,83	9,77	30,59	60,83
11	70,99	38,65	63,64	39,23	35,96	57,95	1,75	22,87	59,71
12	76,97	43,89	54,34	35,66	33,17	60,37	0,00	19,38	63,02

Case G

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	76,25	30,63	56,55	24,81	20,62	67,24	0,00	9,89	65,38
2	63,33	35,48	66,20	33,69	28,79	77,40	1,90	15,30	72,30
3	30,64	48,67	59,65	47,69	42,43	76,17	10,23	22,77	53,53
4	15,08	41,41	39,66	74,23	70,57	49,29	18,99	40,75	25,54
5	10,45	31,03	29,61	73,58	74,95	28,29	40,56	54,26	17,86
6	6,95	24,48	27,29	57,91	73,03	24,09	46,95	47,30	16,48
7	8,22	32,25	29,62	59,60	56,46	26,74	43,28	58,05	15,98
8	11,52	43,51	42,30	55,96	55,04	32,55	31,89	47,71	21,97
9	21,56	44,56	63,03	49,86	53,22	57,80	12,05	31,25	40,09
10	46,12	39,47	68,06	33,70	31,59	63,27	5,42	18,33	61,94
11	70,31	28,82	63,26	25,36	22,47	57,56	0,17	11,81	62,16
12	77,73	29,94	48,55	21,67	20,15	56,18	0,00	9,07	63,00

Case H

Month	BA	BO	DS	DK	KA	LI	LO	SH	RJ
1	55,92	58,31	66,92	41,83	41,25	77,03	0,00	24,80	72,32
2	54,97	60,27	66,69	53,81	51,66	76,48	5,52	34,35	72,72
3	44,48	58,23	64,52	68,53	64,20	75,86	24,99	45,51	68,06
4	30,34	52,72	54,58	77,41	74,27	68,27	44,96	59,47	51,47
5	23,34	50,32	57,07	76,05	74,72	54,19	58,95	64,13	40,42
6	15,83	49,61	51,96	68,26	72,98	49,18	63,96	60,61	33,74
7	17,72	50,31	56,90	69,46	63,80	51,96	60,62	68,84	36,22
8	24,96	55,56	63,45	63,70	63,72	54,21	55,51	64,47	48,33
9	37,32	54,37	69,60	65,70	69,74	69,01	34,35	55,60	59,94
10	48,06	54,92	71,28	54,34	56,26	68,21	14,01	40,19	68,81
11	51,09	51,36	69,14	45,31	43,90	69,09	1,02	29,73	66,15
12	55,69	54,76	68,52	38,12	38,22	73,89	0,00	25,78	73,08

Source: own author.

Appendix G: Assistance with statistical aspects of research

The statistical company ABG contributed with specific analysis along the proccess.

For instance, together with them, histograms were made to evaluate data distribution type in Phase I. The generated histograms of indoor daylight performance demonstrated for certain cases an asymmetry to the right and positive distribution of the results, indicating that their distribution is not normal. These results contributed to the understanding of the data and helped to identify proper approaches to analyze the effect of the urban parameters on the results of indoor daylight performance.

Additionally, the ABG conducted statistical complementary tests of the data generated by this author, considering a level of significance of 5%. These tests provided interesting inputs, but they did not interfere substantially in the analysis of the work. Thus, their main results are briefly commented here.

For comparing the cities, they conducted Chi-Square and Kruskal-Wallis tests. These methods are described in Hollander and Wolfe (1999). Chi-Square is indicated for qualitative data (e.g. sky type), and Kruskal-Wallis is adopted for quantitative data (e.g. illuminance). For instance, the Kruskal-Wallis test for msDA' revealed that the monthly indoor daylight of London differs significantly (p-value <0.050) from the others. The simulated Chi-Square test resulted in a p-value< 0.001, indicating that there is a significant difference between at least two cities in terms of monthly and annual sky type, as expected.

In the analysis using Pearson's correlation, ABG calculated the p-value to verify whether the correlation is relevant. For monthly inputs, results indicated a significant and strong positive correlation between illuminance data *vs*. msDA', while for sky cover *vs*. msDA' a significant negative correlation appeared (p-value < 0.05). ABG remembers that Pearson correlation assesses the linear relationship between two continuous variables, translating it in an interval from inversely to perfectly correlated (respectively −1.0 to 1.0), where 0 indicates no correlation.