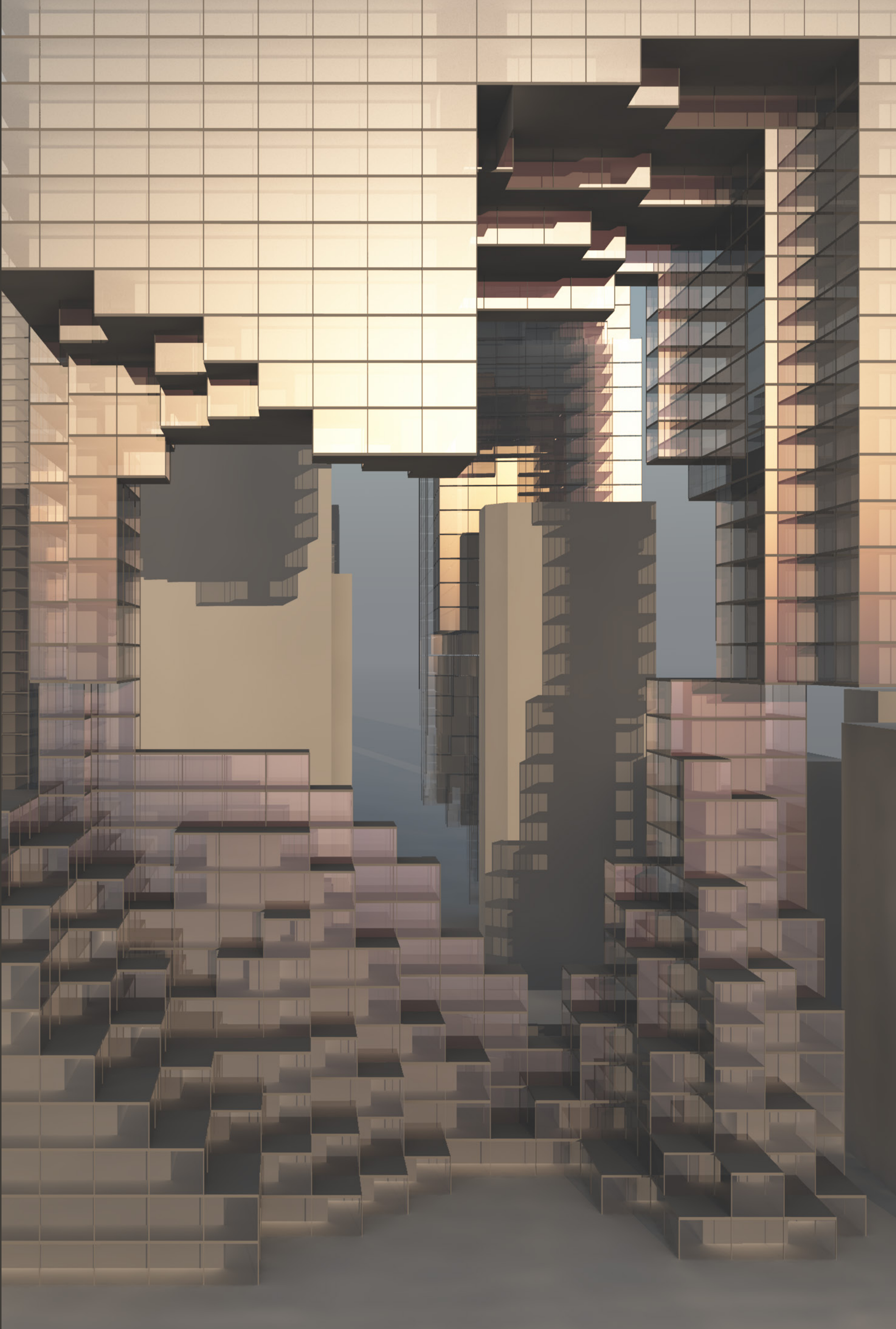
Michele Leidi
DISS. ETH NO. 22237

Volumetric Site Analysis for the Conceptualization of Architecture in the Urban Context



Volumetric Site Analysis for the Conceptualization of Architecture in the Urban Context

Michele Leidi

DISS. ETH NO. 22237

Volumetric Site Analysis for the Conceptualization of Architecture in the Urban Context

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

MICHELE LEIDI

MSc in engineering EPFL - MAS in architecture ETHZ

born on *06.11.1981*

citizen of Lugano, Switzerland

accepted on the recommendation of

Prof. Dr. Arno Schlueter

M.Sc. M.Arch. Markus Schaefer

2014

Michele Leidi

michele.leidi@alumni.ethz.ch

Architecture & Sustainable Building Technologies (SuAT)

Institute of Technology in Architecture (ITA)

Department of Architecture (D-ARCH)

ETH Zurich

John-von-Neumann-Weg 9

8093 Zürich

Switzerland

This research was supported by the Swiss National Science Foundation (SNSF)

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

Abstract

The ongoing urbanization stresses the importance of cities in terms of global sustainability. The conception of sustainable and livable architecture in high and dense urban settings is therefore one of the primary challenges for architects and planners. Physical properties of urban sites such as solar radiation, airflows, and visibilities, are key factors necessary to achieve both human comfort and an efficient employment of building technologies. However, the analysis of these features in high and dense urban settings is a difficult task due to the intricate morphology of the built environment.

This research concerns the development and the experimentation of a new design methodology that aims to foster the inclusion of environmental information in the conceptualization of urban architecture. The proposed approach is based on the discretization of the urban site into a volumetric grid of points. At each of these points, different physical properties such as solar radiation, airflow and visibility are computed. The results of the analysis process are then made successively available in a custom visualization framework.

The joint presence of multiple variables and the ability to interact with their quantitative, volumetric, dynamic, and directional dimensions, allows developing an awareness of how these properties are distributed through the site. This enables the recognition of volumetric patterns and the investigation of multivariate and multidimensional correlations through space and time. This new environmental information can also be coupled with specific project demands related, for example, to space, daylight, shading, sight, ventilation, heat, or electricity.

Through the experimentation of the methodology in several case and user studies, it was possible to evaluate the capabilities, pertinence, and usability of the proposed technique in depth. The results confirmed that the methodology enables an augmented perception of environmental resources, and revealed the rich diversity of concepts that can emerge through the application of this process. Application examples concern the distribution of spaces and uses, the configuration of exterior surfaces, and new formal logics.

The inclusion of environmental information in the pre-design stage allows addressing conceptual design from a new perspective. Conventional performance-oriented design methods, such as early-design simulations or heuristic generative design processes, are based on the verification and improvement of an existing design sketch. Inversely, this new methodology allows retrieving initial design propositions directly from the environment. This bottom-up approach, based on an accurate observation of the local resources and constraints of each single urban site, allows designers to explore new conceptualizations, catalyzing the synthesis of beneficial design solutions that would be hardly conceivable otherwise.

Riassunto

L'urbanizzazione in corso accentua l'importanza delle città in termini di sostenibilità globale. La concezione di architetture vivibili e sostenibili in ambienti ad alta densità urbana è quindi una delle maggiori sfide per architetti e pianificatori. Le proprietà fisiche di siti urbani come la radiazione solare, i flussi d'aria, e la visibilità, sono fattori chiave per raggiungere sia il comfort umano che un impiego efficiente di tecnologie sostenibili. Tuttavia, l'analisi di queste caratteristiche è un compito difficile a causa della complessa morfologia dell'ambiente costruito.

Questo lavoro di ricerca riguarda lo sviluppo e la sperimentazione di una nuova metodologia di progettazione che mira a favorire l'inclusione di informazioni ambientali nella concettualizzazione dell'architettura urbana. L'approccio proposto si basa sulla discretizzazione del sito urbano in una griglia di punti volumetrica. Per ciascuno di questi punti vengono calcolate diverse proprietà fisiche, come la radiazione solare, i flussi d'aria, e la visibilità. I risultati del processo di analisi sono successivamente resi accessibili attraverso un'interfaccia di visualizzazione interattiva.

La presenza congiunta di molteplici variabili e la possibilità di interagire con le loro dimensioni quantitative, volumetriche, dinamiche e direzionali, permettono di acquisire consapevolezza su come queste proprietà sono distribuite all'interno del sito. Questo consente il riconoscimento di motivi volumetrici di interesse, e lo studio di correlazioni multivariate e multidimensionali attraverso lo spazio e il tempo. Queste nuove conoscenze ambientali possono poi essere combinate con particolari esigenze del progetto relative ad esempio a spazio, luce, ombra, vista, ventilazione, calore, o elettricità.

Attraverso la sperimentazione della metodologia da parte di svariati utenti e in diversi casi di studio, è stato possibile valutare in modo approfondito le capacità, la pertinenza e l'usabilità della tecnica proposta. I risultati hanno confermato che la metodologia permette una percezione aumentata delle risorse ambientali, e hanno rivelato la ricca diversità di concetti che possono emergere attraverso l'applicazione di questo processo. Esempi d'applicazione concernono la distribuzione degli spazi e dei loro usi, la configurazione di superfici esterne, e nuove logiche formali.

L'inclusione delle informazioni ambientali nella fase pre-progettuale consente di affrontare la progettazione concettuale da una nuova prospettiva. I metodi di progettazione tradizionali orientati alla 'performance' ambientale, quali le simulazioni in fasi preliminari e i metodi di progettazione euristici, si basano sulla verifica e sul perfezionamento di uno schema progettuale esistente. Inversamente questa nuova metodologia permette di ottenere proposte iniziali direttamente dall'ambiente. Questo approccio 'bottom-up', basato su una attenta osservazione delle risorse e delle limitazioni di ogni singolo sito urbano, consente ai progettisti di esplorare nuove concettualizzazioni, catalizzando la sintesi di soluzioni progettuali benefiche difficilmente concepibili altrimenti.

Publications

- ‘Volumetric Insolation Analysis’

  Full paper at the CISBAT conference in Lausanne (Leidi & Schlüter, 2011).

- ‘Formal and Functional Implications of Dynamics-Related Solar Design Schemes’

  Full paper at the ACADIA conference in San Francisco (Leidi & Schlüter, 2012).

- ‘Exploring Urban Space’

  Volumetric Site Analysis for Conceptual Design in the Urban Context

  Full paper in the IJAC, the International Journal of Architectural Computing (Leidi & Schlüter, 2013a).

  Related online Video (Leidi & Schlüter, 2013b).

- ‘Conceiving Design Schemes of Urban Architecture through Volumetric Site Analysis’

  Short paper and poster at the CAADRIA conference in Kyoto (Leidi & Schlüter, 2014a) (2014b).

  Related online Video (Leidi & Schlüter, 2014c).

This report integrates and expands the content of these publications in a wider dissertation.

Acknowledgments

- Cyril Angst
- Roman Bader
- Brian Ballantine
- Marc Bätschmann
- Sasha Cisar
- Tom Doan
- Jonathan Feinberg
- Jimeno Fonseca
- Ben Fry
- Valérie Gass
- Pascal Goffin
- Jung HeeYoung
- Christian Hersberger
- Daniel Howe
- João Ventura Lopes
- Vasco Medici
- Clayton Miller
- Peter Moonen
- Zoltan Nagy
- Basilio Noris
- Matt Parker
- Casey Reas
- Dino Rossi
- Tomoya Senoh
- Markus Schaefer
- Andreas Schlegel
- Arno Schlueter
- Ran Tateyama
- Daren Thomas
- Anja Willmann

Contents

1 INTRODUCTION

1.1 Sustainable Architecture in the Urban Context

Today more than half of the world's population lives in cities. By 2050, this proportion will probably increase to 67% (UN, 2011). This urbanization phenomenon stresses the importance of cities in terms of global sustainability. The conception of sustainable and livable architecture in high and dense urban settings is, therefore, one of the primary current challenges for architects and planners.

Physical properties of an urban site such as solar radiation, airflows, and visibilities are key factors to achieve both human comfort and an efficient implementation of sustainable building technologies. However, the analysis of these features in high and dense urban settings is a difficult task due to the intricate morphology of the built environment.

This research concerns the development and experimentation of a new design methodology that fosters the inclusion of environmental information in the conceptualization of urban architecture.

1.2 The Influence of the Environment on Architectural Practices

Environmental parameters, and in particular those related to the climate, have had a dominant influence on architecture since the development of vernacular practices. As described by Straube (2006), the creation of the first buildings was in fact driven by the essential needs of people to obtain shelter from the forces of nature; mainly from sun, rain and wind. At this time, techniques such as shading and natural ventilation were not intentionally planned but rather learnt over time by a collective trial-and-error process.

With the progressive developments of construction materials, new passive means to thermally control the building interiors, such as heat storage and thermal insulation, became available. From the 1850's on, the technical novelties produced by the industrial revolution such as pumps, fans and artificial lighting, allowed for the creation of a new kind of atmosphere inside the building. From the end of the 19th century, further technological developments, such as steel structures and elevators, allowed for the development of high-rise constructions designed as airtight buildings fully supplied by electrical and mechanical systems. Since then, the local and contextual specificities of site, climate, and surrounding environment have been disregarded in the illusion that technology could solve every issue. In reality, this progression has often resulted in widespread energy consumption and poor human comfort (Straube, 2006).

The oil crisis of 1973 and awareness of the limits to growth (Meadows, et al., 1972) have contributed to a considerable change of perception, resulting in a raised awareness for energy and increased attention to climatic parameters and to the site. These were the years in which the works of the pioneers of bioclimatic architecture, such as the Olgyay brothers (1963), achieved a wide-ranging diffusion.

In the last decades, under the pressure of climate change, the environmental factor has re-gained momentum and has exerted an important influence on the development of many new initiatives. In the developed countries the increasing requirements for more energy efficiency and less greenhouse gas emissions led to the development of a new landscape of building norms, codes and incentives. At the technological level, new energy harvesting and management technologies started to facilitate the transition from fossil fuels to renewables energies. The availability of these new technologies and the multiple and sometimes contrasting approaches to sustainable architecture

(Simon & Moore, 2004) stressed the need for an integrated view, to incorporate questions of energy collection, efficiency, and emissions in the design process.

In the last decade the progress in computational methods and the increasing performance of desk computers have allowed for the wide diffusion of new design methods, such as digital drawing, parametric modeling, and physical simulation, that have augmented the possibilities of the design process.

1.3 Background

1.3.1 Graphical Tools for Site Analysis

Over time, Site Analysis became a typical phase of the design process dedicated to the study of climatic, geographical, historical, legal, and infrastructural aspects of the site. Designers and engineers developed tools to analyze and map site-related information long before the advent of computer technologies. In relation to climatic information, a typical approach consists in retrieving meteorological data in the form of time charts, where variables like temperature, humidity, solar radiation, wind speed, and rainfall are plotted over yearly or daily cycles (Hindrichs & Daniels, 2007, pp. 82-83). Given the physical complexity of these properties, a set of more sophisticated graphical tools has been gradually developed in order to allow correlations between features like magnitude, direction, time and location. Some examples of these tools, which are partially listed by DeKay and Brown (2014), are the Sundial (Brown, 1985), the Sun Path Diagram (Libbey-Owens-Ford, 1951), the Radiation Square, the Wind Rose, and the Wind Square (see Figure 1).

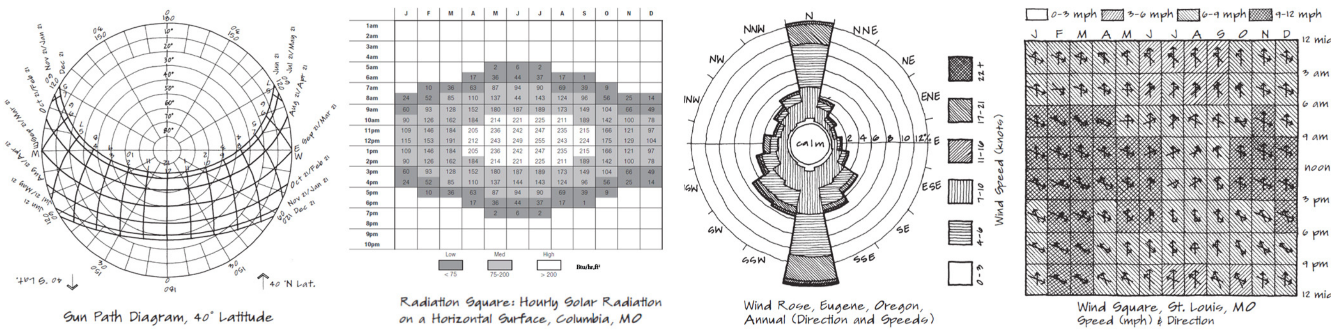


Figure 1: Selection of Graphical Tools for Site Analysis: Sun Path Diagram, Radiation Square, Wind Rose, and Wind Square. Adapted from DeKay and Brown (2014, pp. e.283, e.285, e.289, e.290).

Among these tools, Sun Path Diagrams are probably the most diffused and exist in a range of different configurations according to several types of geometrical projections (NF, 2014). Sun Path Diagrams are also often overlaid with additional information concerning for example obstructions (see Figure 2), solar radiation energy (Hindrichs & Daniels, 2007, p. 276), daylight (Moore, 1991), heating and cooling demands (Hindrichs & Daniels, 2007, p. 277), or sky coverage. Other correlations among climatic variables can be analyzed with further graphical tools, like Psychometric charts initiated by Carrier in 1904 (Donald, 2004), or with Bioclimatic charts (Olgyay, 1963) (Arens, et al., 1980). These tools additionally allow setting the climatic variables in relation with human comfort. Nowadays many of these methods have been integrated with meteorological databases in architectural 3D modeling programs, so that, given the geographical location of a site, representations like Sun Path Diagrams or Wind Roses can be retrieved through a simple click. After the site analysis phase the architectural designer usually integrates the relevant resulting information into a graphical sketch, typically a top view, that sets the environmental features of interest in relation with the physicality of the site in terms of parcel, topography, and built environment. This representation is then often used as a starting point to develop environmental strategies during the conceptual design phase.

Generally, these graphical tools are very adequate to study the environmental resources of simple sites. In fact, if the environmental resources are distributed quite homogeneously through the site, the analysis process can be reduced to a single entity, typically the center point of the parcel. However, if the subject of the study is a more intricate urban site, then most of these tools fall rather short, especially in the presence of close obstructions.

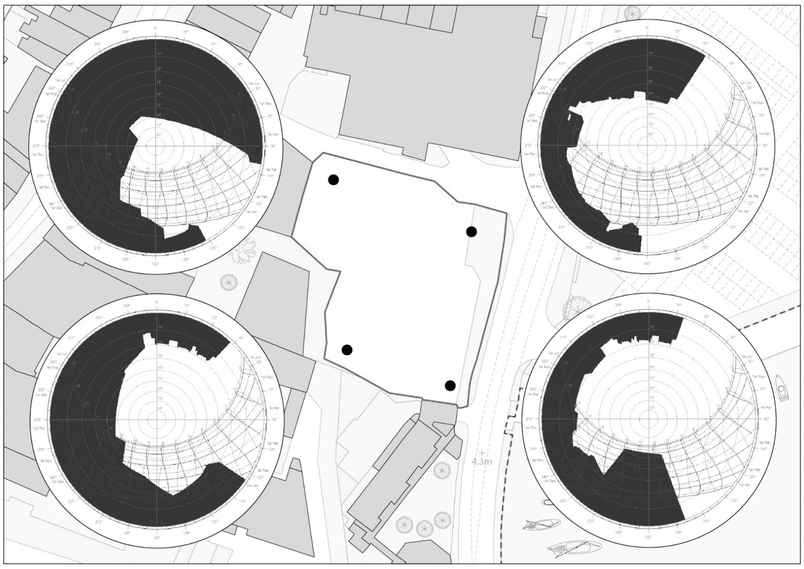


Figure 2: Top-view of a site with the sun path diagrams of the four corners of a parcel (Bennett, 2013).

Figure 2 shows such an example with a top-view of an urban site in a relatively low-rise context (4-6 floors). The four sun path diagrams illustrate clear differences among the corners of the parcel: Diversities that would be even stronger in the case of denser and higher sites or if the vertical positions of the observation points were taken into consideration.

1.3.2 Strategies, Technologies and Concepts of Environmental Architecture

By using these Site Analysis Tools and through growing general knowledge on environmental resources, designers could develop vernacular practices into a series of explicit architectural design strategies related to different climates and contexts. A trace of the development of these practices over time can be found in the research work of Montavon (2010, pp. 9-56), which gives an historical overview on the development of a huge number of architectural and urban strategies related to the sun. These strategies concern for example the orientation of facades and streets, the ratio between building heights and street widths, or the study of urban patterns.

Through time, several authors attempted to classify these methods to make them more accessible to designers. An important reference is the compendium 'Sun, Wind & Light - Architectural Design Strategies' by DeKay and Brown (2014), which concerns passive and formal related strategies. In this work the authors list a huge collection of guidelines and rules-of-thumb that allow integration of matters of energy in the design process with the aim of achieving a carbon neutral and net-zero energy design (that produces as much as it consumes on an annual basis). Such strategies concern for example internal room organizations, zonings, atrium arrangements, courtyard configurations, envelope systems, outdoor microclimates, and side-lighted room depths. Some of the procedures help designers to choose for example the size, location, orientation, and materials of apertures in relation to daylight, solar gains, and ventilation. Other methods assist architects in visualizing maximum buildable volumes to avoid the shading of adjacent sites through concepts like the Solar Envelope, concerning direct beam radiation (Knowles, 2003), the Daylight Envelope, concerning diffuse skylight, and the Climatic Envelope as their combination (DeKay & Moir-McClean, 2003). The compendium also proposes several ways to organize this energy-related design knowledge from the component to the urban scale. It presents methodical tools to assist designers in making choices by selecting, mapping, and combining different solutions through instruments like 'strategy maps', 'strategy bundles', and 'design decision charts'.

Paradoxically, this huge richness of proposals in terms of environmental strategies puts the designer in a difficult situation. Montavon (2010, p. 56) observes that even if a huge number of theories, tools and methods have tried to clarify and define some generalizations, it is presently difficult to make a choice and give a clear answer on which would offer the ideal solution to a given circumstance. Similarly DeKay and Brown confirm that, in relation to environmental strategies, 'the sheer volume of information can be daunting' (2014, p. 194).

In parallel, in the late 30s, some engineers started to implement the first active technologies related to environmental resources. Stimulated by the solar house movement, pioneers such as Hoyt Hottel, from the Massachusetts Institute of Technology, developed and tested the first devices for the collection and storage of solar energy (Denzer, 2013). The initial period, also known as 'the schism', during which there was little communication on these topics between the architectural and the engineering disciplines, was followed by a movement toward integration that started in the 50s and developed until our times. Recently, the ongoing transition from centralized fossil fuels to concepts of distributed renewable energy, has stimulated a broad development and diffusion of harvesting and management technologies such as: photovoltaic cells, thermal collectors, controlled ventilations, wind turbines, heat pumps, ground heat exchangers, etc. Similarly, as for passive strategies, some authors have addressed the classification of these active and technical solutions available to designers. An example can be found in the work of Reichel and Schulz (2012) that focuses on the dynamic nature of demand and supply, and on the influence that mechanical systems and installations can have on the conception of architectural design.

Through the last decades, these continuously evolving passive and active strategies have been combined in different building concepts according to diverse conceptual leanings. Several of these concepts have been promoted combining the term 'Architecture' with other terms such as 'Ecological', 'Green', 'Sustainable', 'Solar' (Denzer, 2013), 'Climatic' (Watson & Labs, 1983), 'Passive' (Fesit 2000), 'Self-Sufficient' (Voss, et al., 1996), 'Zero Energy', 'Plus Energy' (Marszal, et al., 2011), 'Emission-Free', 'Low Exergy' (Leibundgut, 2011), etc. In several countries, many of these concepts have also evolved into commercial, political or regulatory initiatives, and have sometimes been criticized for being too ideological disregarding non-quantifiable aspects of architectural importance. Examples of such issues can be found in extra-thick insulation layers and completely airtight building envelopes without operable windows; measures that improve energy-efficiency but create feelings of imprisonment rather than inhabitation. The current debate in the field suggests that, to foster beneficial innovations, requirements should be defined at the level of the end-performance rather than on how this performance should be reached.

The complexity of this landscape of different strategies, technologies and concepts has stressed the need for an integrated view able to predict the effects of the selected solutions, finding balance between form, construction, and technical systems. In the last decades the progress of computational methods has allowed for the development of simulation tools to assist architects in this challenging task.

1.3.3 Digital Simulation for Environmental Design

Currently a broad range of simulation tools can be used by architects to evaluate and improve different aspects of environmental performance during the early design phases. Although they are partially integrated, these tools can be divided into Solar Design Tools (SDT), Building Energy Simulation programs (BES), and Computational Fluid Dynamics engines (CFD).

The reviews by Dubois and Horvat (2010) and by Horvat and Wall (2012) provide a comprehensive overview on the huge variety of existing digital tools used by architects for solar design. By analyzing the similitudes and differences of 56 computer programs used by the architectural community, the authors illustrate how SDT allow evaluating in different ways features related to both passive techniques, like solar heat gains and daylighting, and active technologies, like the sizing of photovoltaic panels and thermal collectors. These solar simulation methods are sometimes integrated in BES, which allow performing dynamic thermal simulations of buildings. A review by Attia (2011) illustrates a series of BES programs such as *Ecotect* and *Vasari* that allow designers to quickly sketch a building and evaluate the related aspects of energy collection and energy consumption. Other more methodical BES tools, like *OpenStudio* and *eQuest*, allow the user to step into deeper investigations through the connection to sophisticated energy simulation engines like *EnergyPlus* or *DOE2*. In this process, the definition of additional parameters such as construction materials, occupancy, and technical systems allows the user to run more comprehensive simulations and retrieve more detailed feedback on factors such as internal gains, envelope losses, lighting consumptions, etc. Finally the use of CFD engines allows predicting the behavior of airflows inside and outside buildings. As highlighted by the review of Zhai (2006), the application of CFD to building design gained momentum a bit more than a decade ago and is used in fields such as site planning, pedestrian comfort, wind loads, heat transfer, natural ventilation, design of HVAC systems, pollution control, and wind power. Nowadays, as highlighted by a recent and more technical survey by Blocken et al. (2014), CFD engines are widely used in indoor applications, but seem to be less used in outdoor studies. The reasons behind this include the difficulty of defining accurate boundary conditions, and the huge time necessary to define and compute an accurate simulation. Recent interdisciplinary experimentations (Kaijima, et al., 2013) demonstrated that, in relation to the architectural domain, CFD remains a complex discipline that requires deep engineering knowledge in fluid mechanics and building physics and that a correct and accurate use of CFD remains of difficult access to architects. Attempts of simplification and integration of CFD means in architectural modeling environments like the *Vasari Wind Tunnel*, present improved user-friendliness and visual feedback, but involve a critical loss of quantitative accuracy and import/export flexibility, which are necessary to address specific problems and set up accurate experiments.

Current developments in environmental simulation tools suggest further progress towards simplification and towards the integration of SDT, BES, and CFD in architectural modeling programs. However, whether all these tools will have an impact on the generation of really innovative design solutions is a question open to debate. To develop this question some research efforts are currently focusing on the process of using these tools rather than on the tools themselves. The goal is to investigate, if beside mere verification, the use of digital simulation tools could allow to set-up processes capable of identifying or generating better design solutions. This field of research, introduced in the next section, is also the field in which this research work wants to offer its contribution.

1.3.4 State of Research in Digital, Environment-Related, Performance-Oriented Design Processes

Generally speaking simulation tools allow estimating the performance of an existing design sketch, which is then possibly ameliorated through an iterative process as illustrated in Figure 3. In this context, 'generative design processes' are defined as processes that enable the examination of a great number of design possibilities, exploring the variations of parametric models. Current research efforts focus on the partial or total automation of performance-based iterative processes to identify smart design solutions through single- or multi-objective heuristic strategies (Leonardo & Oscar, 2013).

Examples of these studies concern the shape of curved photovoltaic surfaces (Cheng, 2009), the optimization of semitransparent photovoltaic facades (Choo & Janssen, 2014), the balance between the minimization of heat losses and the maximization of solar gains (Janssen, 2009) (Caldas, 2007) (Marin, et al., 2008), passive solar strategies in large buildings (Turrin, et al., 2010), the influence of the shape and orientation of buildings on heating demand (Aksoy & Inalli, 2006), daylighting questions (Castorina, 2012), the generation of form according to energy harvesting objectives (LaBelle, et al., 2008), the coupling of airflow and energy simulations (Yi & Malkawi, 2012), or multicriteria optimization and use of metamodeling in building renovations (Chantrelle, et al., 2011) (Geyer & Schlüter, 2014).

Other research works are instead based on studies of comparative analysis. By examining the performance of a series of real or fictional cases, they try for example to clarify the relationship between architectural form and solar energy in a global context (Rullán-Lemke, 2009), or the role of urban form in relation to daylighting and solar potentials (Montavon, 2010) (Kämpf, et al., 2010).

1.4 Rationale: Before Conception

Through analyzing the research on simulation tools and on the related design processes, it can be observed that they are all based on the same surface-based paradigm: an initial building sketch defined by a set of surfaces is always a necessary prerequisite to start the process (see Figure 3).

Figure 3: Iterative performance-based design process.

As highlighted by Zarzycki (2010) this situation often ends with a conceptual entrapment that resembles the 'chicken-and-egg' problem: a sketch of the building is necessary to run the simulation, and in turn, the aim is to use the simulation results to generate the building sketch. Consequently, the relationship between this closed system and the generation of truly novel design conceptualizations seems to be limited and hugely dependent on the initial constraints set by the designer (question mark in Figure 3).

From this perspective, generative systems that are supposed to be able to generate new design solutions, result to be instead highly constrained by their own definitions (i.e. the parametric-model) and can act only within the boundaries in which they have been defined. Additionally, most of the cited approaches rely on abstract and simplistic schemes that are often disconnected from the specific nature of complex urban sites, an aspect that can have a crucial influence on the performance of urban buildings.

On the other hand, the generalizations extracted from the cited comparative studies are based on the evaluation of existing or imaginary cases and are therefore feebly capable of proposing inventive solutions.

In order to release the conceptual process from these self-referential traps and to place the urban environment at the inception of the process, a radical shift was proposed. A new approach, that is neither simulative, in the meaning of a verification of assumptions, nor generative, in the meaning of the exploration of the solution space of a parametric model, is suggested.

1.5 Hypothesis and Research Questions

Instead of evaluating the performance of an existing design and improving it through performance analysis, it is suggested to start by evaluating the environmental resources of an urban site and to retrieve from it the initial design propositions. The development of new means of analysis, evaluation, and synthesis, tailored to the physical properties of urban sites could thus catalyze the conception of new design concepts that preempt environmental performance.

The research questions related to this hypothesis are:

- Which approach would allow a comprehensive examination of the environmental resources of urban sites?
- What kind of analytic techniques are necessary to uncover these resources?
- What would be the most suitable means to visualize and evaluate the analytic results?
- How would it be possible to transfer the relevant information to the conceptual design phase?
- What would be the impact of such an approach on the design process and on the design results?

1.6 Proposed Approach: Volumetric Site Analysis (VSA)

As mentioned, in traditional site analysis (Olgyay, 1963) (White, 1983) (Brown, 1985), a building site is usually considered as a single entity for which a series of climatic and contextual variables are retrieved. The aim, oriented to the urban context, is to advance the analysis to the entire volume of the site. The goal is to develop the ability to capture and represent, in a coherent and joint way, a set of important volumetric physical properties that are typically invisible, such as solar radiation, airflow and visibility.

The volumetric analysis of airflows can be achieved in a relatively straightforward way applying existing CFD methods. These methods are in an advanced state of development thanks to ties with various big industrial fields such as the automotive sector and other manufacturing industries. Inversely, the volumetric analysis of solar radiation and visibility in urban settings is a rather undeveloped field.

The field of spatial analysis, pioneered by Hillier and Hanson since the 80's (1984), has produced a number of large-scale urban simulation platforms having different purposes such as *Space Syntax*, *UrbanSim*, *MATSim*, *CitySim*, etc. However, direct utilization of these tools in building-scale architectural design processes present major shortcomings. The large scale of these tools involves an elevated degree of abstraction, a scarce spatial resolution, and usually the limitation to the two horizontal dimensions.

In the last years, few and partial experiments have started to address environmental properties in the urban context at a finer level. In terms of solar radiation, examples are given by the surface-based urban environmental simulation program *Solene* (Miguet, 2007), the urban open-space analysis software *Townscope* (Teller & Azar, 2001), the link between the lighting engine *Radiance* and the volumetric grid of *Ecotect* (Marsh, 2006), and the development of new sky models able to address the penetration of solar radiation in urban settings (Compagnon, 2004) (Robinson & Stone, 2004).

In parallel, in the field of urban visibility analysis, different concepts such as isovists, viewsheds and visibility graphs (Tandy, 1967) (Benedikt, 1979) (Turner, et al., 2001) have been proposed to describe the visibility of volumes or areas from a given viewpoint. Recently, these methods have been expanded to also analyze 3D urban sites (Van Bilsen & Poleman, 2009) (Van Maren & Ma, 2012) (Suleiman, et al., 2012), but none of the proposed approaches was used to describe visibility in urban sites, neither at a volumetric level nor at a directional one.

Generally, a comprehensive approach, that allows the integration of the volumetric analysis of multiple variables into conceptual design processes, is clearly missing. Additionally, several reviews on simulation and visualization techniques (Donn, et al., 2009) (Srivastav, et al., 2009) stated a need for new methods to analyze site-related variables in their full temporal and spatial dimensions. To address these necessities and to verify the research hypothesis stated in the previous section, a new methodology entitled Volumetric Site Analysis (VSA) was proposed. Technically, this methodology has been developed using the open source programming language 'Processing' and some of its libraries (Fry & Reas, 2014).

The logic behind this approach draws inspiration from the volumetric means of CFD and presents some similarities to some cellular design methods that have been proposed for shading design (Kaftan & Marsh, 2005) (Sargent, et al., 2011). In particular, these methods include simulation and mapping techniques capable of handling and visualizing volumetric tensor-fields through color-mapped point-clouds or vector-fields. In this approach, instead of using CFD as an instrument of validation, the aim is to exploit it as a source of suggestion and to extend its volumetric logic to other variables like solar radiation and visibility. The idea is to anticipate the use of simulation from 'early-design' to 'pre-design' phases, empowering Site Analysis, which is usually limited to the use of tools like Wind Roses and Sun Path Diagrams (see Section 1.3) with new computational means.

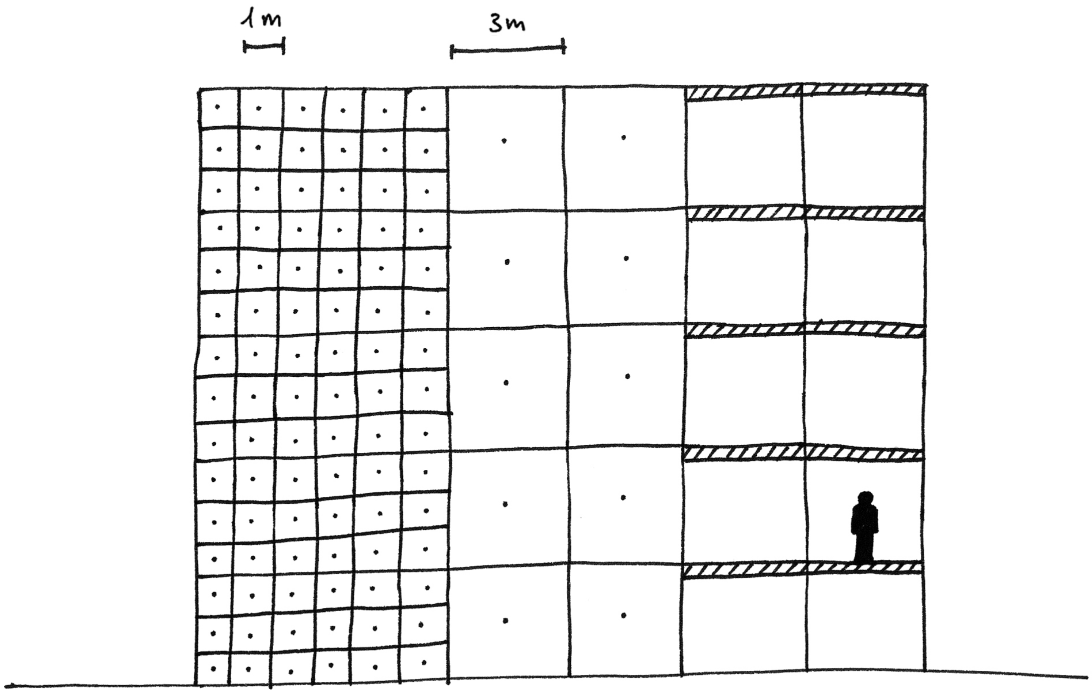


Figure 4: The Volumetric Site Analysis transition matrix.

As shown in Figure 4, the whole approach relies on a discretization of the unoccupied space of a site into an orthogonal matrix of points. At each of these points, different physical properties (radiation, airflow, visibility) are computed through several analytic processes. The computed values, which have either a scalar (v) or a vectorial ($\vec{v} \rightarrow v_x, v_y, v_z$) structure, are then stored into a multidimensional multivariate data set ($\vec{v}, w, \vec{u}$ ...) according to the four spatiotemporal dimensions of the site (x, y, z, t). This data is then made accessible to the architectural designer through a custom visualization framework.

The term 'Volumetric Site Analysis' is used to describe both the analytic phase and also the wider conceptual process that follows the analysis, and includes additional methods of visualization and synthesis. The term 'volumetric' has been chosen for simplicity, however, the methodology involves other important aspects related to 'magnitude', 'dynamics' and 'directionality'; but the volumetric aspect remains its main specificity.

The volumetric grid of the site has a base resolution of 1 meter and can be also visualized in a coarser resolution of 3 meters retaining the values of the central voxels (pixels of volume) or computing an average. While 1 meter is the fundamental unit of length, 3 meters (or 10 feet) is an interesting architectural dimension for multiple reasons: First, it is a common story height (IRAP, 2006), and second, because a room of 3x3x3 meters can also represent a unit of architectural space (see Figure 4). This matrix, thus, allows interesting transitions from an analytic and computational logic to an architectural one. Additionally, in large-scale sites, a higher resolution of 9 meters can be used to simplify visualizations.

In order to address the challenges related to the mentioned approach, an interdisciplinary research setting was set up. This setting is based on a strong horizontal integrative effort among the disciplines of: architecture, physics, building technologies, computer science, and engineering.

1.7 Envisioned Scope

The envisioned users of this technique are architectural designers that are developing projects in urban contexts and are interested in environmental questions. In order to use the main features of the technique these users will need minimal familiarity with the handling and operation of digital data and digital modeling tools. Skilled users, fluent in digital simulation processes and algorithmic design techniques, would be able to exploit the technique in a more comprehensive way.

Once applied, this approach will allow users to observe the space-time of urban sites through a new perspective. Compared to traditional Site Analysis (see Section 1.3) this technique simplifies the information available for single points (see Figure 2), but gives in exchange an access to the whole volumetric dimension of the site. These new observations are supposed to allow the designer to retrieve beneficial suggestions in relation to passive, active and expressive applications, as proposed by the following examples.

1. Passive techniques:

- position, orientation and form of the building
- distribution of the architectural program
- definition of the topology of the building
- position, orientation and form of components (openings, balconies, overhangs, etc.)
- definition of solar heat gains
- use of daylight
- use of natural ventilation

2. Active technologies:

- distribution of photovoltaic surfaces
- distribution of thermally collective surfaces
- distribution of small wind turbines
- distribution of inlets and outlets of mechanical ventilation
- distribution of heat exchangers of air-source heat pumps

3. Expressive aspects:

- articulation of the site identity by reflecting the diversities that are present in its volume
- fusion of multiple functional implementations into cohesive concepts
- addition of a semantic layer that conveys the meaning of the developed concepts

1.8 The Apparent Paradox of Alteration

The specificity of Volumetric Site Analysis is to allow the evaluation of the resources of an unoccupied site before the conceptual design process. However, the future introduction of surfaces in the space of the site will obviously lead to the alteration of the observed values. This essential question could seem paradoxical. The generation of feedback on the interventions in the site is however not the goal of VSA. For this purpose, a number of existing surface-based tools and methods are much more suitable. The goal and the value of VSA are instead to allow the designer to extract preliminary inspirations and advice from the space-time of the empty site with methods tailored to the genesis of the very first sketch of the building. Once the first sketch is established conventional performance-oriented simulation processes (see Section 1.3.3) can be used to validate or to further develop the building sketch.

VSA allows however, to some extent, to guess the effects of future interventions even not knowing them in detail. The key lies in the directional nature of the environmental properties. This directional information in fact allow formulating predictions on the effects of future interventions. In the case of rays, or lines-of-sight, this can be done by simple geometrical projection, and in the case of airflow by considering simple rules on how airflows react to a range of different forms (Olgyay, 1963, pp. 94-112) (Bernaek, 1984) (DeKay & Brown, 2014, pp. e.292-296).

In brief, VSA can be considered as an upstream process, complementary to existing simulation methods, dedicated to the genesis of the initial design propositions.

1.9 Demonstration Sites

The methodology has been developed and experimented using two different urban case studies. The sites of these case studies have been chosen to span from the lower to the upper limit of the application range of the methodology.

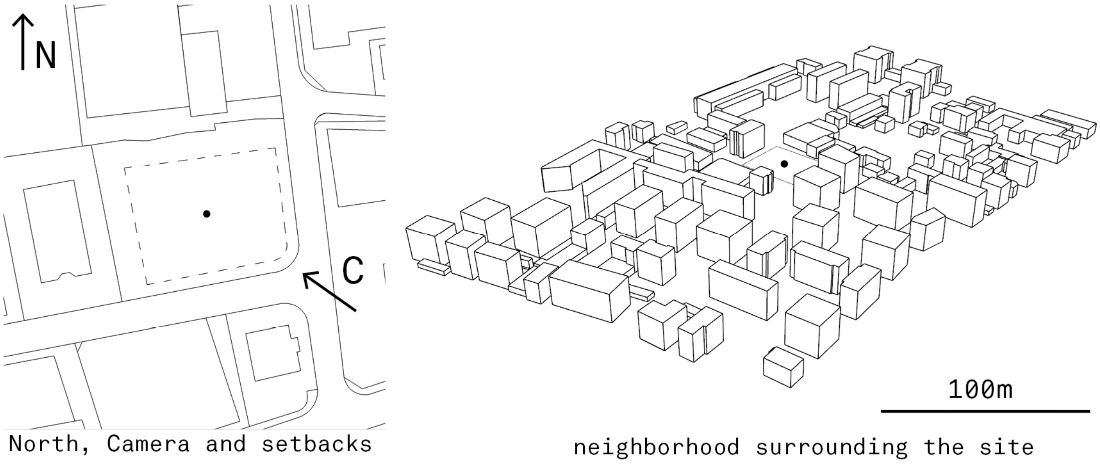


Figure 5: Mid-rise demonstration site.

The first case (Figure 5) concerns a mid-rise context with a typical building height of 20 meters and is located at mid latitude (46°N) in the city of Lugano in Switzerland. The site is situated in the middle of an urban residential area in the position illustrated by the black dots in Figure 5. The limits of the site are given by a maximal construction height of 21 m and by setbacks of 3 m from streets, and of 7 m from other parcels (see dashed line on the left side of Figure 5). The camera arrow (C) indicates the direction from which most of the perspective images of this report have been taken.

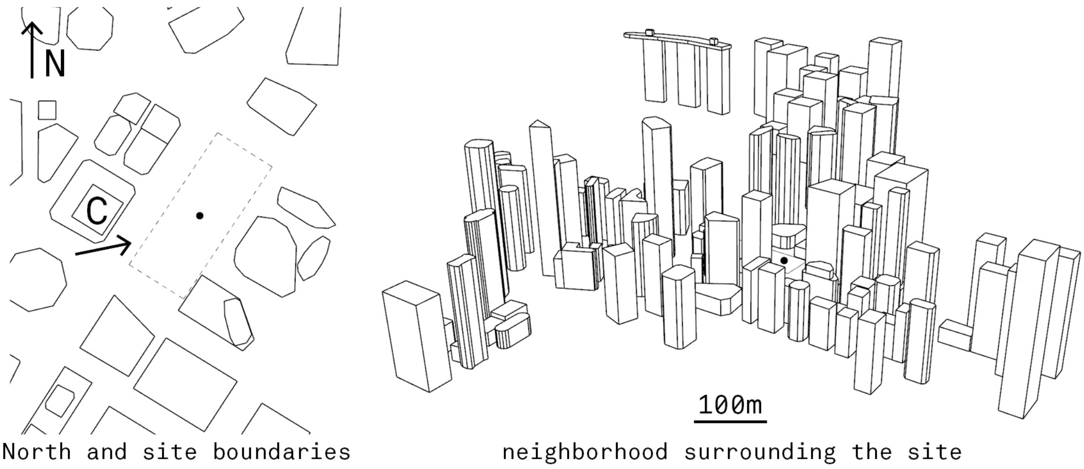


Figure 6: High-rise demonstration site.

The second case (Figure 6) concerns instead a high-rise context, with a typical building height of 200 m, and is located at the equator, in the city-state of Singapore. The site is situated in the middle of an intricate business district close to the sea, and its limits are given by a maximal construction height of 290 m and by its parcel boundaries (see dashed line on the left side of Figure 6).

Several examples taken from these two cases will be used in this report to illustrate the process and its methods. Further details on these sites can be found in Section 3.1 (mid-rise site) and Section 3.2 (high-rise site).

2 METHODS

2.1 Process

To address the mentioned research questions, a whole new conceptual design process was developed and experimented. As illustrated by Figure 7, this process is based on several successive steps. The focus of this research was on two levels: at a higher level, on the entire process itself, and at a lower level, on the methods that had to be developed to achieve some of the steps of the process. The steps marked in black in Figure 7 are simple procedural tasks, those in blue are based on existing methods, and those in red are the methods that have been developed on purpose.

The process starts with preliminary steps such as the allocation of data and the assessment of demands. Successively the site is analyzed through Volumetric Site Analysis and the results are made available in a visualization framework. This interactive framework allows for exploration of the environmental information and the combination of the identified resources with the demands and other constraints of the project. Finally, the visualization framework allows exporting the resulting 2D and 3D representations, and procedural instruments such as Observation Records and Directionality Graphs facilitate the synthesis of Design Schemes that can eventually be verified through a validation process.

This 'Methods' section describes the details related to all the steps of this process.

The still two-dimensional images of this dissertation represent only a limited view of the multidimensional and multivariate features of VSA. Before reading this section, it is thus recommended to view the related online videos entitled 'Exploring Urban Space' (Leidi & Schlüter, 2013b) and 'Conceiving Design Schemes of Urban Architecture through Volumetric Site Analysis' (Leidi & Schlüter, 2014c).

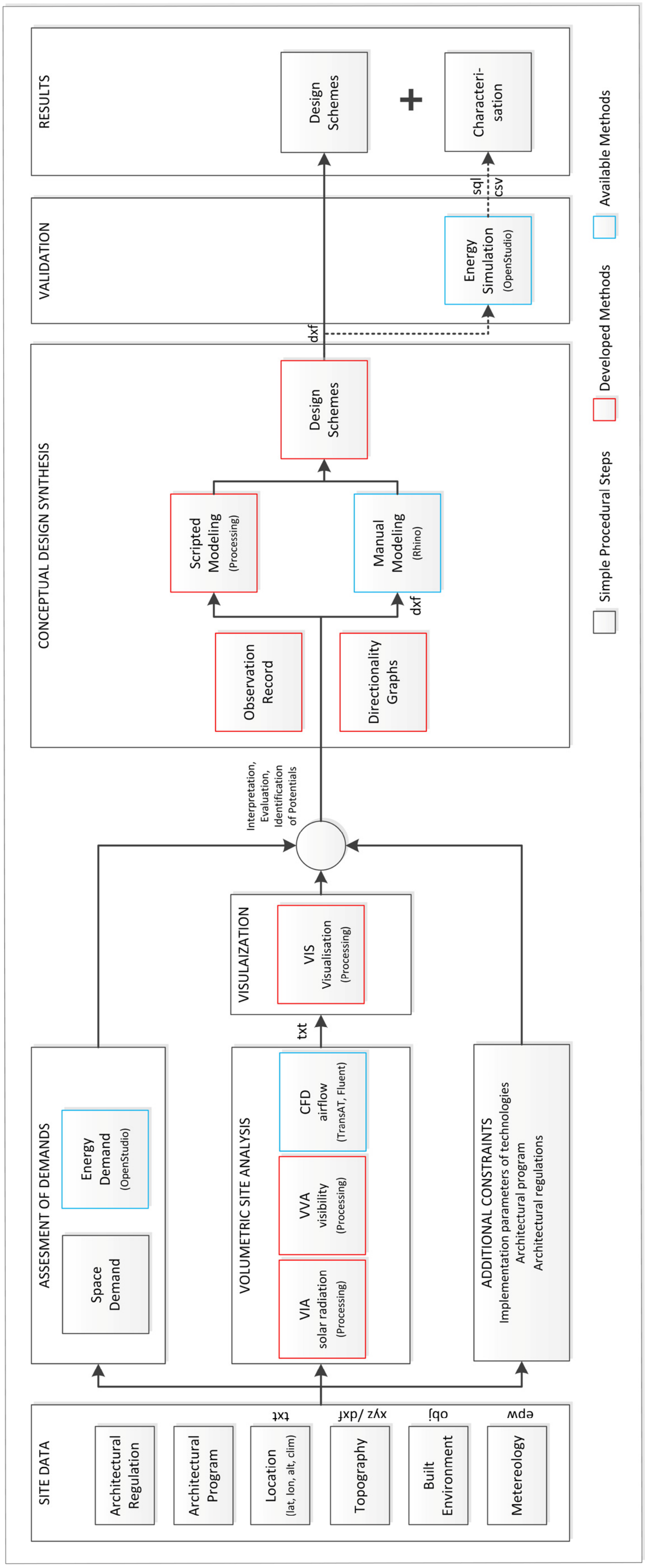


Figure 7: Process of the Volumetric Site Analysis methodology.

2.2 Preliminary Steps

2.2.1 Data Allocation

The first step of the process is to allocate data on the site and on its surrounding area. The information necessary to run VSA typically includes:

- The latitude, longitude and altitude of the site that can be retrieved from geographical maps or geographical information systems.
- Climatic information on the site, particularly the daily and yearly temporal evolutions of temperature, humidity, solar radiation, wind, etc., that can be retrieved from global meteorological databases (e.g. *MeteoNorm*) or from collections of climatic data.
- The spatial boundaries of the site, and the morphology of all the surrounding buildings that have a relevant influence on environmental resources. This information can be retrieved from cadastral offices or through onsite geometric measurements.
- The topography of the site area that has an influence on the environmental properties. This information can be retrieved from digital elevation maps or topographical offices.
- The legal boundaries of the site defined by the local architectural regulation.

It is important to retrieve this data with accuracy because it will be the main subject of the whole investigation. The proposed process relies in fact on nothing else than new principles of data analysis and data mapping. In recent years, digital data, and digital methods to process it, have become increasingly available. This trend is making architects more and more familiar with using such techniques in the design process. Examples of them are digital drawing, algorithmic design, building information modeling, digital topographical maps, and physical simulations. Additionally, digital data has started to become freely and easily accessible through the Internet. Examples of open data sources that have been used in this project are the geographic information system *Google Earth* (to retrieve latitudes, longitudes and altitudes of sites), the digital elevation map 'DHM25' (SwissTopo, 2014), and free meteorological normal values on temperatures and winds (MeteoSwiss, 2014).

This research inscribes itself to the trend of growing digitalization and accessibility of data, with the perspective that architects will anyway become more and more fluent in accessing this data and in using these methods in the close future.

2.2.2 Demand Assessment

Every architectural project presumes certain quantitative and qualitative demands in terms of space (floor surfaces, uses, daylight, sights, etc.) and energy (cooling, heating, electricity, etc.). Before starting to analyze the environmental resources, some basic features of demand need to be assessed to define the objectives of the future investigation. However, in a pre-conceptual phase the formal or material details on the project are not yet defined. For this reason two generic reference models will be used to predict the space and energy demands of the project.

Space Demand

The first aspect of demand concerns the requirements of the project in terms of spaces and uses in relation to the architectural program. To illustrate the Space Demand assessment procedure the mid-rise site will be used as an example (see Section 1.9). In this site, the use of the spaces is envisioned to be residential and the gross floor area to be distributed is 3'249 m^2. Additionally, the spaces have to be arranged over a maximum of seven floors and have to respect the setbacks from the parcel boundaries.

With this information, it is possible to establish a reference configuration for the distribution of space. For this purpose, as illustrated in Figure 8, a number of architectural units of space, of 3x3x3 meters, are positioned according to a conventional configuration and respecting the space demand and the existing regulations. This model allows the user to both dispose of a reference configuration for the future evaluation of alternative solutions and to make an estimation of the energy demand of the project.

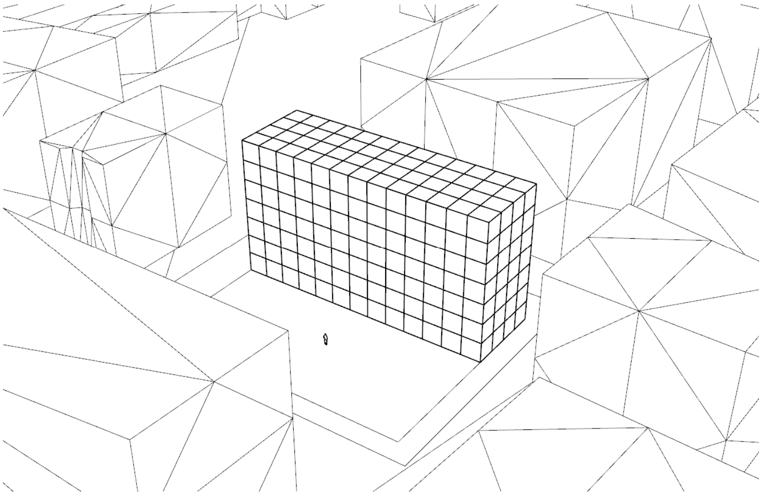


Figure 8: Reference model with conventional configuration of spaces.

Energy Demand

The second important piece of information to be assessed is in fact the energy demand. Given the dynamic nature of environmental resources, the dynamic information of energy demand, and in particular the occurrence of peaks, play a relevant role to attain a good demand-supply match. To estimate the dynamic pattern of the energy that is required for thermal regulation, electrical appliances, and lighting, it is possible to employ typical load profiles corresponding to the use and the location of the project (Knight & Ribberink, 2007). Another possibility is to perform dynamic energy simulations through tools such as *OpenStudio* (NREL, 2014). These simulations are preferable over the reference figures because they allow consideration of several important project-specific factors such as building parameters, local climate, and the geometry of the surrounding area. The building parameters to be defined to run these simulations include wall-window ratios, materials, internal gains, airflows, occupancy, etc. By applying to the reference model of Figure 8 known, best-guessed, or average building parameters and the envisaged use (residential, commercial, etc.), it is possible to establish the energy model illustrated in Figure 9. This model allows running simulations to obtain an estimation of the dynamic nature of the project's energy demand.

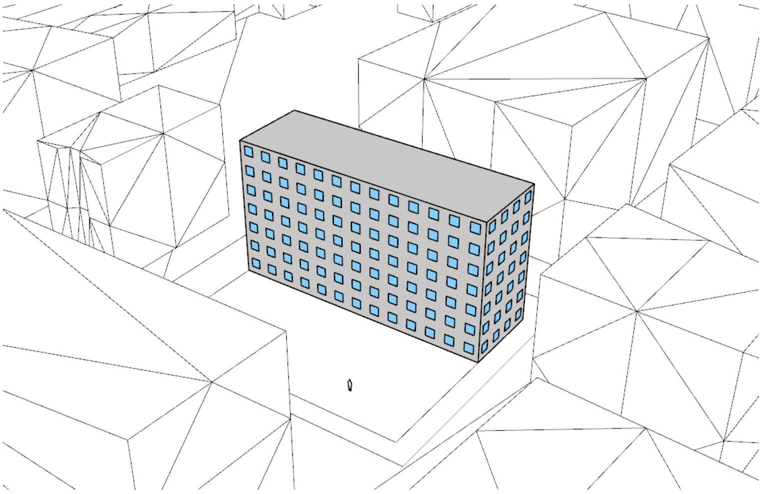


Figure 9: Energy model for the estimation of the energy demand.

In addition, some of these tools are also able to deliver some information on the renewable energy sources available on site, such as wind power and solar energy. In the illustrated example the information on the solar energy incident on all external surfaces of the energy model of Figure 9 was retrieved.

Figure 10 illustrates the energy patterns resulting from the simulation of this model, for both the yearly (left) and the daily (right) cycles. The two upper graphs illustrate heating (red), cooling (blue) and electricity (green) demands as separated components. The two lower graphs illustrate the sum of these components (grey) and the solar energy incident on the building (yellow) using a different scale on the vertical axis.

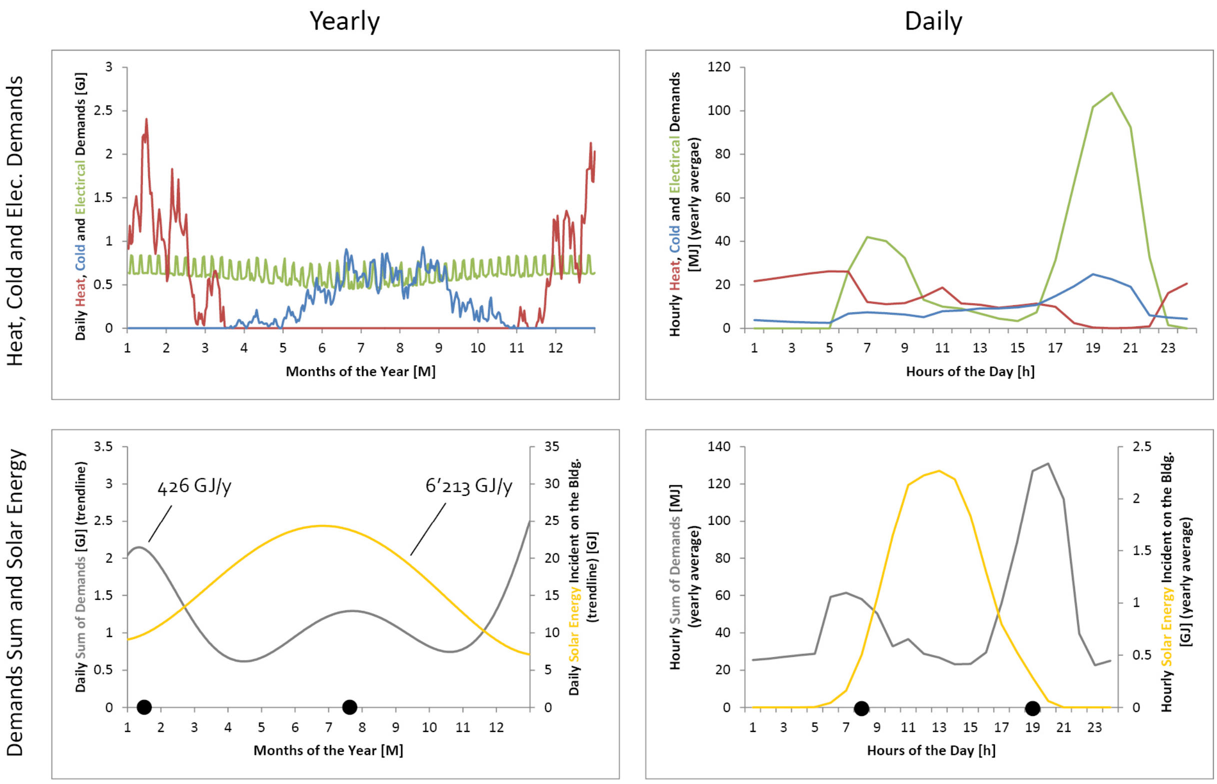


Figure 10: Dynamic patterns of energy demand and solar supply for the yearly and daily cycles.

In terms of total amplitude it can be remarked that the yearly energy demand amounts to 426 Gigajoules (GJ) and the yearly incident solar energy to 6'213 GJ, namely about 15 times more. This ratio highlights the abundance of solar energy even if the efficiencies for energy collection, storage and diffusion were taken into account. However, if the objective was to cover the demand with the available solar supply, then the two lower graphs highlight an evident dynamic mismatch between the curves of demand and the curves of supply at both daily and yearly scales.

Many approaches have been developed to tackle this dynamic mismatch issue. These approaches can focus on the demand side, on the supply side, or on the way these are coupled. In the architectural context, examples of actions that influence demand patterns are the modulation of solar heat gains (see Annex) or the reduction of the demand peaks adapting the behavior of the occupants or the use of electrical appliances. On the other hand, examples of supply management concern the optimal positioning and orientation of photovoltaic panels or wind turbines. Finally, regarding the coupling of demand and supply, the common practice is to cover the remaining mismatch by relying on electrical and thermal storage, either locally or through networked systems.

One of the new opportunities offered by VSA is to investigate whether more detailed information on the dynamics of the environmental resources could allow for the development of new solutions that would offer a better demand-supply match. To explore this possibility, it is necessary to retrieve information in relation to the temporal occurrence of the energy demand peaks in both the yearly and daily cycles. This temporal information will successively allow for the implementation of corresponding passive measures, to reduce the demand peaks, and corresponding active measures, to shift the supply peaks closer to the remaining demand peaks.

The four black dots in Figure 10 illustrate the occurrence of the four demand peaks of this model. In selecting these occurrences, it is important to both target the demand peaks and also to verify that at these instants the supply possibilities (yellow curve) are not totally absent. The following information has been determined from the graphs of the example in Figure 10:

- 1st month winter heating peak
- 7th month summer cooling peak
- 8th hour morning electricity peak
- 19th hour evening electricity peak

On this basis it is possible to define further objectives and their temporal correspondences on additional passive and active aspects such as solar heat gains, daylight, shading, ventilation, electrical collection, thermal collection, etc. This information will be useful later in the process to achieve beneficial matches combining these demand peaks with the dynamic information on environmental resources that will be made available by VSA.

2.3 Analysis Methods

Several analytic methods are necessary in order to evaluate the distribution of the environmental resources through the volume of an urban site. As illustrated in Section 1.6 the volumetric analysis of airflows can be achieved using existing CFD methods. New custom methods have instead been developed to analyze solar radiation and visibility at a volumetric level. The next sections cover the details of the developed methods and summarize the implementation of regular CFD methods for the analysis of airflows.

2.3.1 Volumetric Insolation Analysis (VIA)

Introduction

The common approach in exploiting solar energy in architecture is based on the maximization of the incident radiation on a given transparent or opaque surface. The global radiation on the surface is composed by the sum of the direct, diffuse, and reflected components. The direct component, arriving straight from the sun, represents in most cases the major part of the global radiation and is the only component with an easily definable direction. For most applications, the position and orientation of surfaces is therefore optimized towards the mean direction of the direct component with possible angular shifts due to higher heat demands in winter or higher electricity demands during certain hours of the day.

As illustrated in Sections 1.3.1, 1.3.3 and 1.6, many tools and methods are available to simulate the interaction between solar radiation and buildings. However very few address the analysis of the urban space and none is able to deliver information at all quantitative, volumetric, directional and dynamic levels. For this purpose a methodology entitled Volumetric Insolation Analysis (VIA) that allows assessing the relative distribution of direct solar radiation in urban sites (Leidi & Schlüter, 2011) was developed by recompiling existing textbook models (Duffie & Beckman, 2006).

Insolation (solar radiation energy) is traditionally computed for surfaces. VIA expands the analysis to the whole volume of an urban site including features of dynamics and directionality. The objective is to identify ideal positions and directions of future surfaces, taking also into consideration the effects of the surrounding topography and built environment.

The principle of VIA consists in tracing for every point of the site a set of rays in the direction of the sun, and then verifying if the rays are obstructed by an obstacle. If the rays reach the point without any obstruction, then the insolation values of the ray are added to the point, taking into consideration also directional and dynamic information.

```
Import site parameters
Import obstacles and transform them into triangles
Create sensor points representing the site volume
Create rays with a specific time interval over a specific period

For each point
   For each ray
      For each triangle
         Test ray-triangle intersection
         If the ray is reaching the point, add ray values to the point
```

Figure 11: Pseudo-code of the VIA method.

Modeling of Site and Proximity

Several parameters have to be taken into consideration in order to perform the analysis: the sun path at the site (influenced by location, day of the year, and time of the day), the geographical situation (local altitude and climate type), the surrounding environment (topography and buildings), and the volume of the site itself. In a first step (see pseudo-code in Figure 11), a 3D model containing the topography and the built environment of the area surrounding the site is established by importing terrain elevation points and building geometries. Topography and buildings are then transformed into a series of triangles to allow for faster treatment during the analysis process (see Figure 12). In a second step, the empty volume of the site itself is discretized into an orthogonal three-dimensional grid of points for each of which the insolation will be computed. Finally, to calculate the insolation, a set of sunrays has to be generated according to the sun path.

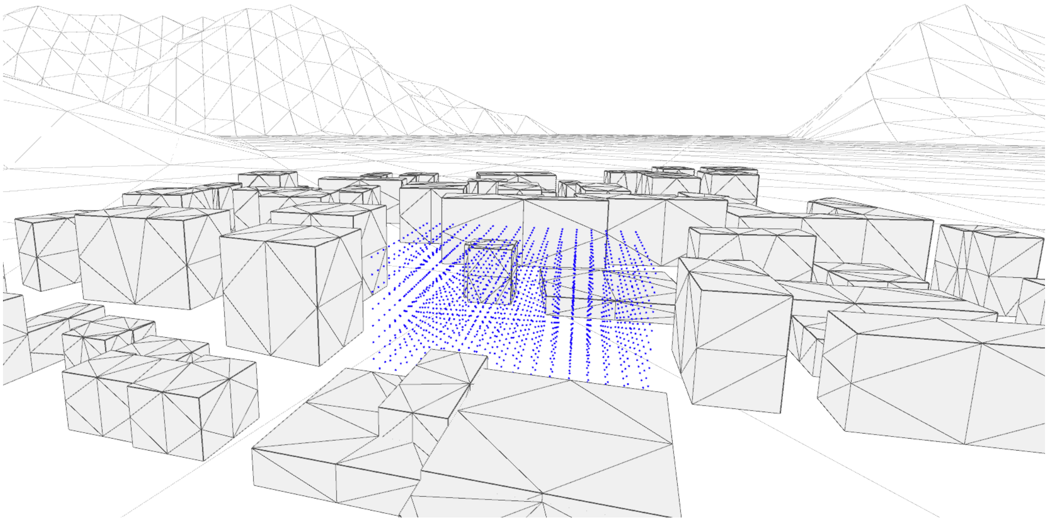


Figure 12: Site discretized into a grid of points surrounded by buildings and topography represented by a series of triangles.

Generation of Rays

As described in the book by Duffie and Beckman (2006), the direction of the sun can be retrieved from simple parameters like the latitude, the local hour, and the date of the observation.

As illustrated in Figure 13, geometrically this direction is defined by the zenith angle (θ_z), the angle between the vertical and the line to the sun, and the azimuth angle (γ_s), the horizontal angle between the south and the vertical projection of the sun.

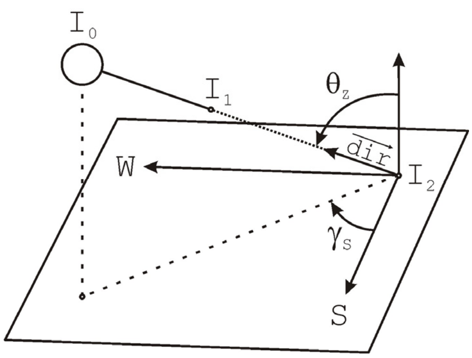


Figure 13: Ray direction and irradiances.

These two angles (see eq. 1-2) are defined by the latitude of the site (φ), the declination angle (δ), and the hour angle (ω).

$$\theta_z = \cos^{-1}(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta) \quad (1)$$

$$\gamma_s = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta_z\sin\varphi - \sin\delta}{\sin\theta_z\cos\varphi}\right)\right| \quad (2)$$

In turn the declination angle (δ), and the hour angle (ω) are defined by the day of the year (n) and the solar time of the day (st).

$$\delta = 23.45° \ \sin\left(360\frac{284+n}{365}\right) \quad (2)$$

$$\omega = 15°(12 - st) \quad (3)$$

The solar time (st) can be calculated from the local time (lt), the local time zone (ltz), the meridian of the observer (obm), and a correction by the equation of time (e).

$$st = lt + 4((15°\ (ltz)) - obm)\ + e \quad (4)$$

$$e = 229.2(0.000075 + 0.001868\cos b - 0.032077\sin b - 0.014615\cos 2b - 0.04089\sin 2b) \quad (5)$$

where $$b = (n-1)\frac{360°}{365} \quad (6)$$

Through a first verification it is then possible to discard the rays obstructed by the earth by checking if the hour angle is in-between the sunrise and sunset angles.

$$\omega_{sunset} = -\omega_{sunrise} = \cos^{-1}(-\tan\emptyset\tan\delta) \quad (7)$$

Finally, the computed zenith (θ_z) and azimuth (γ_s) angles are used to generate the components of the vector that points in the direction of the sun ($\overrightarrow{dir}$), which is successively normalized.

$$\begin{aligned} dir_x &= \cos(90° - \theta_Z)\sin\gamma_s \\ dir_y &= -\cos(90° - \theta_Z)\cos\gamma_s \\ dir_z &= \cos(90° - \theta_Z) \end{aligned} \quad (8)$$

Using these calculations a set of rays (see Figure 14) can be generated according to specific hourly and daily time intervals of choice, for example for every 30 minutes of each 5th day, and for a specific period of choice, such as an entire year.

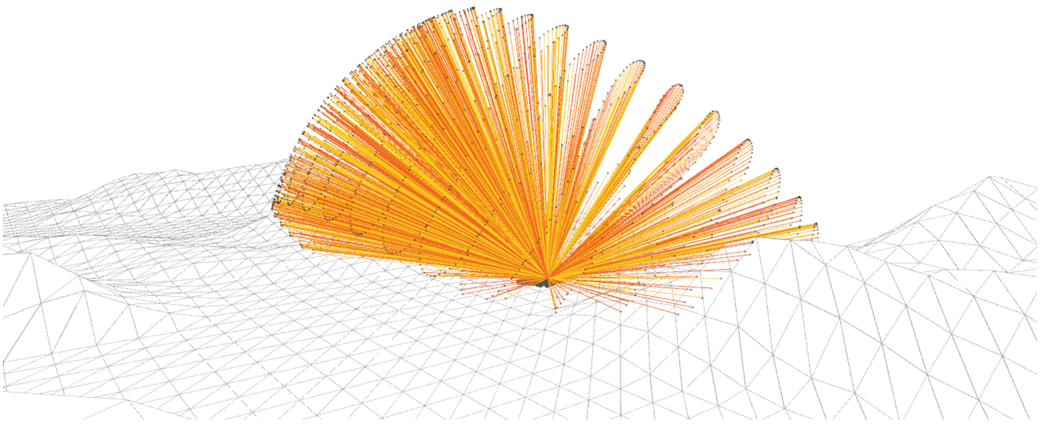


Figure 14: Example of a set of rays, with a ray generated every 30 minutes of each 5th day of the year.

Calculation of direct irradiance

Each generated ray will have a different irradiance (power incident on a surface) due to the sun-earth distance of its specific occurrence and because of the different mass of air to be crossed in the atmosphere, inducing more or less losses. The solar constant ($I_0 = 1367\ W/m^2$) is the irradiance received outside of the atmosphere at the mean sun-earth distance (see Figure 13). To estimate the extra-terrestrial irradiance (I_1) the actual sun-earth distance is taken into consideration according to the current day of the year (n) and the elliptic orbit of the earth as illustrated in equation 9 (Duffie & Beckman, 2006).

$$I_1 = I_0 \left(1 + 0.033 \cos \frac{360\ n}{365}\right) \tag{9}$$

Finally, the direct irradiance at the earth's surface (I_2) can be calculated by applying a transmittance factor (τ) to the extra-terrestrial radiation (I_1) to take into account the atmospheric losses (eq. 10). A simplified method introduced by Hottel (1976) allows the evaluation of the atmospheric transmittance through clear atmospheres (eq. 11). In this model the transmittance factors (a_0, a_1, k) depend on the altitude of the site and on the local climate type.

$$I_2 = \tau\ I_1 \tag{10}$$

$$\tau = a_0 + a_1\ e^{(-k/\cos\theta_z)} \tag{11}$$

Finally all these calculations allow obtaining a set of rays (see example in Figure 14) with all their directions ($\overrightarrow{dir}$) and their irradiances (I_2) known.

Intersection test

The core principle of the analysis consists then in verifying whether, for each point of the grid, the sunrays reach the point or are blocked by an obstacle. The number of intersection tests to be performed, results from the multiplication of the number of points, rays and triangles, and can be considerably large. For this reason, a fast minimum-storage ray-triangle intersection algorithm from Möller and Trumbore (1997) has been used to perform the test. If it is verified that the current ray meets the current point of the volume without being obstructed, the following values are retrieved for each ray:

- the ray direct insolation time (T) in seconds (time interval at which rays were generated)
- the ray direct insolation energy in J/m² (irradiance I_2 multiplied by the time interval T)
- the ray direction as a normalized 3D vector ($\overrightarrow{dir}$)

The total insolation time and insolation energy are finally computed for each point by adding up the values of the related rays that join the point. The total values are computed through both scalar (eq. 12-13) and vectorial (eq. 14-15) addition.

$$T_s = \sum_i \; T_i \qquad\qquad I_s = \sum_i \; T_i I_{2i} \qquad (12\text{-}13)$$

$$\overrightarrow{T_v} = \sum_i T_i \, \overrightarrow{dir_i} \qquad\qquad \overrightarrow{I_v} = \sum_i \; (T_i I_{2i}) \, \overrightarrow{dir_i} \qquad (14\text{-}15)$$

In this set of results, the scalar values (T_s and I_s) represent the total amount of insolation arriving at a point independently from the directions, and the vectorial values ($\vec{T_v}$ and $\vec{I_v}$) represent instead the mean direction of insolation at a specific point obtained through a vectorial addition weighted over energy. $\overrightarrow{I_v}$ is typically used to retrieve suggestions to optimally position and orient energy collecting surfaces. The scalar value $|\overrightarrow{I_v}|$ will also correspond to the insolation energy incident on a surface in that position at the conditions that the surface is perpendicular to $\overrightarrow{I_v}$ and that all the rays reach its front face. It is however important to remark that using this direction to orient the collecting surfaces is a simplification that is not appropriate to every site and situation. To identify accurately the optimal directions, more detailed techniques, which are able to handle local maxima and minima, should be developed (Leidi & Schlüter, 2011).

These four calculations for each point of the grid produce a so-called 'multidimensional multivariate' (mdmv) scalar and vectorial dataset. This '3d4v' dataset represents the insolation within a volume in terms of both time and energy, considering magnitudes and mean directions over a defined period of time. Additionally, the calculation can also be done separately for a set of different time frames (e.g. at every hour of the day). This will result in a '4d4v' dataset representing the evolution of the insolation also over time.

The three basic simulations that are usually run for a new site on a yearly scale are the 3D yearly simulation, the 4D monthly simulation, and the 4D hourly simulation. Additional simulations could be run according to specific periods of interest that would correspond to particular daylight, shading, heat gains, or energy demands (see Section 2.2.2).

2.3.2 Volumetric Visibility Analysis (VVA)

Geometrically speaking, visibility is simple to define. Given a set of obstacles in space, two points are said to be visible to each other if the line segment that joins them (line-of-sight) does not intersect any obstacles. Based on this principle, a set of different volumetric visibility analysis measures have been developed exploiting the heritage left by previous researches (see Section 1.6).

The computational procedure of this methodology is very similar to the procedure used for the VIA methodology (see Section 2.3.1) but in this case lines-of-sight replace rays (see Figure 15).

```
Import site parameters
Import obstacles and transform them into triangles
Create sensor points representing the site volume
Create lines-of-sight according to the type of visibility

For each point
   For each line-of-sight
      For each triangle
         Test line-triangle intersection
         If the line is reaching the point add line values to the point
```

Figure 15: Pseudocode of the VVA method.

As shown by Figure 16 and Figure 17, visibility from a point can be quantified as a fraction of a visible area or volume. In this study, visibility was computed for the three different cases illustrated in Figure 16: as a fraction of a horizontal circle (HOR), as a fraction of a sphere (SPH), or as a fraction of a field of view (FOV). Given the fact that, for a human observer, an accurate perception of space becomes greatly inaccurate for distances over 100 meters (Oliva, et al., 2011), all these elements have been sized with this radius length. The FOV visibility has two vertical angular limits of +/- 30° that can represent the angular limits of color discrimination in the human field-of-view (ERM, 2009), or angular limitations given by the floor and the ceiling from a viewpoint inside a building. Each of these three cases, which can be selected depending on the goal of the analysis, delineates a different notion of visibility.

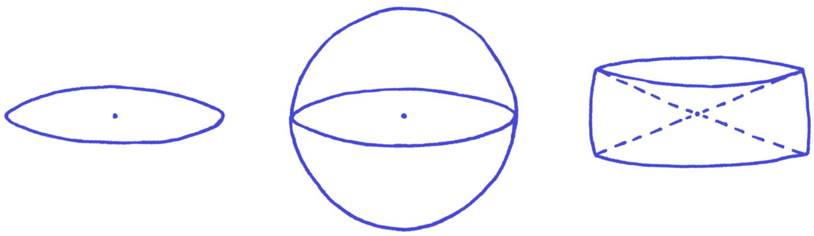


Figure 16: Horizontal (HOR), spherical (SPH) and field-of-view (FOV) visibilities.

As illustrated in Figure 17, for the quantification of visibility these areas and volumes are discretized in a series of lines-of-sight. A sphere or a field-of-view can be discretized into lines using the Rusin algorithm (Rutten, 2007) that allow distributing the lines in a uniform way in three dimensions. Imagining a number of small circles of radius r (representing the endpoints of the lines-of-sight) that need to be distributed uniformly around the surface of a bigger sphere of radius R (or a filed-of-view of angle α) then the number N of small circles that can be arranged over the meridian line (arc from the south pole to the north pole) is given by:

$$N = (int)\frac{\alpha R}{2r} \tag{16}$$

Each of these N circles can then be equally distributed over the meridian at intervals of latitude (φ):

$$\varphi = \frac{\alpha}{N} \tag{17}$$

Finally, at each of these latitudes, the number M of small circles that can be arranged on horizontal parallels around the sphere (or the field-of-view) is given by:

$$M = (int)\frac{\pi R \cos\varphi}{r} \tag{18}$$

Once this set of uniformly distributed lines-of-sight is created (see example in Figure 18), an intersection-test verifies if an obstacle obstructs the lines. If so, the distance between the viewpoint and the closest intersection point is computed (Möller & Trumbore, 1997). The addition of the lengths of all the lines, divided by the number that would be obtained in the case of an unobstructed situation, provides a percentage that can represent the relative visibility of the environment from that point of view.

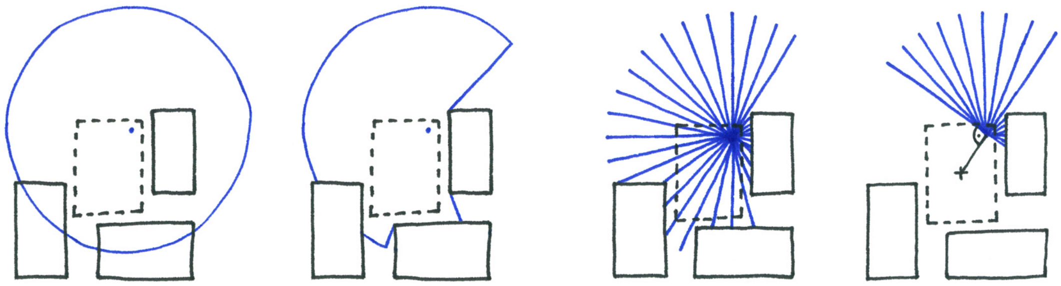


Figure 17: Isotropic (ISO) and outward (OUT) visibilities in the case of a horizontal circle (top-view).

So far scalar (SCA) information on visibility has been obtained. In order to obtain directional information, two additional methods were tested. Considering the lines as vectors starting from the viewpoint, and carrying out a vectorial addition (VEC), will allow to obtaining a directional result. However, given the isotropic (ISO) distribution of the lines in circles and spheres, the compensations of a vectorial addition often leads to results that are difficult to interpret. As an example, a point with full-visibility, or a point with equal visibilities on opposed sides, will both result in a null-vector. Additionally, in densely obstructed contexts the visibility measured through the space of the site itself will have a huge influence on the result, but in reality the future building will probably obstruct this space. The actual goal would be rather to measure the visibility 'from' the site 'to' the surrounding urban space. To obviate these issues a polarized analysis, called outward visibility analysis (OUT), has been tested. This method considers only half of the visibility area or volume that 'looks outwards' from the center of the parcel as illustrated in Figure 17 to the right. In this way, the directional deviations between the resulting vector and the radial direction will indicate a direction towards which visibility is higher. If the position of the future building is known and does not correspond to the center of the parcel, this new position can be taken as the center to define the outwards direction.

The combination of the previous HOR/SPH/FOV, SCA/VEC, and ISO/OUT variants, results in 12 different analysis methods each of which has its own specificity and meaning. For the purposes of this research the field-of-view, vectorial, outward method (FOV-VEC-OUT) presented a good compromise. Its balanced volume (between a circle and a sphere) and its ability to provide directional and outwards-oriented information made it the method of choice in all the studies that will be illustrated in this report.

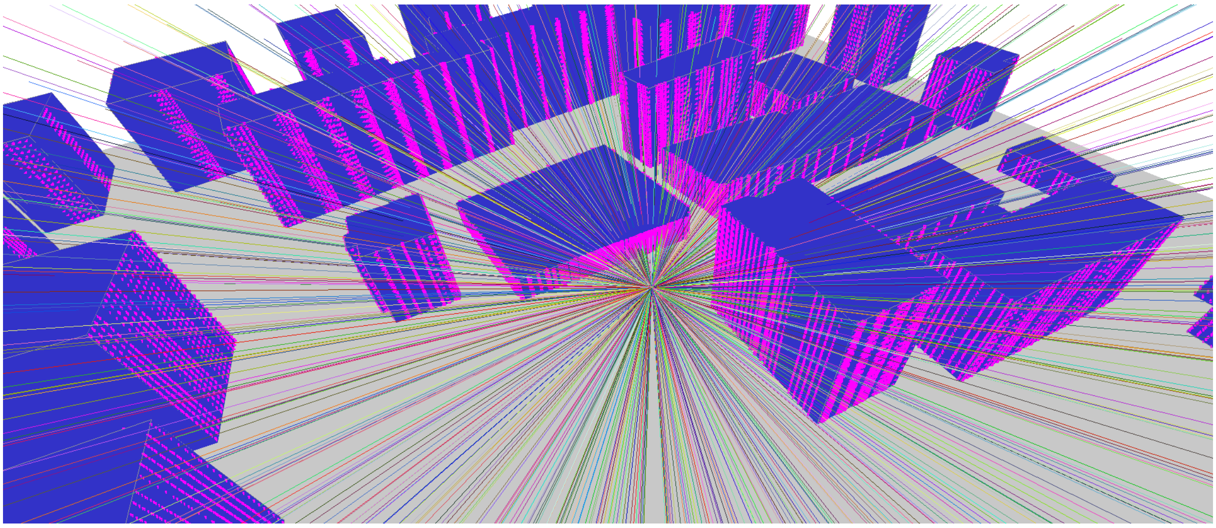


Figure 18: Example of spherical visibility analysis with lines-of-sight and intersection points.

It has to be remarked that these visibility analysis methods have been developed in a preliminary manner and require further developments and verifications.

2.3.3 Computational Fluid Dynamics (CFD)

For the analysis of airflows and turbulences, two different existing CFD engines have been used throughout the experiments. The first is called *TransAT* (Ascomp, 2014) and the second, *Fluent* (Ansys, 2014). Both engines allow sophisticated CFD simulations and enable the required import-export functionalities that are necessary to link the results to the custom visualization framework.

The CFD simulation process starts by acquiring the average annual wind speed in meters per second (m/s) and the average annual wind direction from the meteorological station closest to the site. If the wind speed is rather constant and the direction rather concentrated, a single average speed and angle can be selected. If the wind pattern presents instead different speeds and/or directional peaks, for example depending on the seasons, several simulations will be carried out with different input values.

Successively, the variation of wind speed in relation to the height (vertical wind shear) must be considered. At the ground level, obstacles and landscape roughness lower the wind speed, while high above ground, these effects no longer influence the wind. Knowing the height of the sensor (h) at which the average speed (v_0) has been measured and the roughness class of the landscape (z_0) it is possible to compute the vertical wind profile with a logarithmic formula (Manwell, et al., 2003):

$$v(z) = v_0 \frac{\ln(\frac{z}{z_0})}{\ln(\frac{h}{z_0})} \tag{19}$$

Finally some additional parameters, such as the 3D volumes of the neighborhood, the simulation domain size (Franke, et al., 2007, p. 49), and the position of the measurement points in the site volume, have to be defined. All this data is used to configure the CFD simulation that can be carried-out with a 3D, steady-state, Reynolds-Averaged Navier-Stokes (RANS) model. The outputs of this analysis are several scalar and vectorial fields that contain information on velocity (speed plus direction), pressure and turbulence intensity (ratio between the mean velocity and its fluctuation).

2.4 Visualization Methods

2.4.1 Visualization Elements

The aggregation of the results of the analytic methods presented in the previous section result in a complex multidimensional and multivariate dataset. To be able to visualize this dataset effectively a custom, flexible visualization framework has been developed. The framework illustrated in Figure 21 relies on different visualization elements, which allow volumetric, dynamic and directional representations, and on a graphic user interface that allows interaction with the data. The implemented visualization elements are shown in Figure 19. The first five elements shown in the image are common glyphs and surface-based volumetric visualizations. The last four illustrate a set of custom visualization elements have been introduced to enhance the visualization of certain features like the perception of directionality and the ability of visualizing oriented surfaces and volumes.

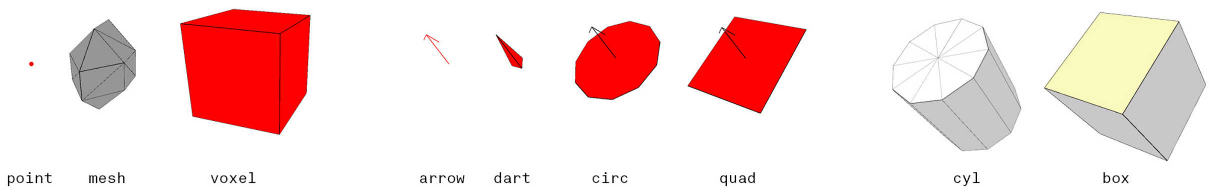


Figure 19: Set of visualization elements.

All these elements share the ability to visualize data dynamically and volumetrically. Red indicates that the color reacts to the magnitude of the element, ranging over a defined color-gradient scale. Other colors (grey, white, yellow, etc.) mean that, in these elements, the magnitude is disregarded and that they are displayed with fixed colors in order to focus the visualization on other aspects such as volumetries or directionalities (e.g. mesh, cyl, box). To point in specific directions, one surface of these elements may hold a particular fixed coloration depending on the nature of the data (e.g. yellow for radiation, blue for visibility, and white for airflow).

The left group of elements (point, mesh, voxel) is usually associated with scalar-fields, while the rest of the elements are used to visualize vector-fields. Figure 20 illustrates an example of how the perception of the same dataset can drastically change if different visualization elements are applied.

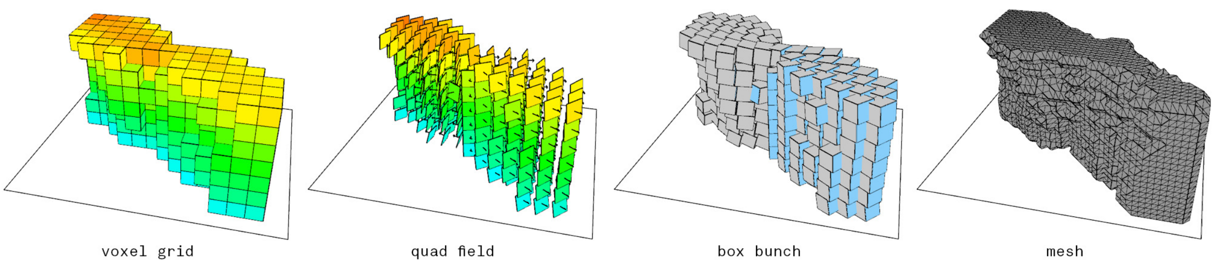


Figure 20: Different visualization elements applied to the same dataset.

These visualization elements aim at allowing a simple and direct interpretation of data in relation to the potential distribution of volumetric and directional items such as spaces, openings, photovoltaic surfaces, wind turbines and other, as listed in Section 1.7.

2.4.2 Interactive Interface

Often the complete display of complex datasets produces visualizations that are difficult or even impossible to interpret. In this context, one of the challenges is to find effective ways to visually represent the data to allow a simple and intuitive interpretation of information. For this purpose, filtration and interaction techniques to explore and understand the data play a crucial role in the visualization process. The graphical user interface of the framework allows users to set constraints on:

- variables (selection of a specific physical property)
- position (x-y-z slicing of the volume)
- value (min-max threshold values)
- grid resolution (1 meter or 3 meter grid-steps)
- time (selection of the active frame), etc.

Figure 21 illustrates this user interface and its multiple commands. Additionally, colors are used to visualize the magnitude of the resources. The units and scale of the color system are indicated in a legend at the bottom right of the interface. All the images of this report use an increasing linear gradient spanning from blue (weak) to red (strong).

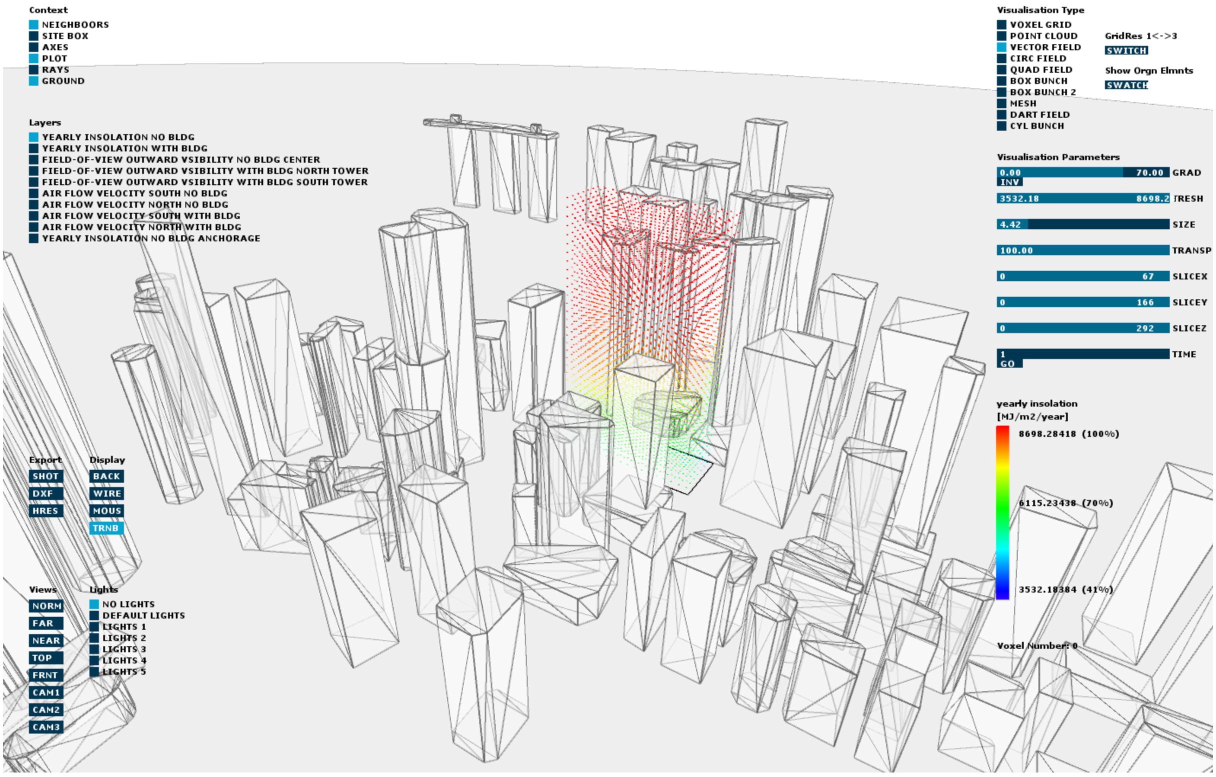


Figure 21: Visualization framework with interactive interface.

Through these interactive techniques, it is possible to narrow the investigation towards the issues of interest while uncovering patterns that are typically hidden. For example, the user can reduce the observation to a smaller portion of the site or investigate the availability of some resources above the minimal operational values required by some building technologies (e.g. photovoltaic panels or wind turbines). All representations visualized in the framework can be also exported as 2D images or as 3D models for further elaboration in other programs.

2.4.3 Scripted Filters

In addition to the interactive interface, the framework offers scripting possibilities that allow an expansion of the visualization process. Algorithmic filters can act directly on the data to generate visualizations of architectural interest. Some preliminary experiments have been done in regard to the identification of volumes according to the magnitudes of the environmental properties. To identify, for example, positions with highest visibilities, it is possible to apply a simple minimal threshold to the layer containing that information. This often results in a visualization of a volume on top of the site, where obstructions have a lower influence (see Figure 22 a). However, for structural reasons, buildings are usually conceived as a stack of floors. It could thus be desirable to visualize the distribution of a volume not only according to a threshold, but also maintaining the volume equally distributed on each floor. Furthermore, for some floors, typically high ones, the voxels could all have identical values and it could therefore be difficult to define the volume of interest (see Figure 22 b). In these cases the voxels with a higher number of adjacent neighbors could be, for example, privileged to favor the creation of compact volumes (see Figure 22 c).

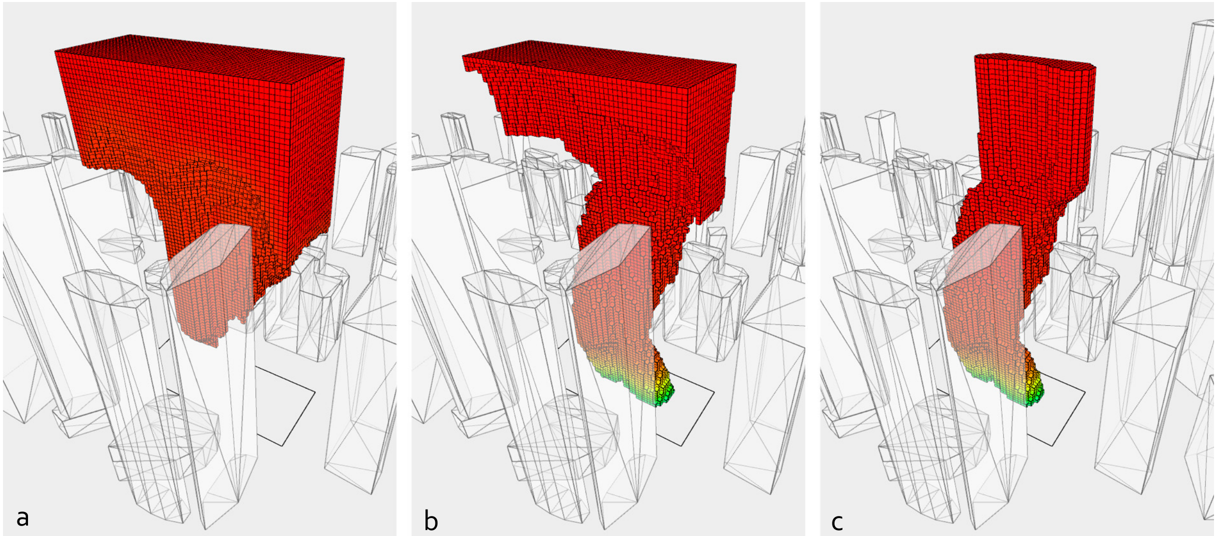


Figure 22: Example of visualizations produced by scripted filters that operate on layers of environmental data.

Other scripting operations can concern visualizations that combine different physical properties. It could be for example interesting to visualize a volume that offers both high solar radiation and high visibility. This can for example be done by mapping the data of the two primary layers to the same scale, for example having values from 1 to 100, and successively applying thresholds to a new layer obtained from the addition of the data of these two layers.

2.5 Synthesis Methods

2.5.1 Observation Records

Browsing the data in the visualization framework and trying to combine the observations with the demand requirements exposes the user to a huge amount of information that quickly becomes confusing. For this reason, all interesting observations are recorded by the user through a simple screenshot that also stores all the related interface parameters for further use. The collection of these records, completed by explanatory notes from the designer, constitutes the Observation Record. Figure 23 illustrates an example of such a record containing a series of volumetric and directional patterns. These representations concern a set of selected variables that respond to specific constraints on magnitudes, time, or on more elaborated requirements defined by Scripted Filters (see Section 2.4.3).

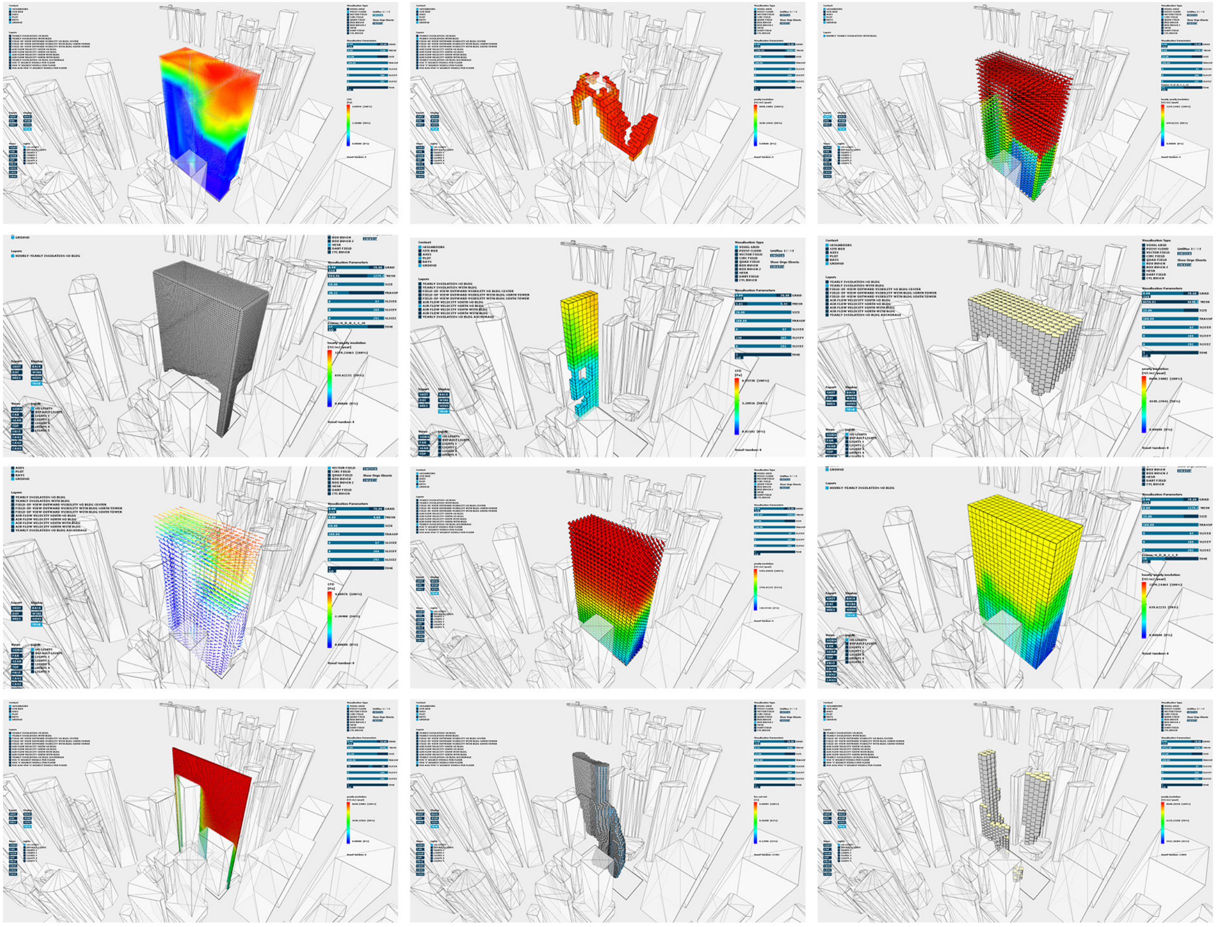


Figure 23: Example of an Observation Record excerpt.

Although the boundaries between visualization and synthesis are rather blurred, the Observation Record can be considered as the first formal step of the synthesis process. This document delivers an overview of selected visual suggestions that could be useful for the conceptual design process. From this new design document, it is possible to start to make evaluations, selecting important observations, discarding what is judged irrelevant, and making decisions on priorities and mixtures.

2.5.2 Directionality Graphs

The interesting action of combining multiple resources opens an additional level of complexity and potential confusion. The complexity is given by the fact that, besides the simple selection and combination of the resources, each of them can be considered differently in their quantitative, volumetric, dynamic and directional dimensions. Some resources could be simplified and be considered as constant through the site, while others can be regarded in their full volumetric and directional variability. In this context, the understanding of the combination of resources that have different directionalities is particularly challenging. The use of directionalities can in fact also be restrained to single components, such as the horizontal one, or those that are orthogonal to the orientation of the parcel.

To help the designer in these operations a new graphical tool entitled Directionality Graph was introduced. This tool summarizes the set of resources that have been selected for a given conceptualization, and defines the details on how they are combined and used. Directionality Graphs draw inspiration from existing environmental graphical tools (see Section 1.3.1), but they are here applied for scopes of synthesis rather than analysis.

As illustrated by the examples of Figure 24, Directionality Graphs contain information on:

- the north direction
- the parcel form and its orientation
- the selected resources (colored arrows with text labels)
- their dynamic nature (defined in text labels)
- their direction (arrows), and its possible variability (wave on arrow)
- the original resource direction (grey arrow) in the case of the use of sub-components that are horizontal or orthogonal to the parcel.
- the volumetric variability (dot on arrow)

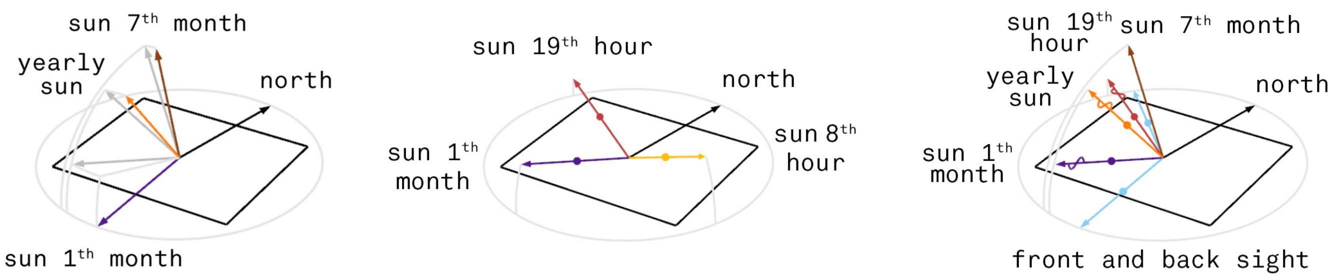


Figure 24: Examples of Directionality Graphs.

Figure 24 illustrates three examples of Directionality Graphs. In the first one, representing the combination of three solar features, the tree directions are considered as being constant and present through the whole site and they will be used in their orthogonal (and additionally horizontal for one) components. In the second example, the three solar resources are considered with a constant direction but with a volumetric variability (for example they will be present in some regions of the site and absent in others depending on their magnitude). The last example features a more sophisticated combination of six resources subject to different directional and/or volumetric variabilities.

2.5.3 Synthesis of Design Schemes

Finally the combination of the resources with the demands of the project (see Section 2.2.2) can be used to synthesize Design Schemes. With some analogies and differences to the conceptualization introduced by Janssen (2004), a design scheme is intended here to be an objective schematic representation that encloses and describes the essential logic of a specific design intention. By linking specific demands of the project through a functional rule with information on environmental resources, a design scheme delivers formal propositions based on physical criteria. Examples of such design schemes can be rules to distribute photovoltaic surfaces according to the solar resources, or rules for the distribution of openings according to the best available sights. As illustrated by Figure 25, design schemes can be articulated over different spatial scales starting from the component scale, going through rooms, apartments, and floors, up to the entire building.

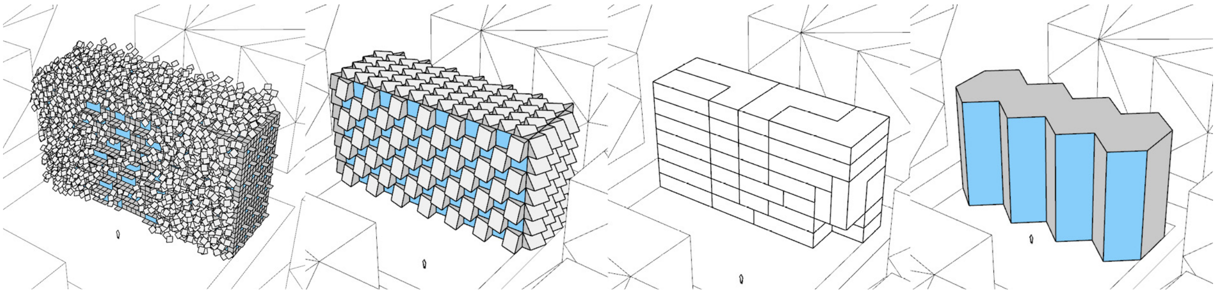


Figure 25: Examples of design schemes articulated over different scales: component, room, apartment, building, etc.

Through design schemes the designer can obtain beneficial suggestions related to a multitude of functional aspects such as: daylighting, shading, solar energy, airflows, visibilities, topology, and the morphology of the building and its components.

The goal of design schemes is not to retrieve finalized design solutions, but rather to get initial suggestions and inspirations based on functional and physical criteria. Design schemes can thus be used as instruments, and can be evaluated, compared, and combined. Once satisfied, the designer can develop the selected environmental design schemes merging them with all the other usual aspects of the conceptual design phase. In this process design schemes can be used as an abstract source of inspiration, or can be translated in a more direct manner into concrete architectural suggestions, at the discretion of the designer.

As mentioned in Section 1.8, while conceiving a design scheme, the designer can also take into consideration the future alteration of the observed volumetric values that will be generated by the planned interventions by using the directional information of the environmental properties.

2.5.4 Validation of Design Schemes

In most cases, it is judicious to submit the conceived design schemes to a validation process. This is particularly important when the design scheme relies on non-trivial physical phenomena such as daylight, solar incidence, or airflows. For this purpose, the performance of a design scheme can be simulated with a conventional surface-based simulation tool (e.g. *EnergyPlus*) (NREL, 2014) and evaluated through a comparison with a baseline design.

Figure 26 illustrates an example of the validation of a design scheme. This design scheme has been conceived with the goal of shifting the daily collection of solar energy from the midday, towards the morning and evening energy demand peaks (see Figure 10). For this purpose the surfaces of the building have been structured into a series of oriented scales that have been geared to face the solar directions of the morning (yellow) and the evening (red). The performance of this design scheme is then compared to a baseline design in which, according to conventional practice, the solar collecting surfaces have been placed on the roof and oriented towards the yearly solar direction (orange).

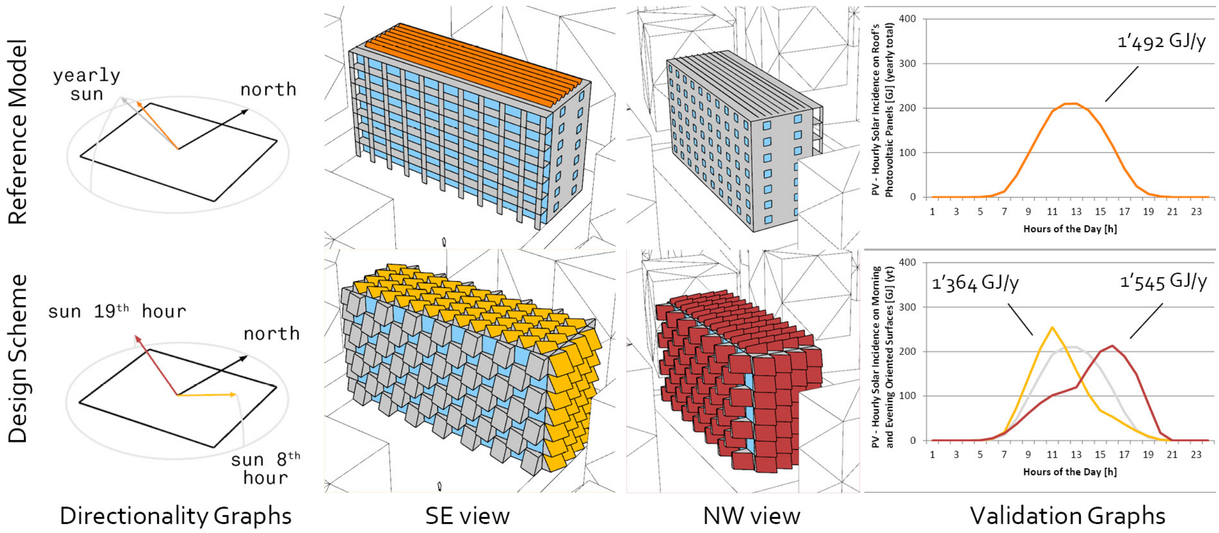


Figure 26: Example of design scheme validation.

The results of the simulations show that the energy incident on the orange surfaces of the baseline design amounts to 1'492 GJ/year, while the energy incident on the design scheme under validation amounts to 1'364 GJ/year for the morning oriented surfaces, and 1'545 GJ/year for the evening oriented surfaces. The design scheme ensures therefore double the energy collection and a much better dynamic pattern, as illustrated by the curves in the graphs of Figure 26 (see Section 3.1 for additional details). This example illustrates how a design scheme can be quantitatively validated and how it is possible to verify the weight of its performance through comparative analysis. In addition this validation process can be the starting point of an iterative performance optimization process as illustrated by Figure 3.

3 CASE STUDIES

The methodology presented in Section 2 was experimented for the first time on the two case studies introduced in Section 1.9. Through these case studies, all steps of analysis, evaluation, and synthesis were tested in depth in order to evaluate the capabilities and the pertinence of the proposed technique. This section presents a summary of this experimentation. The mid-rise case study covers all the steps of the process starting from the allocation of data up to the validation of design schemes. The high-rise case study is instead presented in a leaner way focusing on the specificities related to its different scale and climate.

3.1 Mid-Rise Case Study

3.1.1 Site Data

- The site is located in the city of Lugano, Switzerland, at a latitude of 46.01, a longitude of 8.96, and an altitude of 280 m.a.s.l.
- The location has a humid subtropical climate involving the alternation of mild winters and hot summers with temperature differences spanning between about -1 °C and 27 °C.
- The yearly wind rose shows one prevalent wind flowing from NNW at an average speed of 1.9 m/s at 37 m height.
- Horizontal construction limits are given by the parcel boundaries, defined approximately by a rectangle of 49 x 40 m, and by setbacks of 3 m from streets and 7 m from other parcels (see Figure 27 left).
- The vertical construction limit is 21 m and 7 floors.
- The surrounding built environment is taken into consideration in its current configuration (0y) and in its potential evolution of it in a thirty years perspective (30y) as illustrated in Figure 27.

Figure 27: Mid-rise case study site.

3.1.2 Space and Energy Demand

The most important Space and Energy Demands of the project and the related functional requirements can be summarized as follows:

- Space demand: 3'249 m².
- Space use: residential.
- Heating demand peak: 1st month (→ solar heat gains, solar heat collection).
- Cooling demand peak: 7th month (→ shading, ventilation, electricity collection).
- Electricity demand peaks: 8th and 19th hour (→ daylight, electricity collection).

Further details on these demands can be found in Section 2.2.2.

3.1.3 Observation Record

This section presents a collection of the volumetric observations that were later used for the synthesis of design schemes. Figure 28 illustrates the primary layers of information of the site displayed for its whole volume. Through these observations it is possible to perceive interesting volumetric patterns that can already provide some preliminary conceptual design suggestions to the designer.

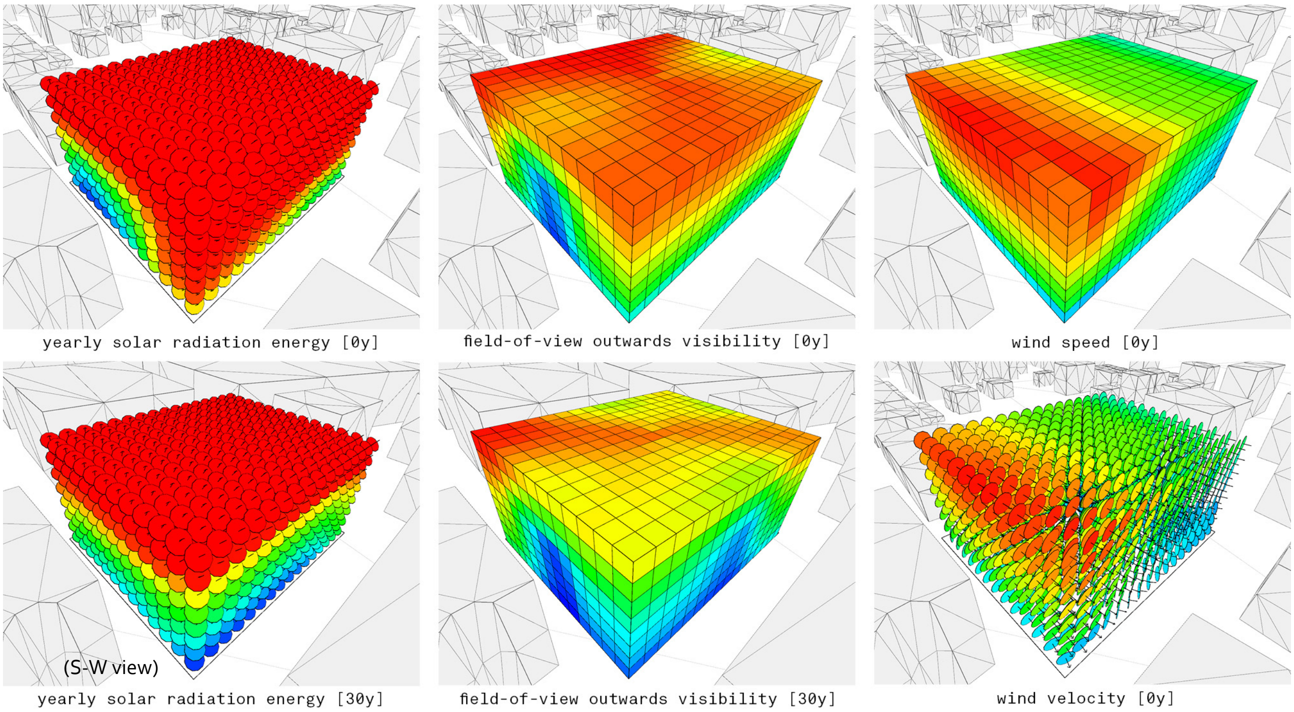


Figure 28: Main layers displayed for the whole volume of the site. Radiation 0y: 4.3-6.8 GJ/m2/y, Radiation 30y: 2.3-6.8 GJ/m2/y, Visibility: 4-51%, Wind: 0.18 m/s.

Figure 29 and Figure 30 show the results of some massing studies based on highest values of solar radiation and visibility. Figure 29 illustrates three shapes, with an equal volume, corresponding to the space demand of the project, that have been distributed according to the highest values of solar radiation, considering in turn the boundaries given by the whole site, the setbacks from the parcel borders, and the ground occupation index given by the building regulation.

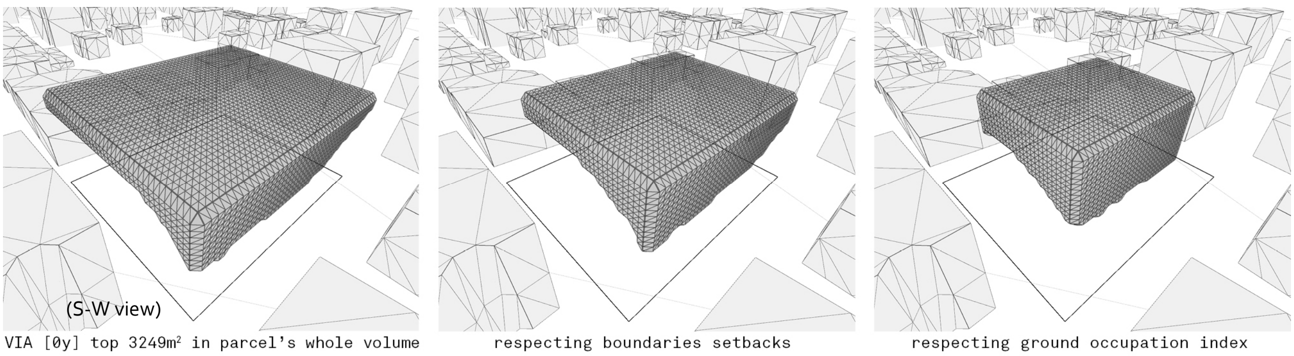


Figure 29: Space demand volume distributed according to highest values of solar radiation considering different boundary conditions.

The observations of Figure 30 regard a similar study in which the mutual influence of several variables has been additionally taken into account. The goal was to distribute a fixed amount of volume in positions with highest values of solar radiation and visibility, considering the following variants:

- The two variables as independent (first two rows) or as combined features (last row).
- The current urban context (uneven columns) and its future evolution in a thirty year perspective (even columns).
- The distribution of the volume through the entire site (two left columns) or evenly on each floor (two right columns).

The combination of all these variants produces the twelve different outcomes visible in Figure 30. By analyzing the differences and the similarities among the outcomes, it is possible to understand the influence of the different factors on the definition of these volumes.

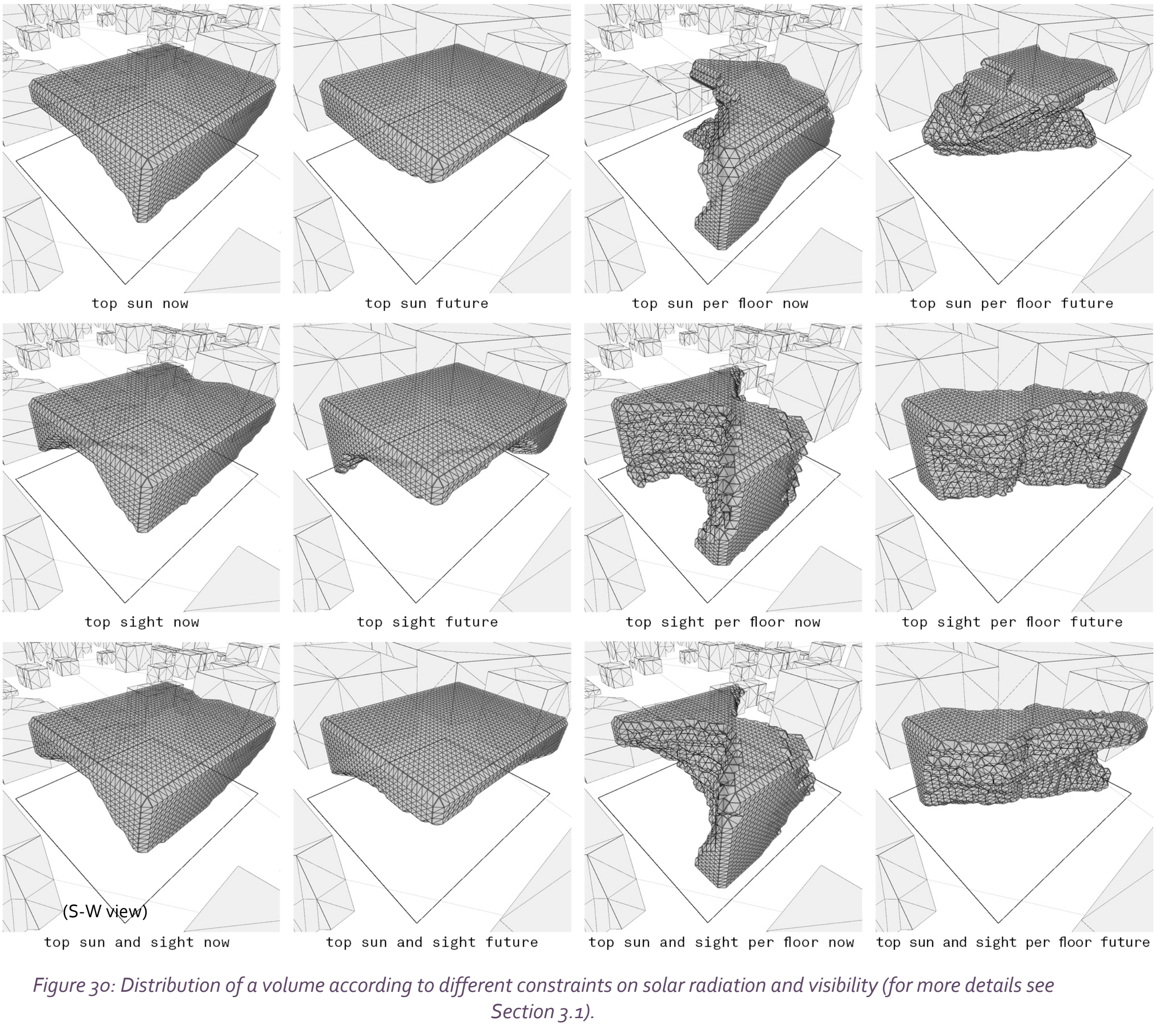


Figure 30: Distribution of a volume according to different constraints on solar radiation and visibility (for more details see Section 3.1).

By analyzing the distribution of these environmental resources through the site, it can generally be observed that, as could have been expected, the best conditions of sun, air and sight are located at the top of the site, where obstructions have less influence. This phenomenon could lead to the idea of positioning the whole building volume at the top levels of the site (see Figure 31 left). However, this configuration is problematical for several reasons. Beside structural issues, that usually lead to conceiving buildings as a stack of floors, this volume proportion would feature mediocre performances in terms of environmental exchange: First, for the lower amount of horizontal surfaces that are exposed to the environment, second, because the important depth of the building would hinder environmental resources to reach the central region of it. For these reasons, it is common practice to conceive vertically coherent volumes with a limited depth. At mid-latitudes, a conventional approach to gathering daylight and solar heat gains is to define the building proportions by maximizing the equator-exposed face. The resulting form is then positioned along the opposite border, to reduce the effects of close obstructions on the exposed face, as can be observed in Figure 31 right.

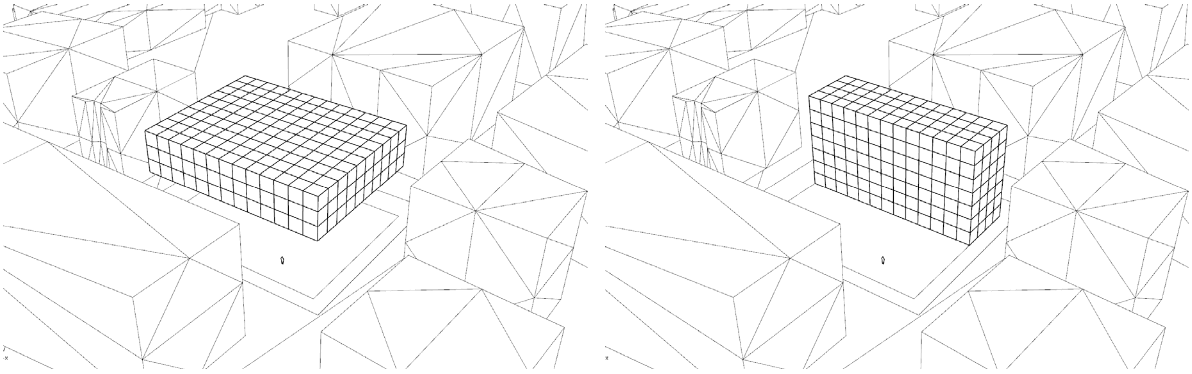


Figure 31: Volume on top of the site (left) and conventional configuration with volume along the northern border (right).

The following observations will use this form as a base for further observations on visibility (Figure 32), airflows (Figure 33), and yearly, monthly, and hourly solar radiation (Figure 34, Figure 35 and Figure 36).

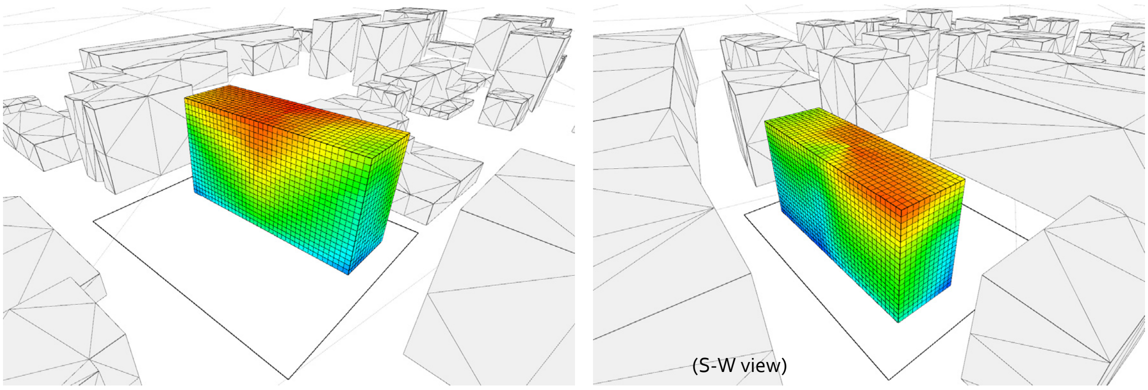


Figure 32: Visibility in the reference volume (10-100%). Left: Front View, Right: Back View.

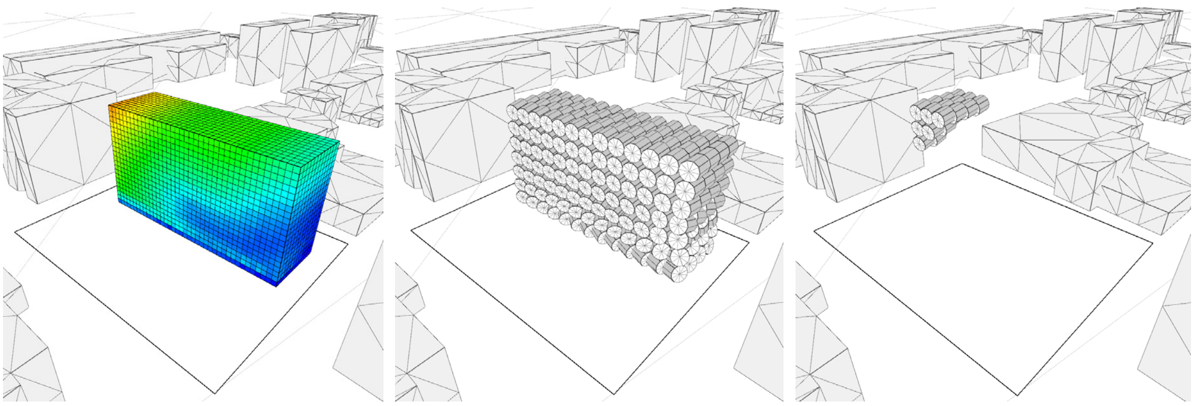


Figure 33: Airflow in the reference volume (1.2-1.8 m/s). Right > 1.54 m/s.

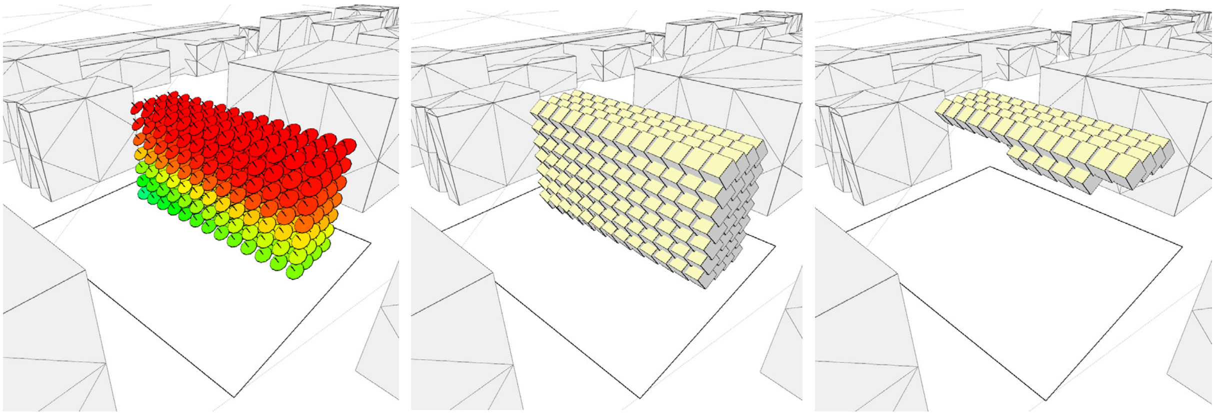


Figure 34: Yearly solar radiation energy in the reference volume (4.3-6.8 GJ/m²/y). Right > 5.6 GJ/m²/y.

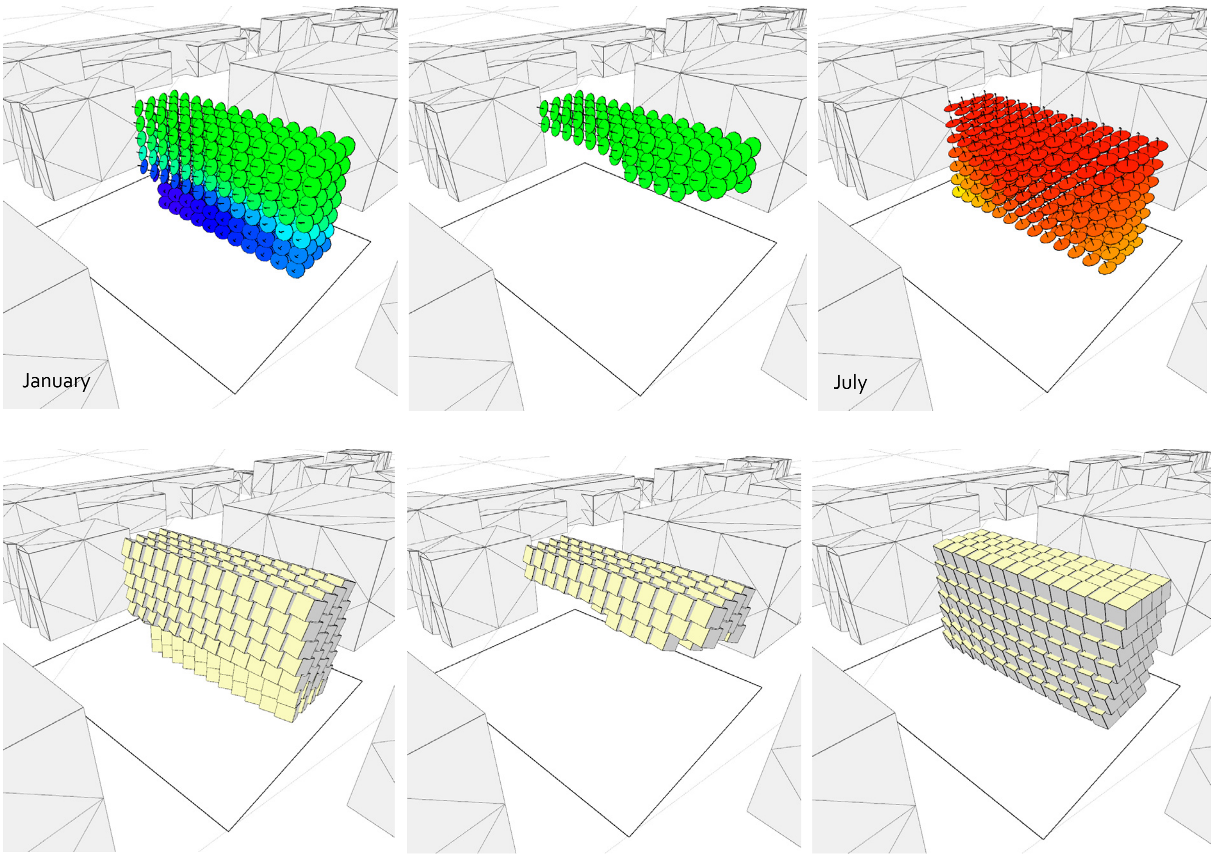


Figure 35: Monthly solar radiation energy in the reference volume (0-838 MJ/m²/y). Left: winter (1st Month), Middle: winter >348 M//m²/y. Right: summer (7th Month).

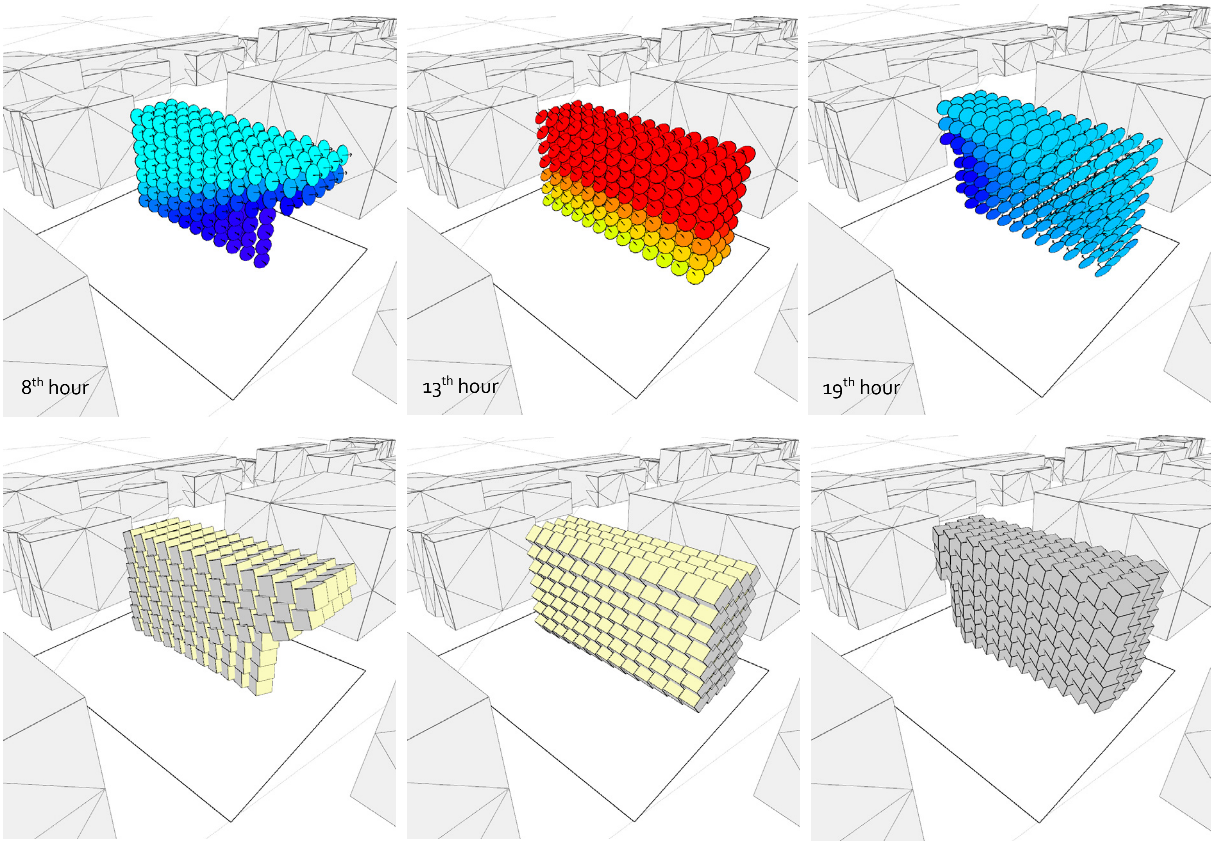


Figure 36: Hourly solar radiation energy in the reference volume (0-1 GJ/m²/y). Left: morning (8th hour). Middle: noon (13th hour). Right: evening (19th hour).

Finally, Figure 37 illustrates the distribution and the directions of solar energy in the whole site in correspondence to the winter, the morning and the evening demand peaks (see Section 3.1.2).

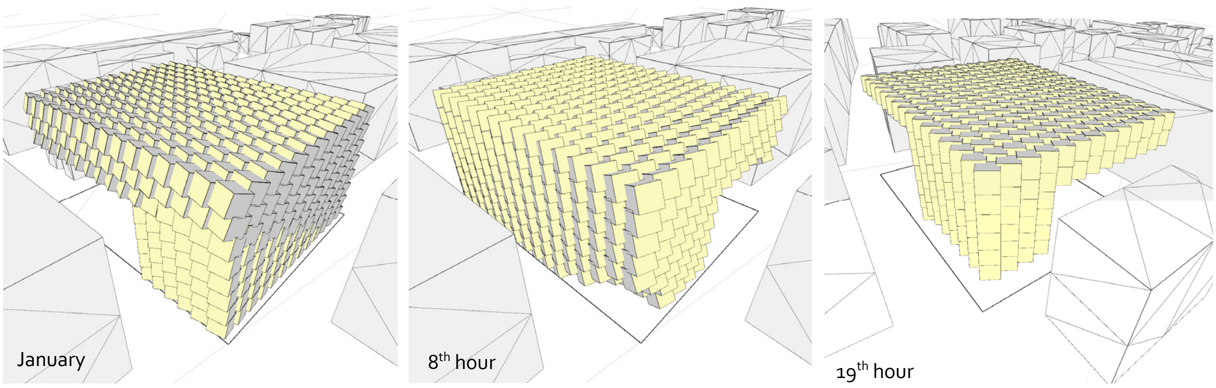


Figure 37: Monthly and hourly solar radiation energy for the whole volume. Left: winter (1st Month), Middle: morning (8th hour). Right: evening (19th hour) viewed from N-W.

3.1.4 Synthesis of Design Schemes

This section contains some examples of design schemes that have been synthesized, drawing suggestions from the Observation Record of the previous section. Each example is presented with images, a brief explanation, and a Directionality Graph (see Section 2.5.2), which summarizes the use of the selected resources.

Conventional Form

As already mentioned, at mid-latitudes a conventional solution consists in maximizing the equator-exposed face and in positioning the building to the opposite border in order to gather winter heat gains and daylight. As shown by the Directionality Graph this design scheme exploits the horizontal orthogonal component of the winter radiation.

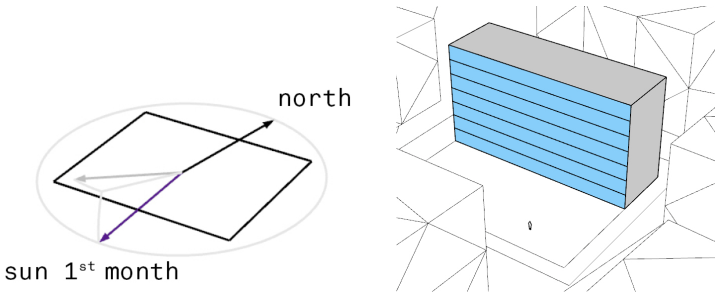


Figure 38: Big transparent facade exposed to the equator.

Directional deformation

The daylight penetration can be adapted according to the morning and the evening daylight demand peaks determined by the building occupants. For this purpose, the conventional shape of the previous design scheme can be deformed, orienting the openings towards the horizontal component of the solar directions at the 8th and 19th hours of the day.

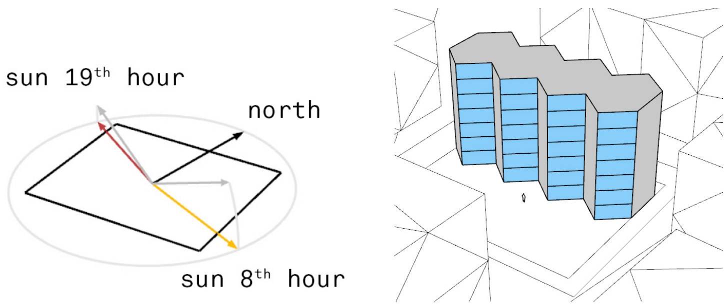


Figure 39: Openings directed to the morning and evening solar directions.

Extroverted Approach

This other design scheme is based on the volumetric distribution of the winter, the morning and the evening solar radiation (see last 3 images of the Observation Record in Section 3.1.3). Following an extroverted approach the building was shaped in order to face the incoming resources directly at their entry in the site. The combination of these three resources and the consideration of self-shading effects led to a form that presents ties to a classic courtyard typology, but additionally includes the influence of the surrounding obstructions and of solar directionality.

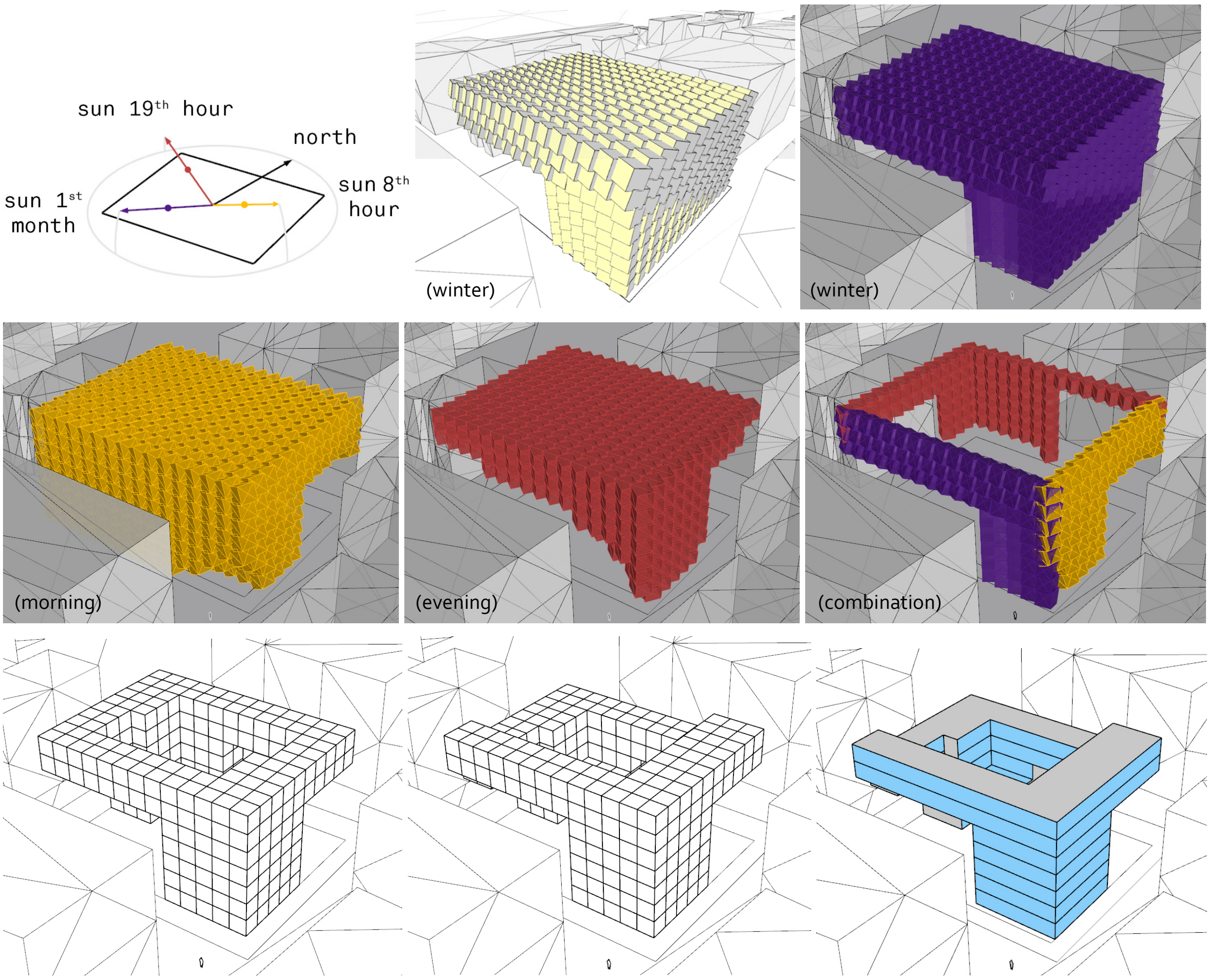


Figure 40: Extroverted approach that relies on facing the resources at the incoming borders.

Introverted Approach

By overlaying the same tree resources in the whole site, it can be observed that they are all jointly present and vertically coherent in a definite region of it. This information can be used to define the position and the form of a vertically coherent building that would have access to all three resources this time from the inner space of the site.

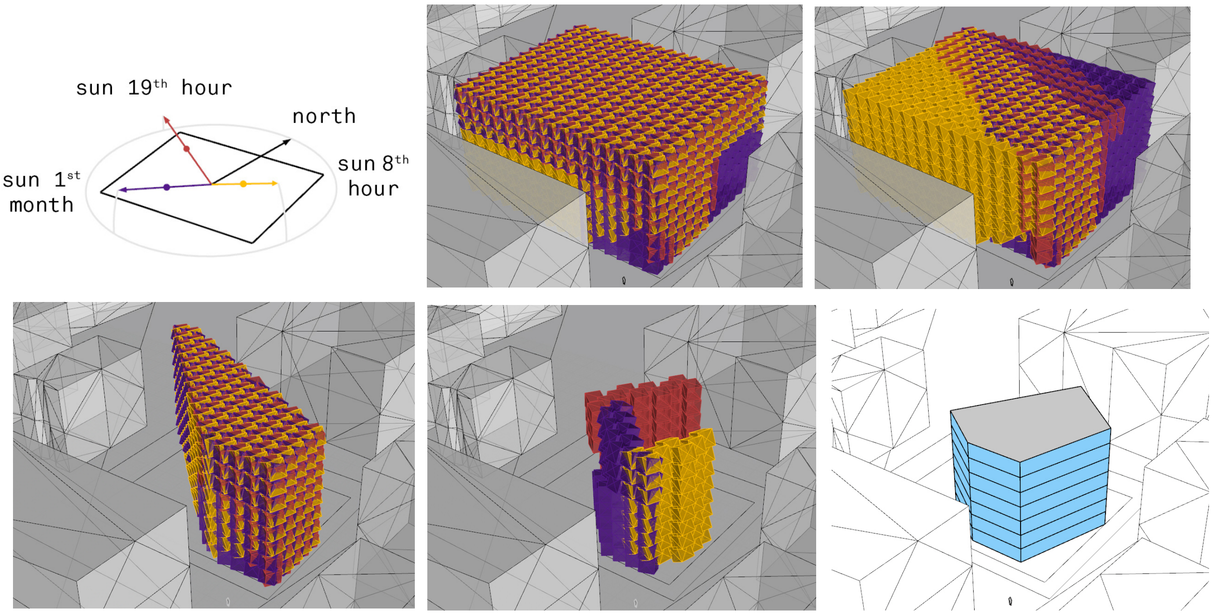


Figure 41: Design scheme based on the joint presence of winter, morning and evening solar radiation.

Negative Approach

Similarly it can be observed where the morning and the evening radiation are jointly present and vertically coherent in the site. It is then possible to facilitate the penetration of these resources in the site by placing the building in the remaining spaces beside the identified volume. Successively the incoming resources are captured laterally through zigzagged facades.

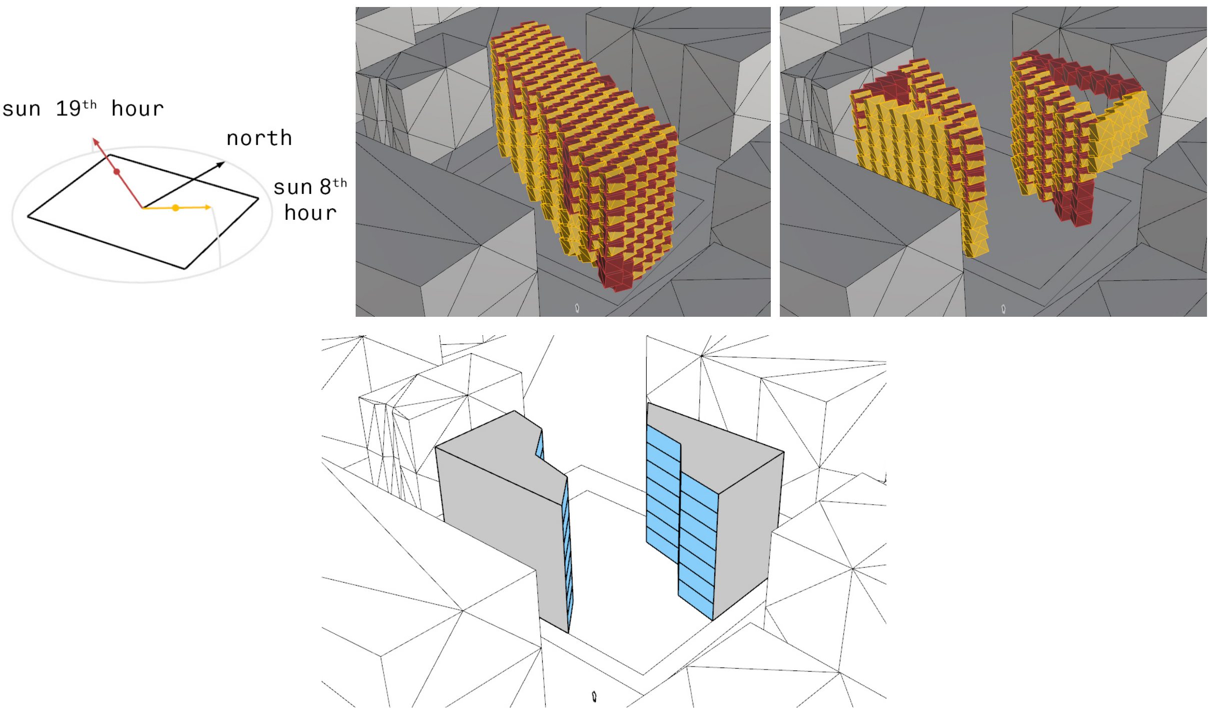


Figure 42: Design scheme based on the penetration of morning and evening solar radiation in the site.

Access to Sunlight and Views

This design scheme is again based on the reference building form of Figure 31. The apartments of this building have been shaped to ensure access to the morning and evening daylight (yellow and red voxels) and to the front and back sights (blue voxels) to the largest possible number of living units. Finally, the main entrance of the building has been placed in a location of scarce environmental interest.

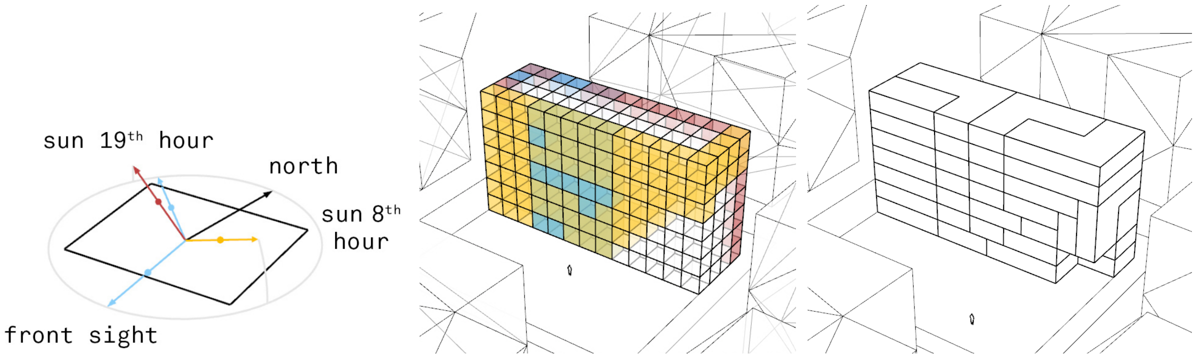


Figure 43: Design scheme in which the apartments are shaped according to their access to daylight and sight.

Conventional Envelope

In terms of external surfaces, in conventional buildings the equator-oriented face is usually shaded from the summer solar radiation with overhangs that typically function also as balconies (brown). Additionally photovoltaic panels (orange) are usually positioned on roofs and tilted towards the yearly solar direction, and thermal collectors (violet) are often positioned on facades that are well exposed to the winter solar direction.

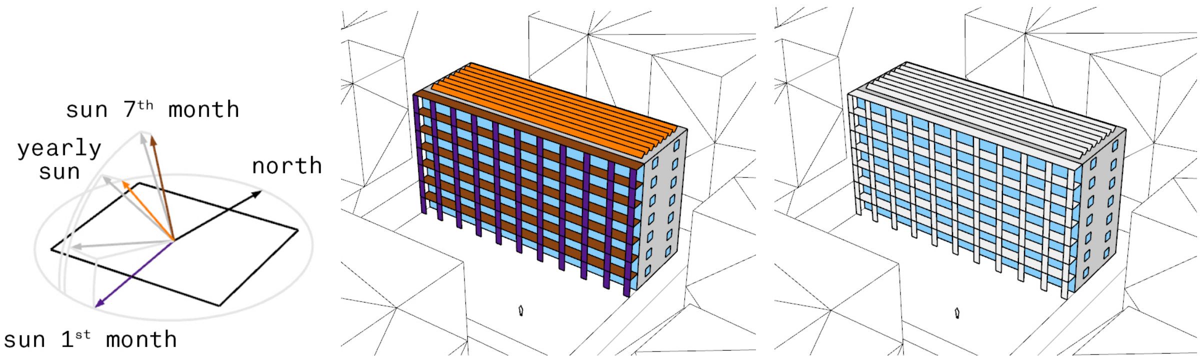
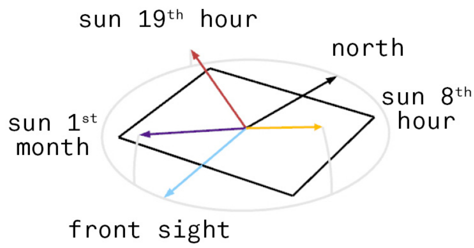


Figure 44: Conventional envelope modulating solar heat gains and collecting electrical and thermal solar energy.

Scaled Envelope

In this scales-based design scheme, the two main facades of the envelope are characterized by a checkered alternation scheme. Half of the 3x3 meter squares of this scheme are composed by vertical transparent openings that are responsible for daylight, sight, ventilation and access, while the other half is composed of oriented surfaces that are dedicated to the collection of different types of solar energy. The positions and orientations of the surfaces have been defined to match the demands listed in Section 3.1.2 with the volumetric observations illustrated in Figure 35 and Figure 36. Electricity is collected according to the morning (yellow) and evening (red) directions, and thermal energy according to the winter direction (violet).

The lateral facades are instead completely dedicated to the collection of energy and, on the roof, the morning and the evening solar directions concurrently shape the oriented elements. Finally, the interplay between these transparent and opaque elements generates spatial situations that are exploitable for balconies and overhangs that shade the undesired summer radiation.



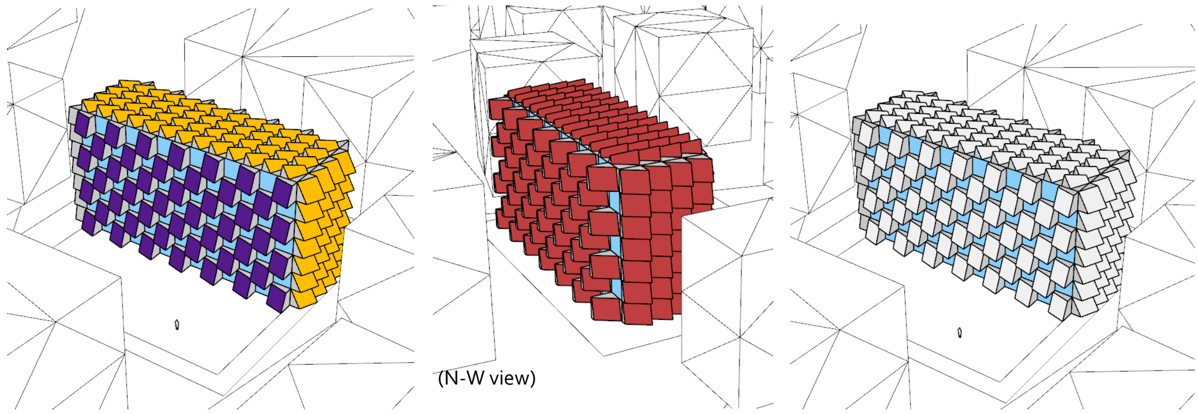
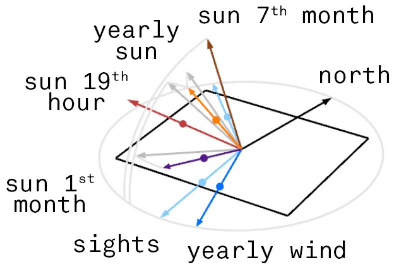


Figure 45: Scaled envelope composed by oriented collecting surfaces alternated with transparent openings.

Flaps-based Envelope



In this flaps-based design scheme, squared surfaces of 1x1 meter have been distributed around the envelope and tilted at a specific angle. These elements represent components like transparent openings, opaque walls, panels collecting different types of solar energy, overhangs, balconies, etc. As illustrated by the images below, these surfaces are positioned and oriented according to the available resources (see Observation Record) and to a priority scheme defined by the designer.

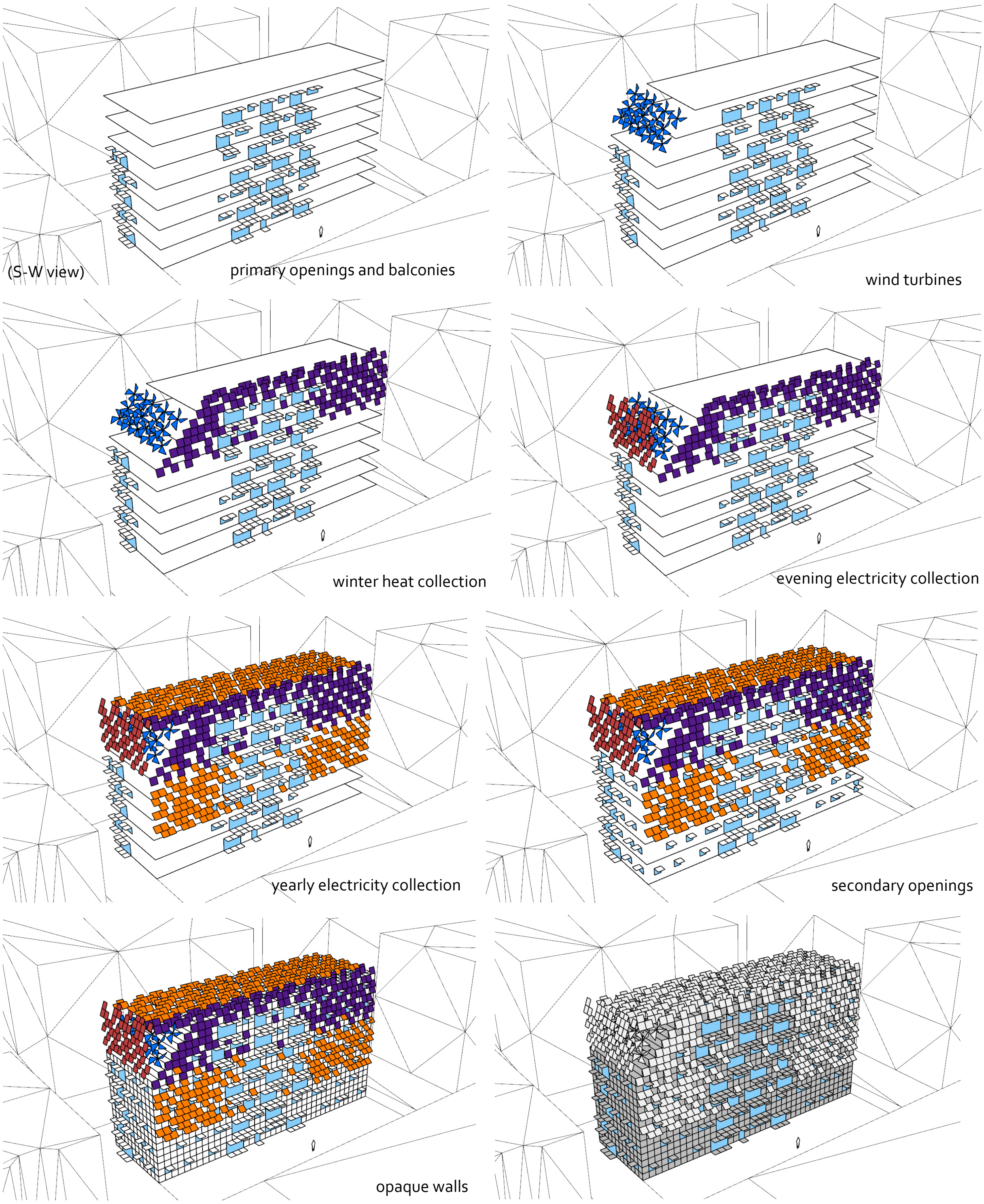
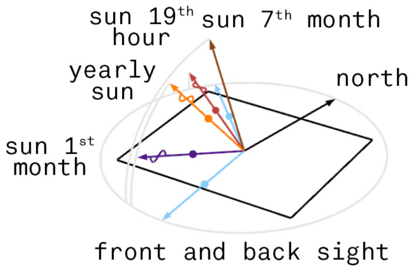


Figure 46: Flaps-based design scheme.

Leaved Envelope



This leaves-based design scheme continues on the precedent scheme removing the wind turbines and augmenting the solar surfaces. Successively all these surfaces are disconnected from the envelope and doubled in number. In this way more surfaces become available for environmental exchanges, and the surfaces regain their azimuthal degree of freedom to assume a better orientation towards the different solar directions (see last three colored images of Figure 47).

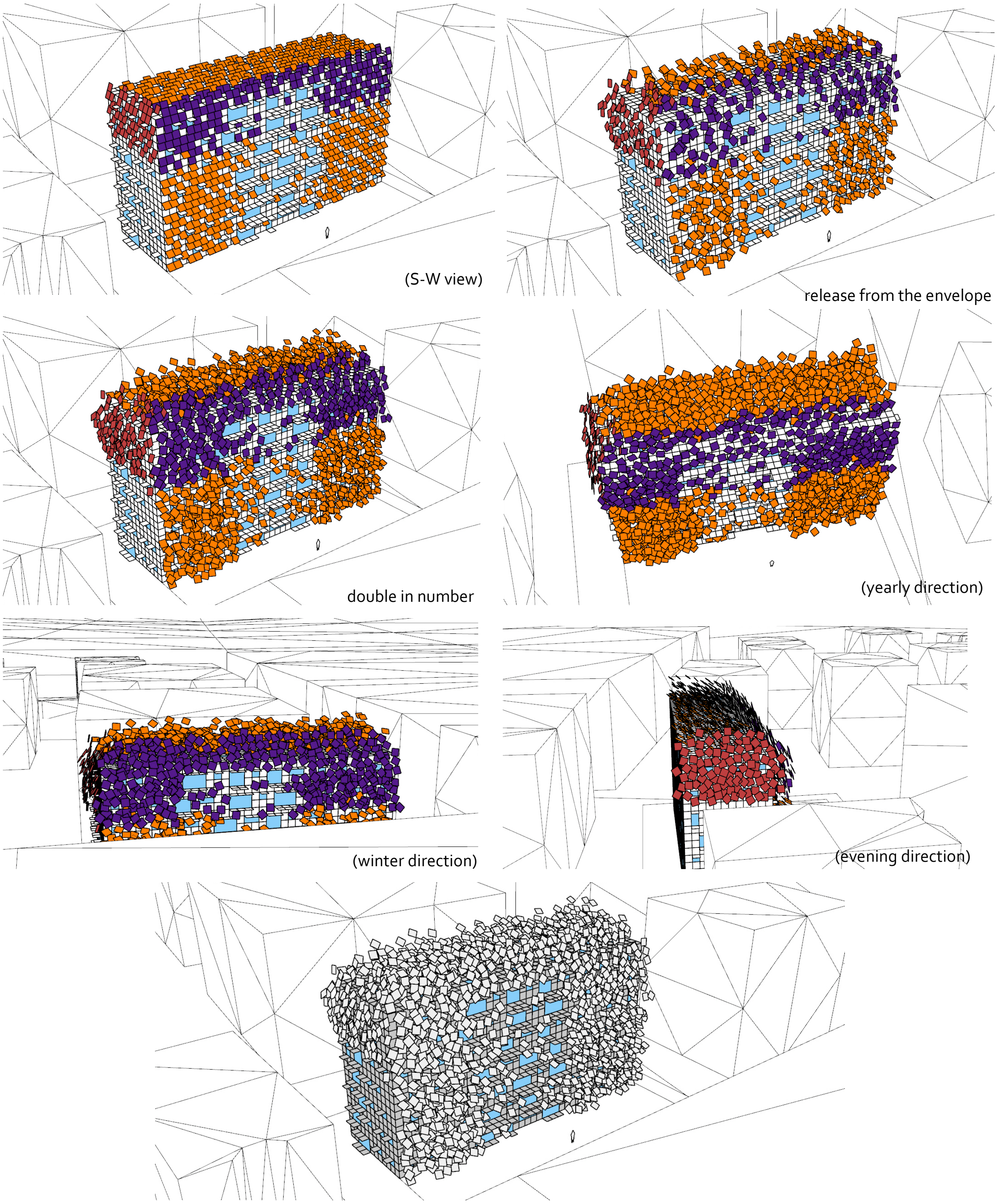


Figure 47: Design scheme with leaved envelope.

3.1.5 Validation

To verify if the aimed goals were achieved, a selection of the design schemes that were presented in Section 3.1.4 has been subjected to validation. The validation process consisted in the simulation and the comparative analysis of the solar features of two different series of design schemes.

The first series, illustrated in Figure 48, concerns the definition of the form of the building according to criteria related to daylight, solar heat gains, and solar access on potential balconies and terraces. For this purpose the performance of the two zigzagged models was compared with the performance of the baseline design represented by the conventional building form.

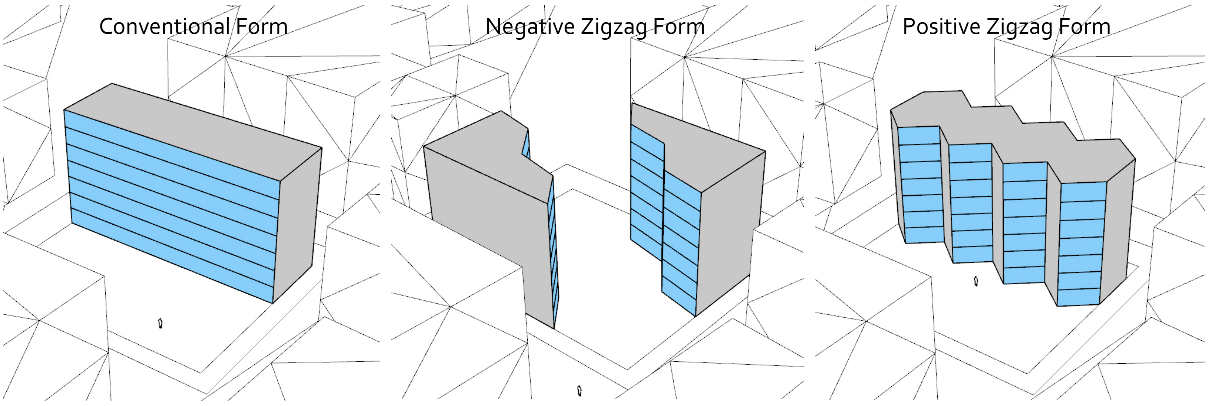


Figure 48: First validation series concerning the form of the building in relation to daylight, heat gains and solar access criteria.

The second series, illustrated in Figure 49, concerned the definition of exterior surfaces according to criteria related to solar heat gains and electrical and thermal energy collection. In this second case, the performances of the Scaled and the Leaved Envelope models have been analyzed in comparison to the baseline design represented by the conventional envelope configuration.

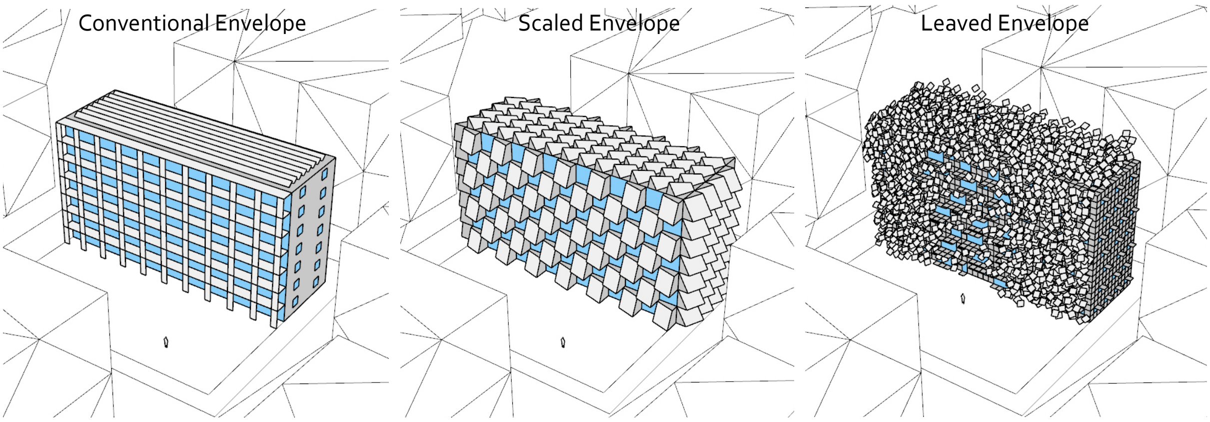
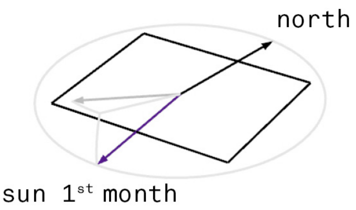
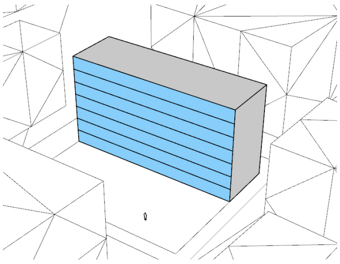


Figure 49: Second validation series that concerns the configuration of exterior surfaces in relation to criteria of heat gains and energy collection.

In the following part of this section the captions of images have been omitted to ameliorate readability.

Conventional Form

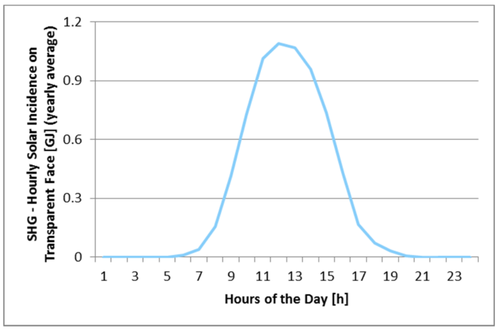


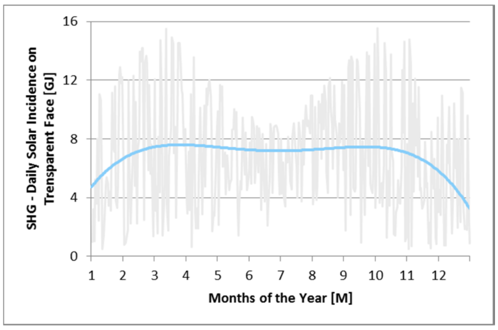


Transparent surfaces: 819 m².

The results of this baseline design will serve as reference for the comparative analysis of this series. Its curves will be reproduced in dark gray in the graphs of the next design schemes.

South Incidence on transparent: 2'527 GJ.

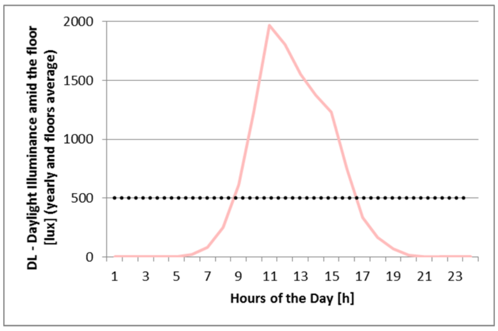




Poor pattern* for both energy and daylight.

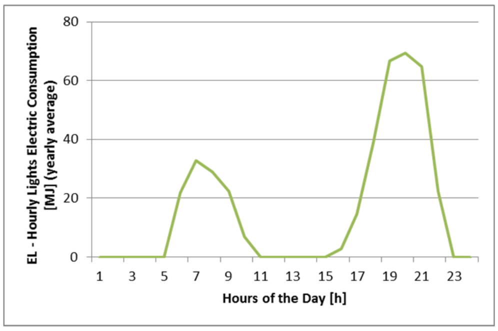
Relatively good pattern for heat gains.

Daylight Illuminance, time over 500 lux: 8 h.



As predictable, the daylight pattern features correspondences to the solar incidence illustrated in the previous graph.

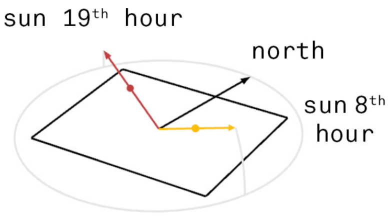
Lights Electrical consumption: 143 GJ.

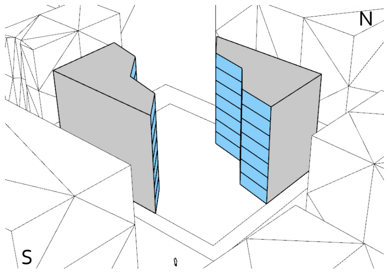


As predictable, the artificial light demand befalls before and after the daylight availability visible in the previous graph.

* The appreciation of patterns is made in relation to the demand patterns (see Figure 10) and to conventional solar patterns (see Annex).

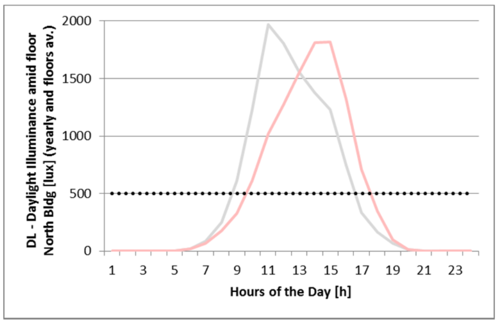
Negative Zigzag Form





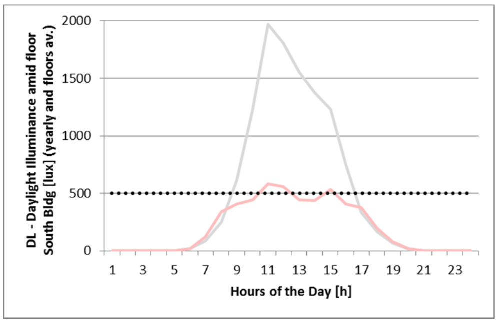
Transparent surfaces: 1'322 m².

North building Daylight Illuminance time over 500 lux: 8 h.



Reduction of 1 h in the morning and extension of 1 h in the evening.

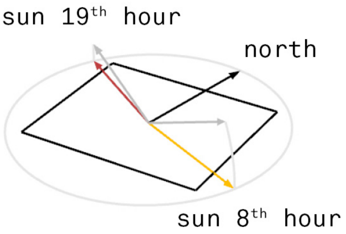
South building Daylight Illuminance time over ~500 lux: 5 h.

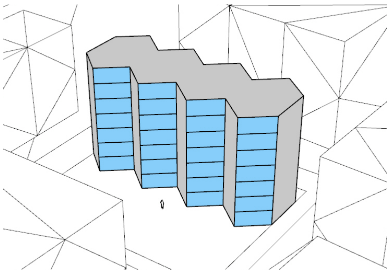


Light ameliorations in the morning and evening and partial but uncritical reduction over the whole day.

Compared with the baseline design, this design scheme does not present the intended results in terms of daylight. From this first verification, it appears to be difficult to conceive zigzag facades and achieve a beneficial compromise between the capture of lateral and by-directional resources and the limitation of the effects of self-shading given by the form of the facade itself. On the basis of these outcomes, further variations of the form could be eventually explored.

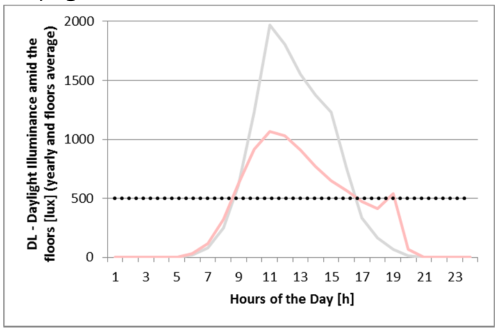
Positive Zigzag Form





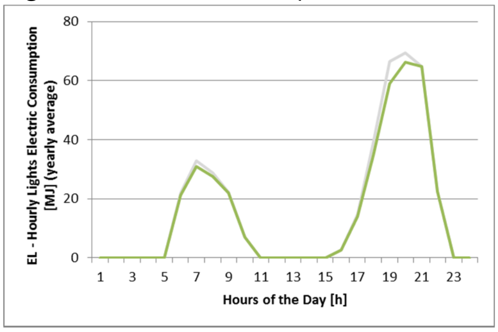
Transparent surfaces: 1'059 m².

Daylight Illuminance, time over ~500 lux: 10.5 h. **+31%**



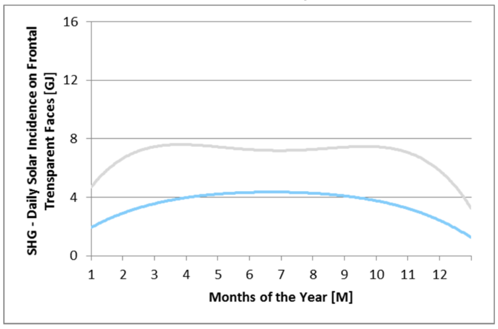
Light amelioration in the morning, and substantial amelioration of the indoor daylight in the evening with 2.5 hours extra time. This extended solar access would be also exploitable in outer spaces like balconies and terraces.

Lights Electrical consumption: 136 GJ. **-5%**



The decreases in energy consumption correspond to the increases in daylight are visible in the previous graph.

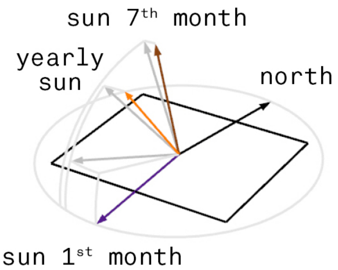
South Incidence on transparent: 1'304 GJ. **-48%**

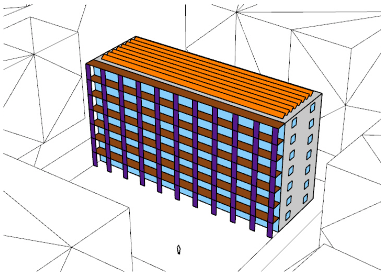


Worse amplitude and worse pattern for the exploitation of solar heat gains.

On these graphs it can be observed that the northern and the southern facades of the model present sensibly different outcomes. The northern zigzag facade could beneficially augment the indoor daylight and the outdoor solar access, and could consequently also reduce the energy consumption of the artificial lights. In contrast, the southern zigzag facade would have only limited effects on daylight while sensibly reducing the exploitability of solar heat gains. As a first conclusion of this series, it can be considered that the combination of the straight southern facade of the conventional form with the northern zigzag facade of this design scheme could be an interesting solution.

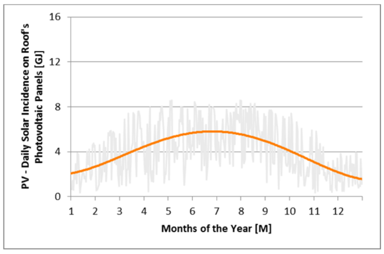
Conventional envelope

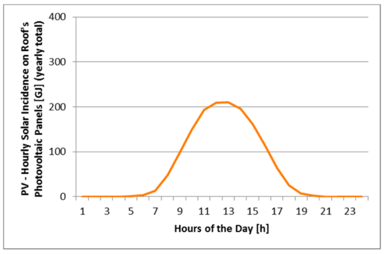




In turn, the results of this second baseline design will serve as a reference for the comparative analysis of this second series. Similarly, its curves will be reproduced in dark gray in the graphs of the next design schemes.

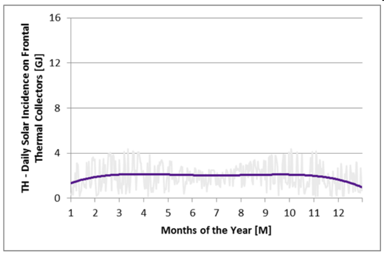
PV - Solar Incidence on Roof panels: **1'492 GJ**. (296 m², 5.0 GJ/m²)

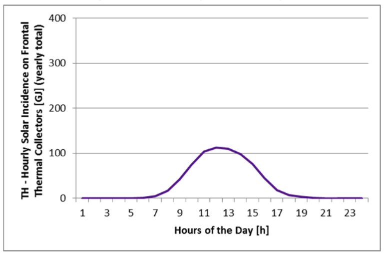




Poor pattern. Poor pattern.

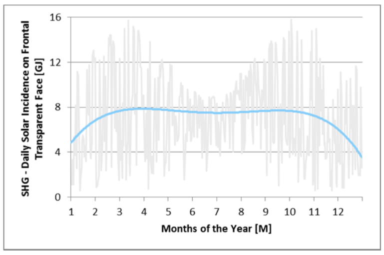
TH - Solar Incidence on Frontal panels: **713 GJ**. (231 m², 3.1 GJ/m²)

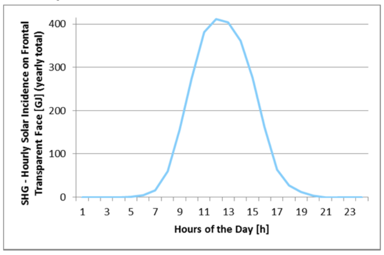




Relatively good pattern.

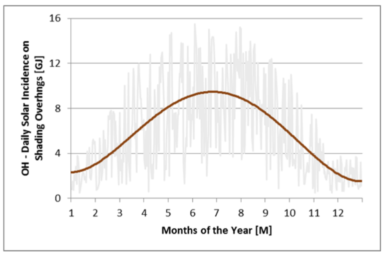
SHG - Solar Incidence on Frontal transparent face: **2'613 GJ**. (819 m², 3.2 GJ/m²)

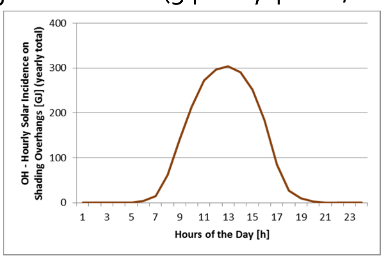




Relatively good yearly pattern also due to the peak cutting effect of overhangs (see below).

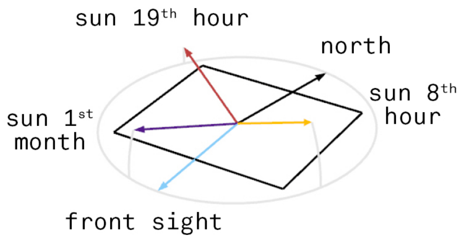
OH - Solar Incidence on Overhangs: **2'160 GJ**. (546 m², 4.0 GJ/m²)

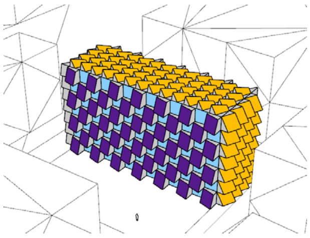


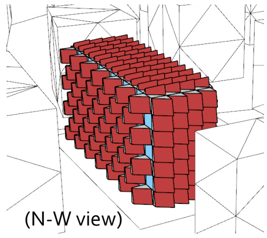


Good pattern.

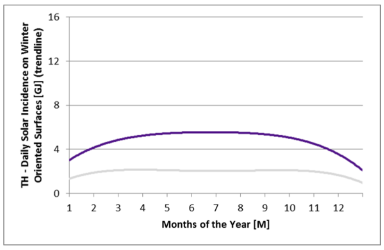
Scaled Envelope





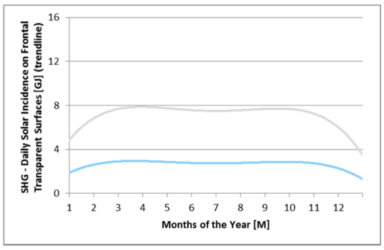


TH - Solar Incidence on Winter oriented surfaces: 1'752 GJ. **+145%** (456 m², 3.84 GJ/m²)



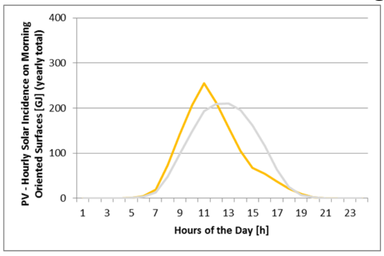
There is a higher amplitude with a relatively good pattern. The amelioration of the amplitude is due to the higher amount of surfaces and their higher energy density. The curve pattern could be ameliorated with the addition of shading overhangs on collectors to reduce the thermal collection during the summer.

SHG - Solar Incidence on Frontal transparent surfaces: 975 GJ. **-63%** (404 m², 2.41 GJ/m²)



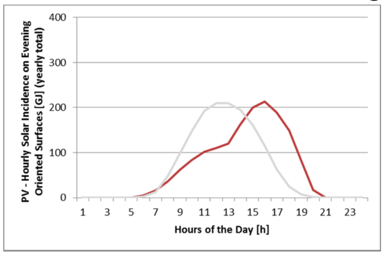
There are lower solar heat gains due to the lower amount of transparent surfaces. The flattening effect of the curve given by the overhangs is maintained.

PV - Solar Incidence on Morning oriented surfaces: 1'364 GJ. (597 m², 2.29 GJ/m²)



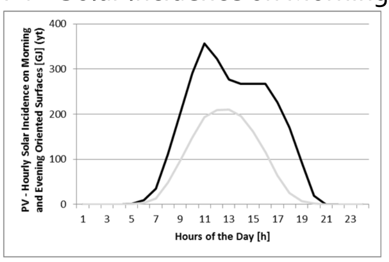
Good amplitude and good morning-shifted pattern.

PV - Solar Incidence on Evening oriented surfaces: 1'549 GJ. (1'086 m², 1.43 GJ/m²)



Good amplitude and good evening-shifted pattern.

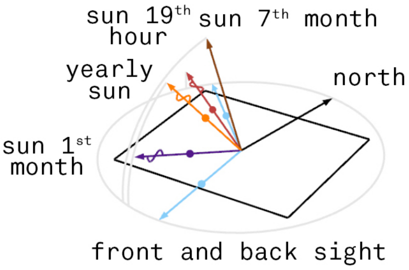
PV - Solar Incidence on Morning + Evening oriented surfaces: **2'913 GJ**. **+95%** (1'683 m², 1.73 GJ/m²)

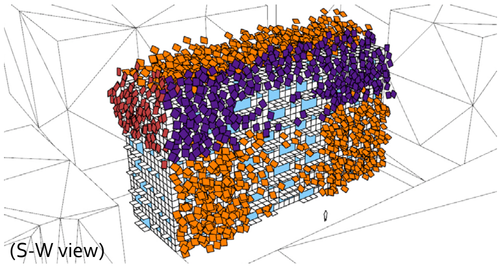


Substantially better amplitude. Better pattern that improves the coverage of the morning and evening demands due to the higher amount of surfaces and their orientation. As predictable, worse energy density due to the lower irradiance of the morning and evening rays in comparison to the midday rays occurs.

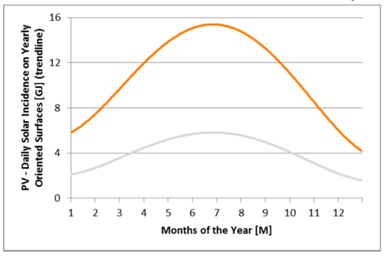
The comment to this model will be made jointly with the next model at the end of the next page.

Leaved Envelope



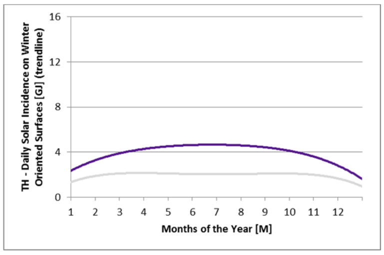


PV - Solar Incidence on Yearly oriented surfaces: **4'021 GJ**. **+170%** (855 m², 4.7 GJ/m²)



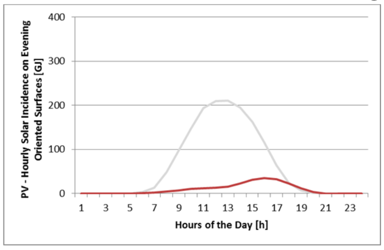
Substantially higher amplitude due to the higher amount of surfaces.

TH - Solar Incidence on Winter oriented surfaces: **1'429 GJ**. **+100%** (337 m², 4.2 GJ/m²)



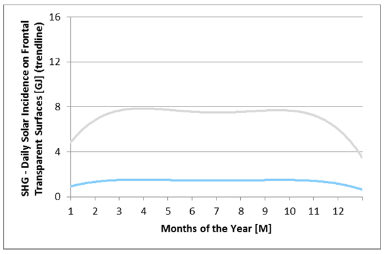
Substantial amelioration of the amplitude due to the higher amount of surfaces, to their position and their orientation. The pattern could be further ameliorated with the addition of shading overhangs over the collectors to reduce the thermal collection during the summer.

PV - Solar Incidence on Evening oriented surfaces: **227 GJ**. (97 m², 2.3 GJ/m²)



Good pattern but low amplitude due to the low amount of surfaces.

SHG - Solar Incidence on Frontal transparent surfaces: **505 GJ**. **-81%** (160 m², 3.16 GJ/m²)



Lower solar heat gains due to the lower amount of surfaces.

The results of the Scaled and Leaved design schemes illustrate that the amplitudes of both thermal and electrical energy collections can be massively increased in comparison to the baseline design. The results also confirm that it is possible to positively influence the dynamic patterns of the electricity production in order to ameliorate their match with electricity demand patterns. Both the orientation and the amount of surfaces proved to play an important role in these processes.

3.2 High-Rise Case Study

This case study is presented in a leaner way focusing on the higher scale and on the equatorial climate of its site. The experimentations have been based on different scenarios involving different uses of the spaces of the building that span from new constructions to renovations. The energy and space demands have thus been defined case by case, and are briefly mentioned before the presentation of each design scheme.

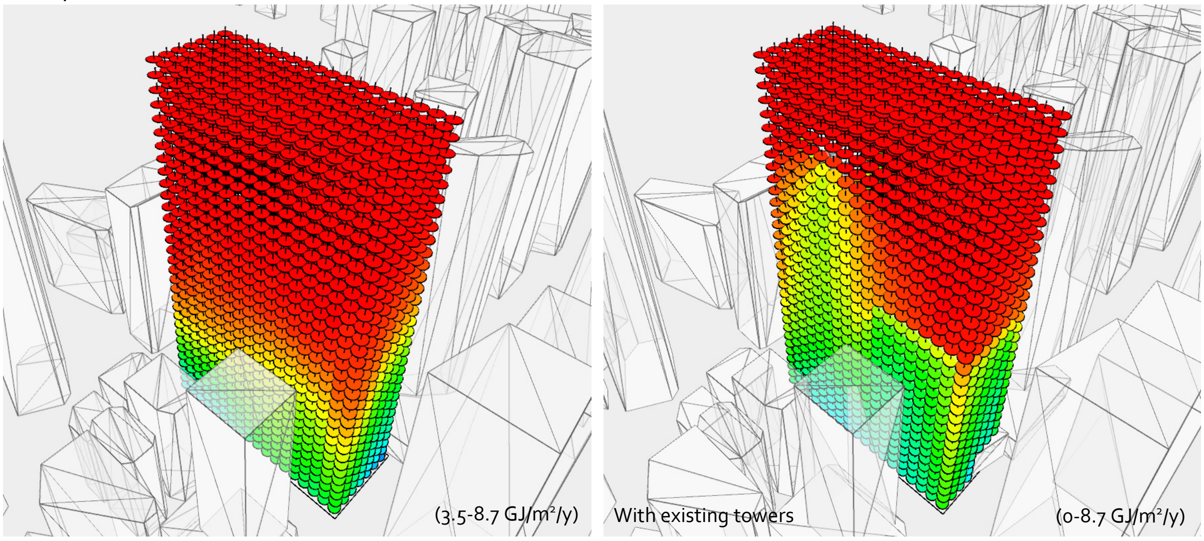
3.2.1 Site Data

- The site is located in the high-rise business district of the equatorial city-state of Singapore. It has a latitude of 1.28, a longitude of 103.85, and an altitude of 3 m.a.s.l.
- The location has a tropical rainforest climate with no distinctive seasons, a relatively uniform temperature spanning from 22 to 35°C, a high humidity, and abundant rainfalls.
- The yearly wind rose shows two prevalent winds. The first flows from the south during the period from May to October with an average speed of 1.88 m/s at a height of 10 m. The second flows from NNE during the period from November to April with an average speed of 1.75 m/s at 10 m height.
- Horizontal construction limits are given by the parcel boundaries (see Figure 50 left) defined by a rectangle of 165 x 66 m.
- The vertical construction limit is 290 m.
- The built environment is taken in consideration only in its current configuration, and the site is considered in two states: empty, or containing the two existing towers, in order to study the scenario of a renovation (see Figure 50).

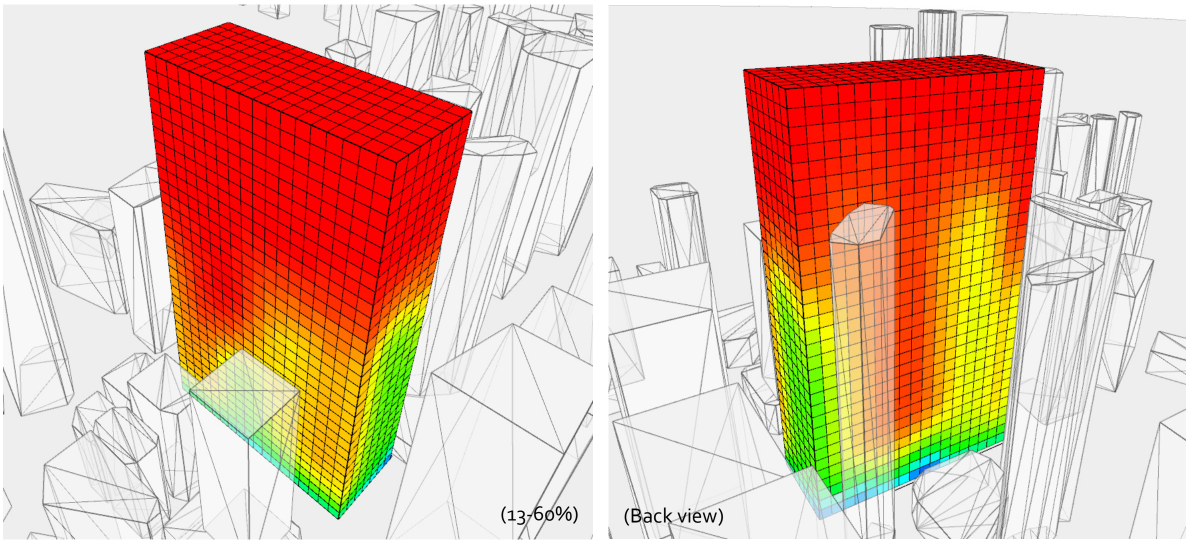
Figure 50: High-rise case study site.

3.2.2 Excerpt from the Observation Record

Yearly Solar Radiation



Visibility



Airflows

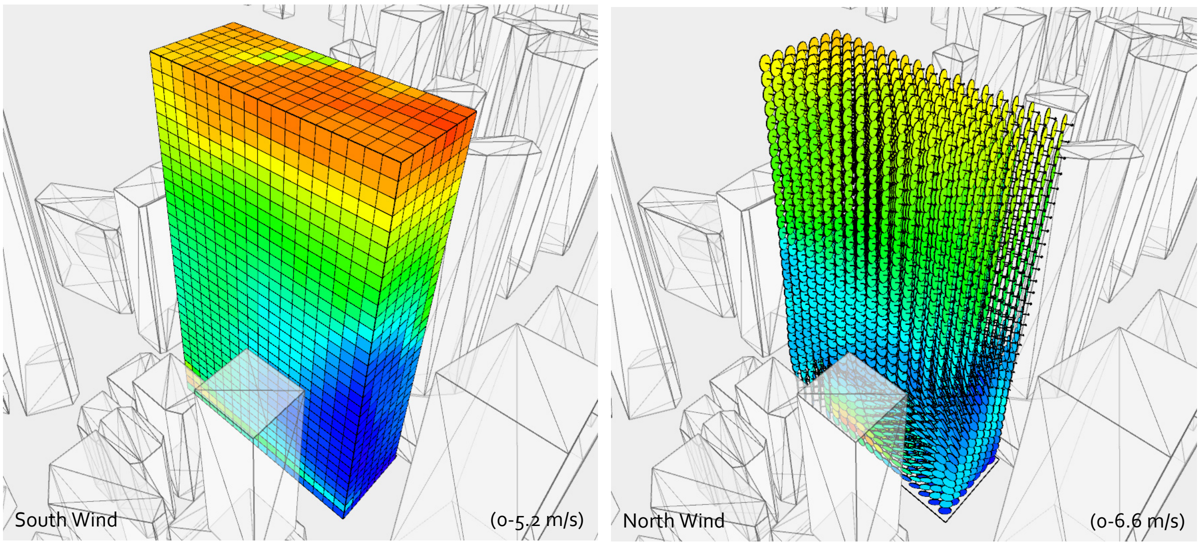


Figure 51: Excerpt of the primary layers of information displayed for the entire volume of the site.

Hourly Solar Energy (0-1.28 GJ/m²/y)

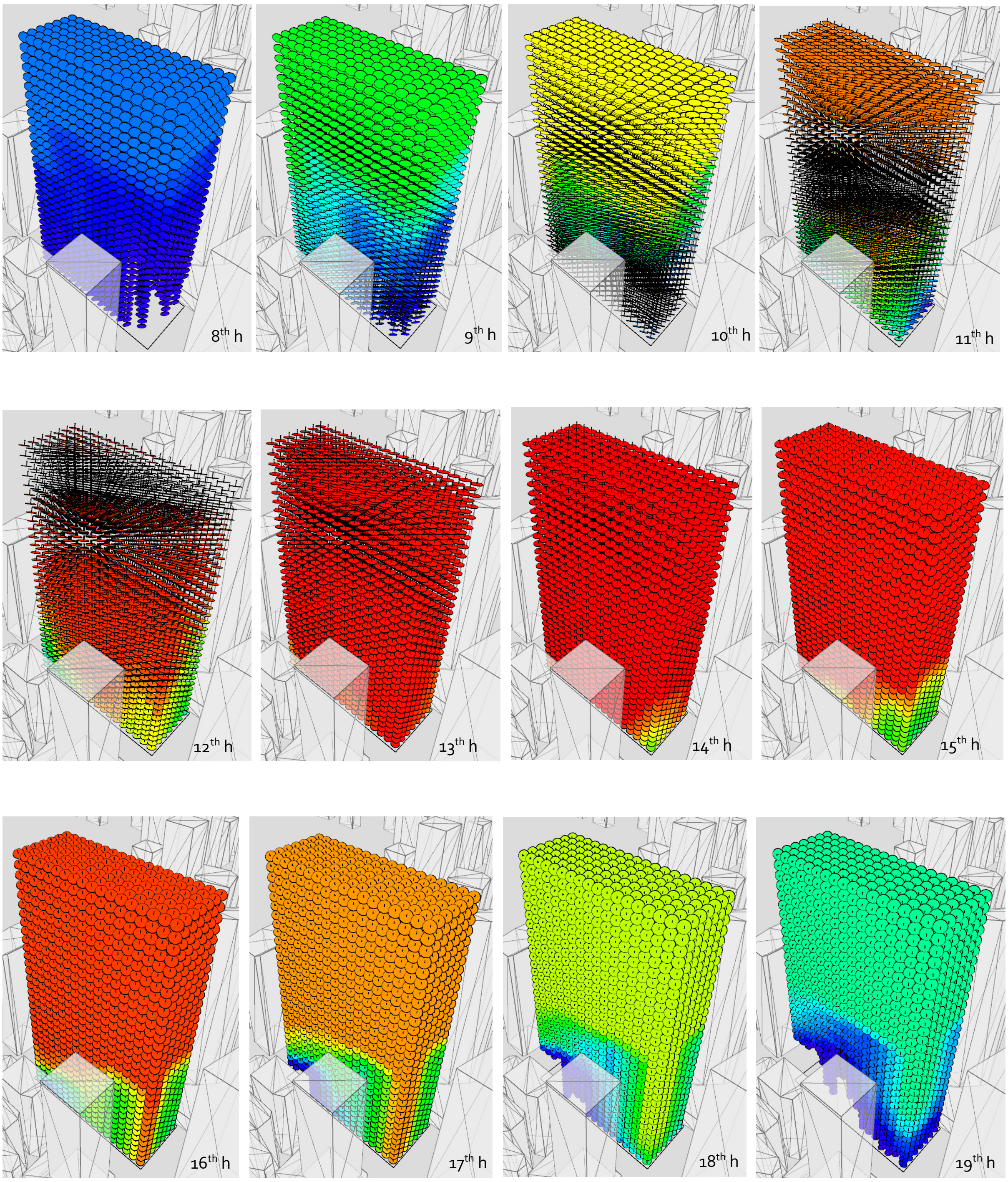


Figure 52: Hourly solar radiation energy in the empty volume of the site.

3.2.3 Synthesis of Design Schemes

Distribution of Uses

The goal of this first experimentation was to renovate the two existing towers in order to find the most efficient locations to collect photovoltaic energy, to gather evening daylight, and to take advantage of the highest visibilities. Observing the volumetric information close to the building envelope, and by applying a lower threshold on it, it is possible to retrieve suggestions for a smart distribution of exterior surfaces and uses.

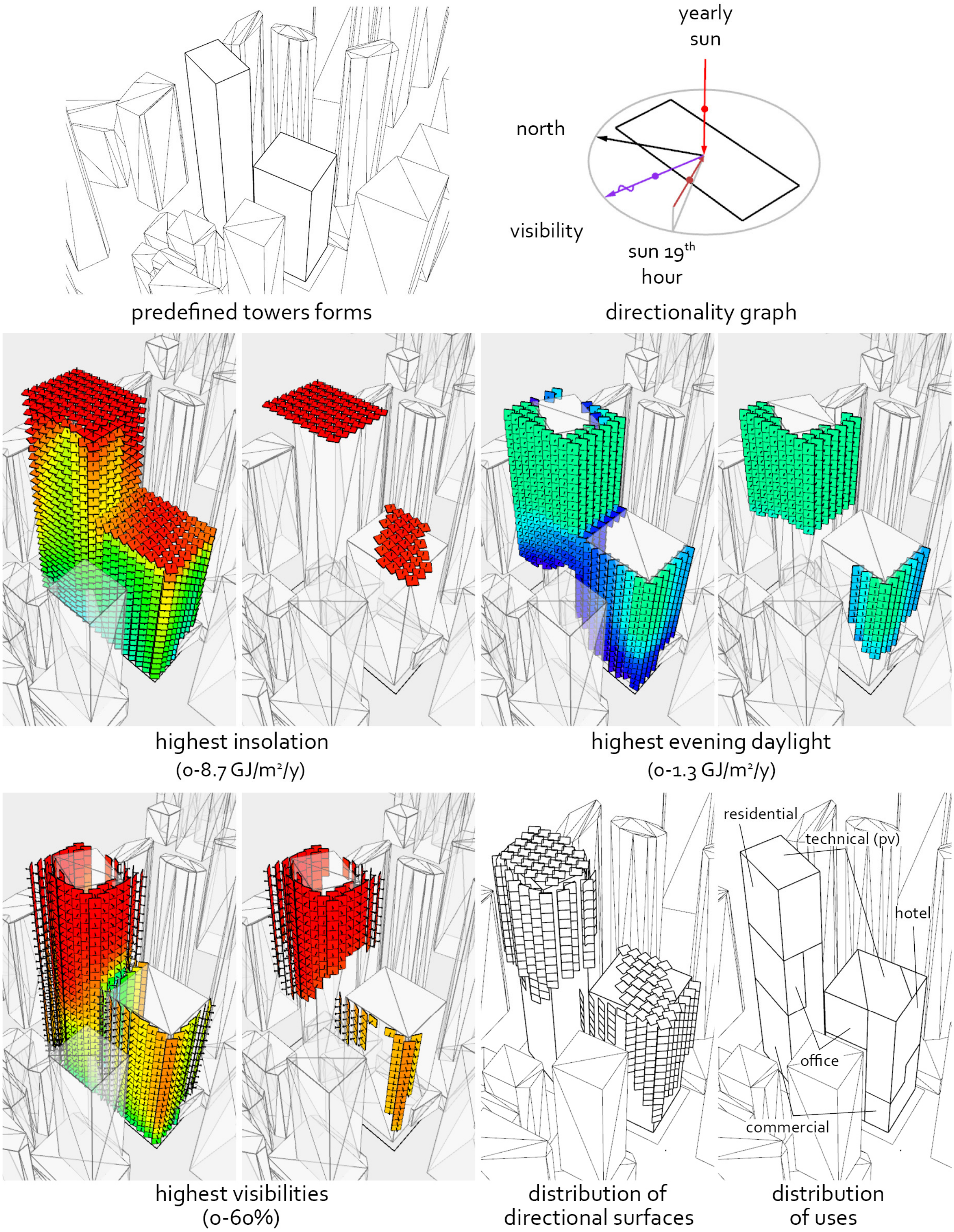


Figure 53: Distribution of surfaces and uses in two mixed-use towers according to volumetric criteria.

Cooling Surfaces

The goal of this experimentation was to shade the facades of the existing tall tower from undesired solar heat and to gather photovoltaic energy to cut its cooling electricity demand peak. Information of the hours of peak radiation and of peak cooling demand has thus been used to retrieve the corresponding volumetric information on solar radiation. This information has then been used to define the form of shading and of photovoltaic surfaces on the facades.

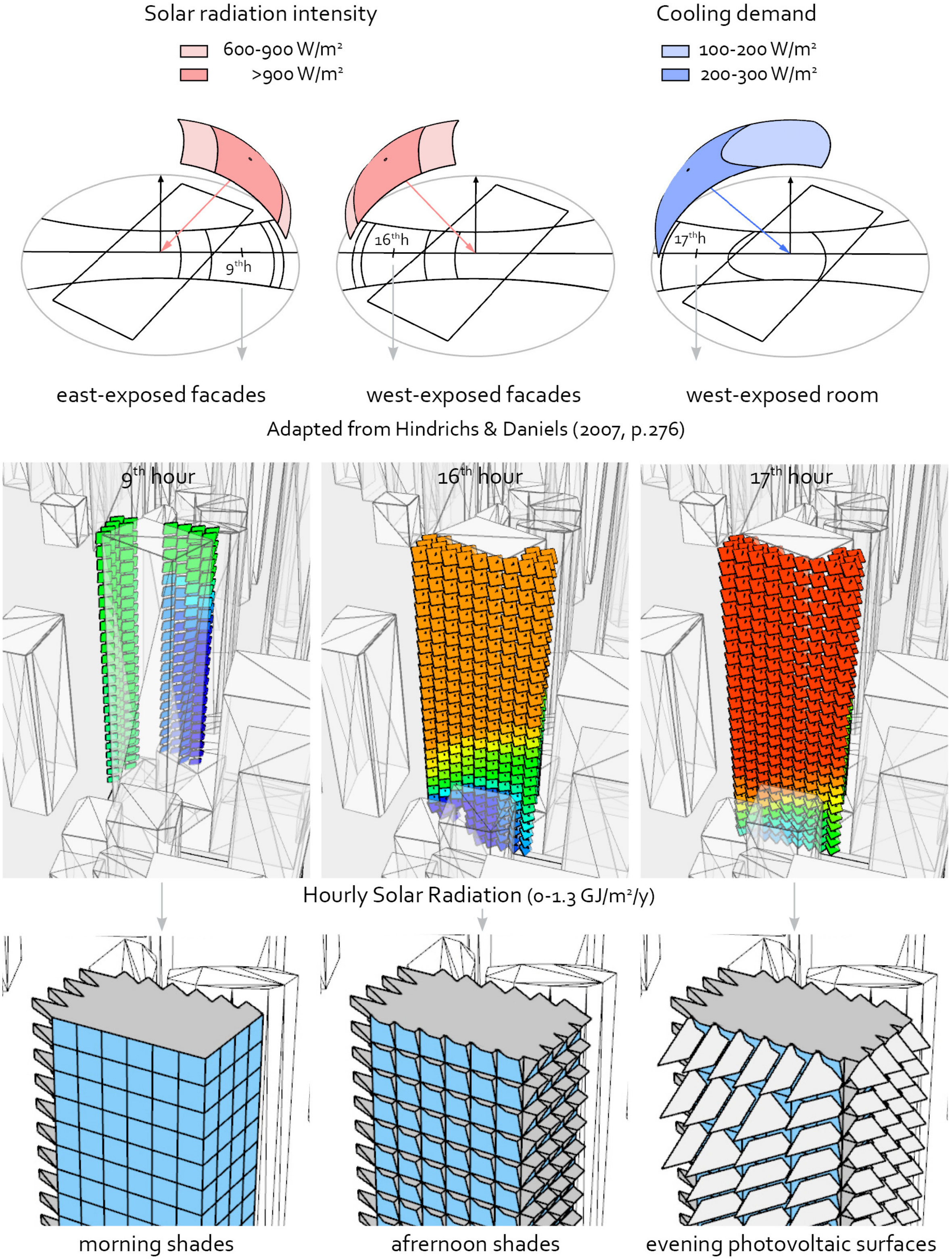


Figure 54: Design of shading and photovoltaic surfaces according to the solar radiation intensity and the cooling demand.

Proportions and Facades from Solar Energy

This experimentation concerned the design of a new office building. Observation of the environmental information suggested the possibility of cutting the morning and afternoon electrical demand peaks of the offices by maximizing the production of photovoltaic energy during these periods. For this purpose, the building was proportioned to get the main facades exposed to the corresponding solar directions, and was positioned to reduce the impacts of shading. The photovoltaic surfaces have then been located at less shaded positions on the facades and oriented towards the two corresponding solar directions.

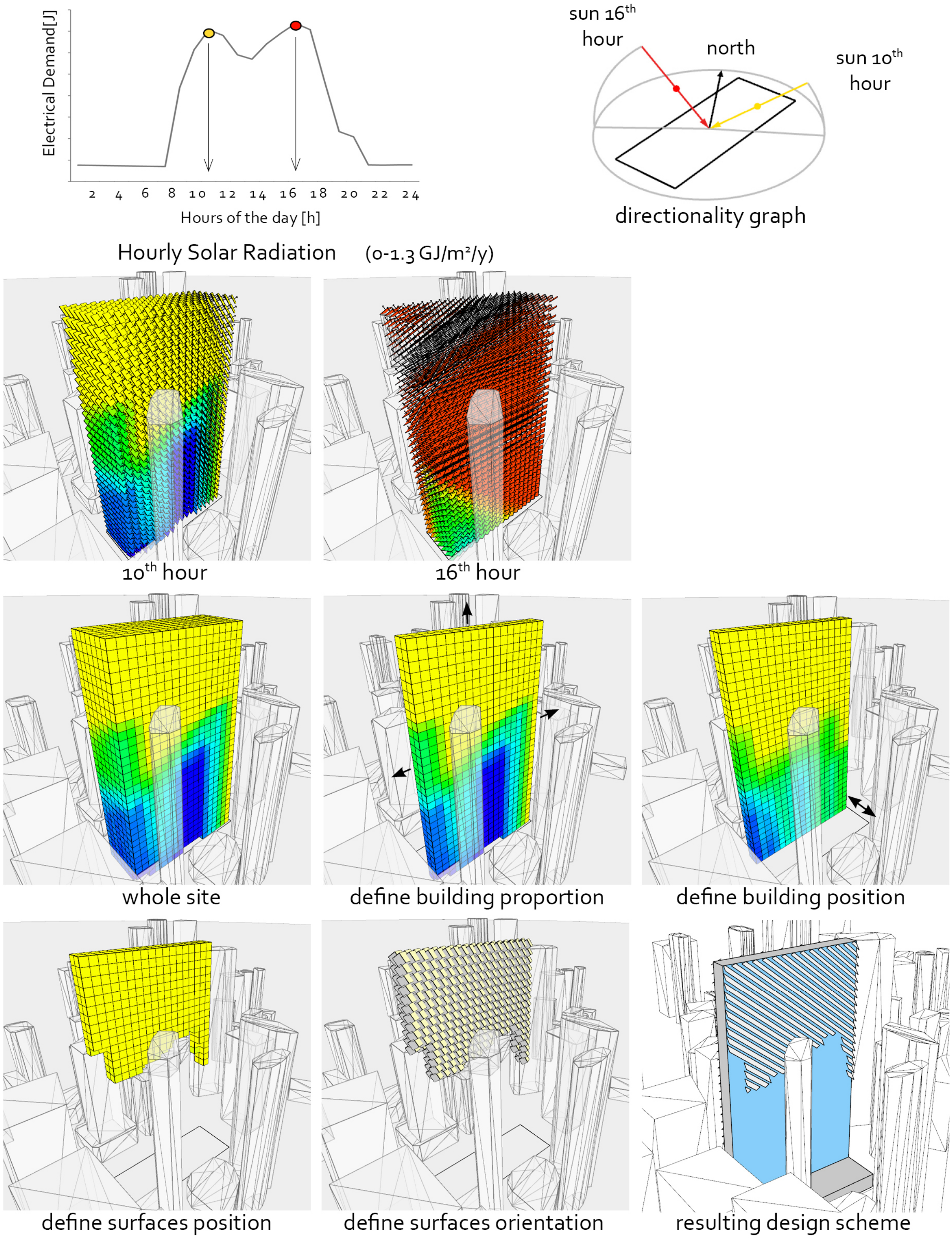


Figure 55: Definition of the building proportion and position, and of the form of the facade, to optimize energy collection.

Environment-Receptive Form

In this case the aim was to determine a form for a new residential building that would be capable of gathering the morning and evening daylight, of facilitating the inflow of light-gentle airflows (cf. Beaufort scale), and of ensuring highest visibilities. Following an extroverted approach the building was shaped to face the incoming resources directly at their entry in the site. The depth of the building was kept limited to allow for the penetration of the resources in the interior spaces, and the final shape was defined combining the identified resources and limiting the effects of self-shading.

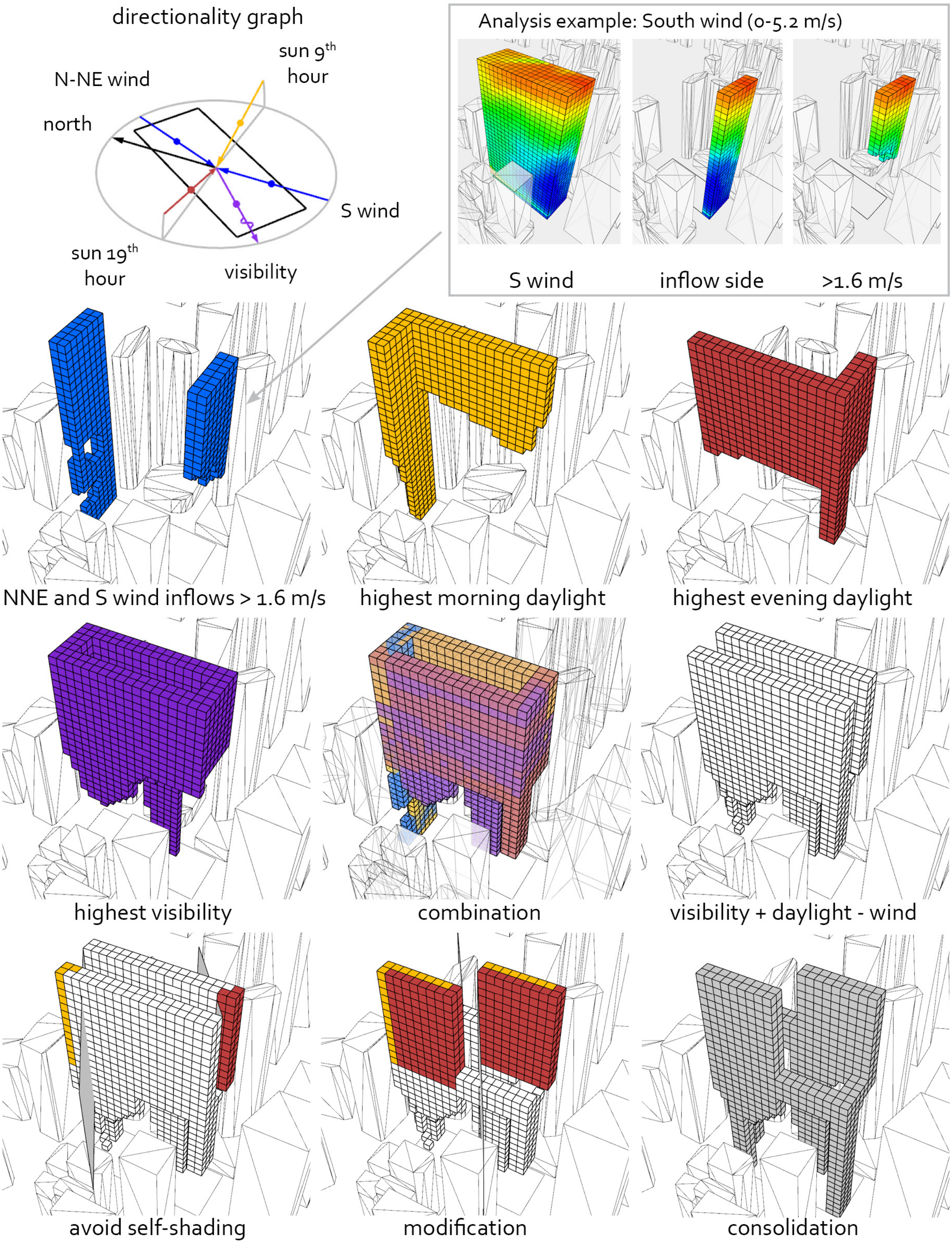


Figure 56: Definition of the form of the building according to objectives of daylight, airflows, and visibilities.

Form from Visibility

In this last example, the aim was to determine a form that would ensure the highest possible visibilities to the spaces of a new office building. In a first step, a simple lower threshold was applied on the visibility layer in order to identify the volume with the highest visibility values, this volume was then consolidated to visualize the form of a potential building designed upon this criterion.

In a second step, the same exercise was continued maintaining the volume distributed equally on each floor. However, at top levels, where obstructions have less effect, the thresholds were not able to arbitrate the volume because the voxels all had identical values. The volume was thus cleared privileging the voxels with a high number of adjacent neighbors to favor the creation of a compact form. Finally, by changing the visualization elements from voxels to oriented boxes it was also possible to visualize the directions in which these visibilities would be higher.

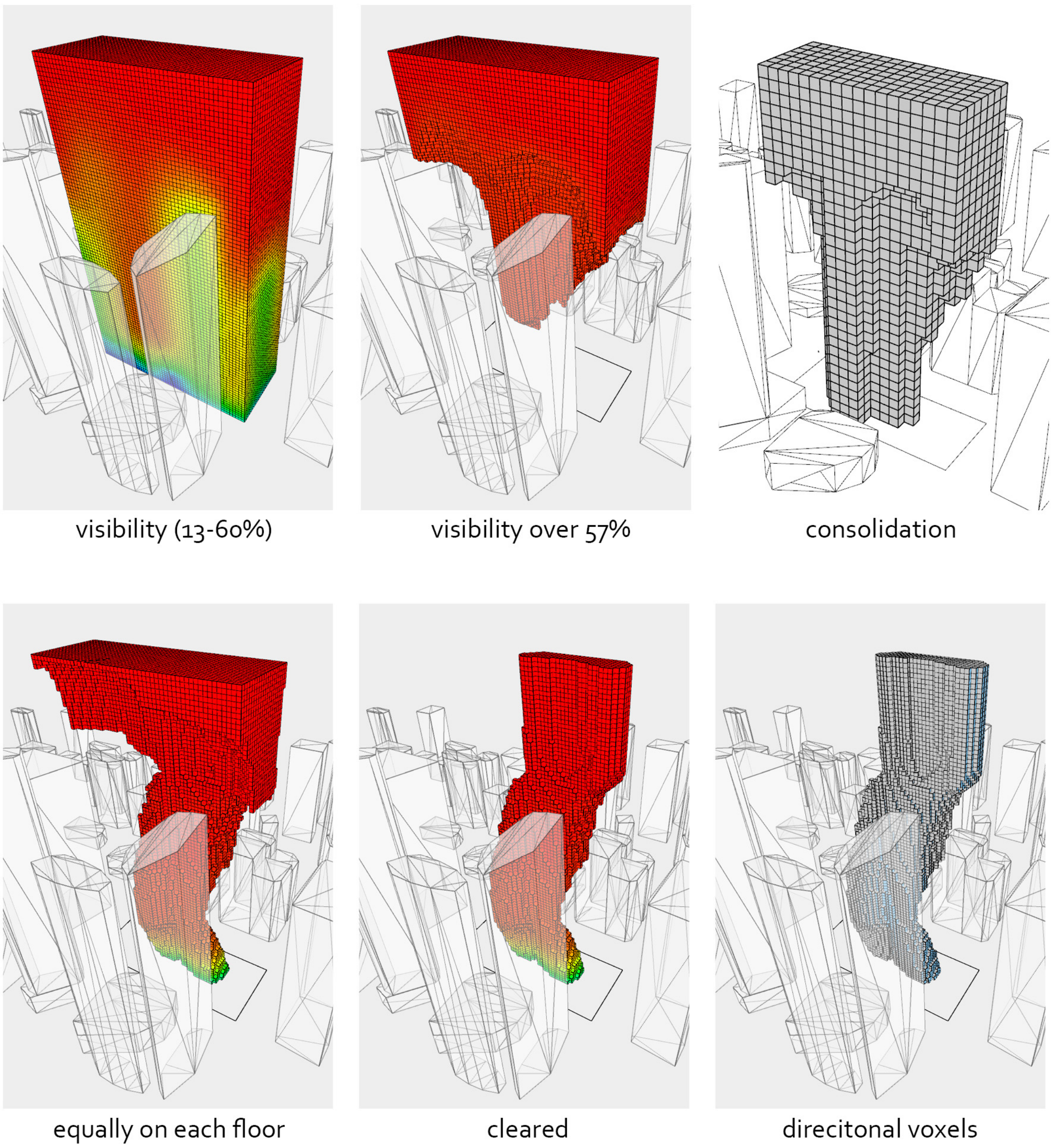


Figure 57: Form finding experiments based on the definition of shapes that ensure the highest possible visibilities.

4 USER STUDIES

In addition to the case studies presented in Section 3, a series of user studies have been carried-out to evaluate the employment of VSA by external users. The first user study occurred as part of a short project developed by a student named Tom Doan at the ETH Zurich in 2013. The second user study was organized during a three-day workshop held in the frame of the CAADRIA conference 2014 in Kyoto. The following participants of the workshop were selected to take part in the user study: Ran Tateyama, from the Keio University Tokyo, Tomoya Senoh, from the Osaka City University, and João Lopes, from the Instituto Universitário de Lisboa. In total, the four user profiles included two architecture students, one civil-engineering student, and one architect with decennial experience in the practice.

All experiments realized by the users concerned the high-rise site in Singapore (see Section 3.2). The site information on solar radiation, wind, and visibility was made available to the users through a prototypical visualization framework (see Figure 21). By interacting with the interface the users could explore the environmental information of the site, develop interest for specific resources, and export the corresponding images and geometries as JPG and DXF files. All users were asked to first create an Observation Record (see Section 2.5.1) with the summary of their most important observations, and successively to develop a design sketch using their habitual 3D modeling program. Additionally, after the experimentations, they were asked to answer a questionnaire about their experience using the VSA methodology.

This section presents a summary of the experimentations of the users, and the outcome of the questionnaire.

4.1 User Experimentations

4.1.1 Experimentation by Tom Doan

Excerpt of the Observation Record

By interacting with the interface, the user first tried to understand the volumetric and directional characteristics of different resources, and then he set them in relation to different spatial sectors of the site as illustrated in Figure 58.

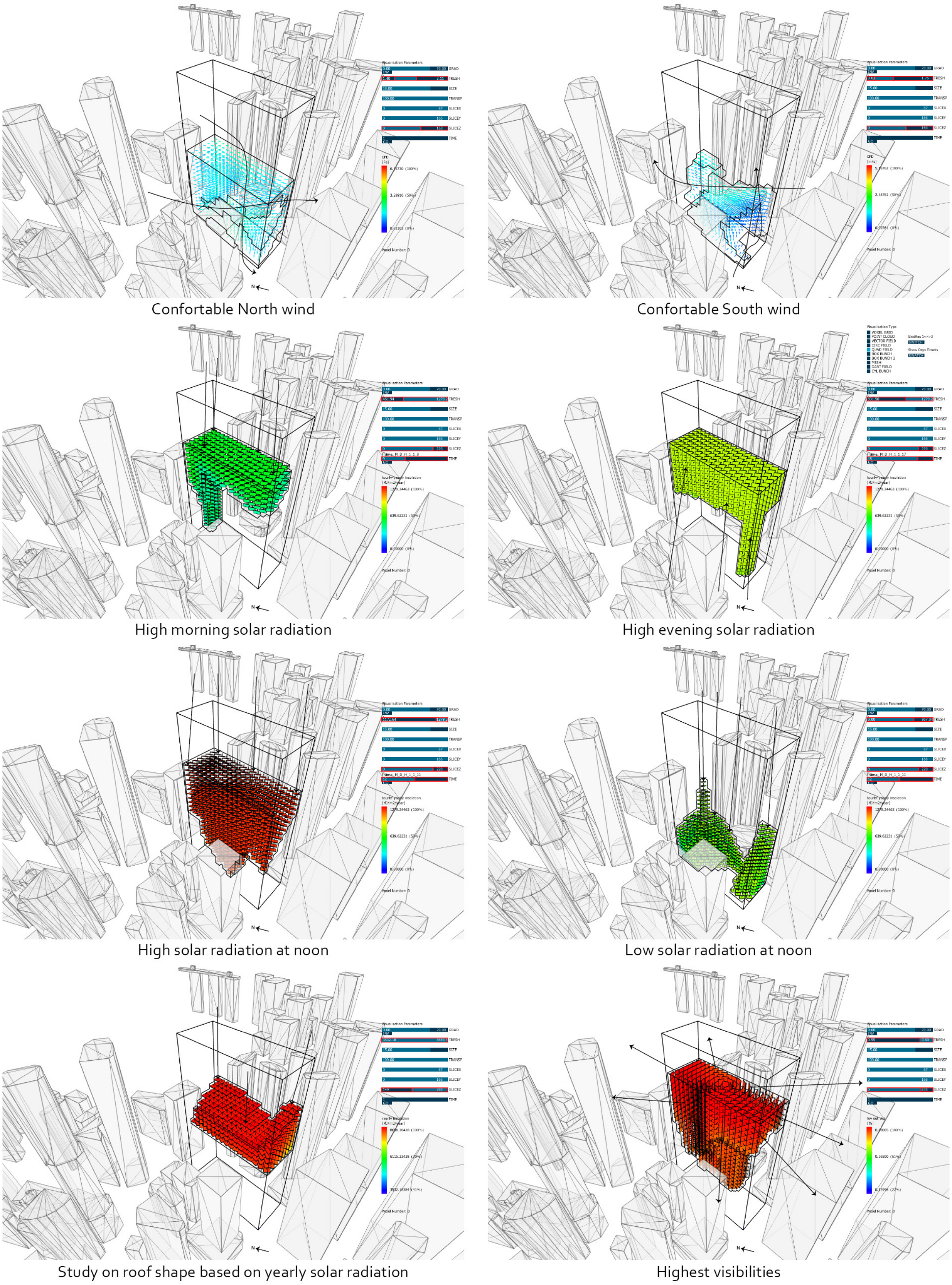


Figure 58: Presence of specific resources in different sectors of the site (Image: T. Doan, M. Leidi).

Excerpt from the Design Schemes

In a second step, the user tried to combine these sectorial observations, generating a series of different formal configurations. These buildings are characterized by the alternation of voids and fills that correspond to the presence of specific environmental resources (see Figure 59). Successively he distributed different types of uses (residential, office, and commercial) through these spaces according to the nature of the available environmental resources. In combination with that, the user developed concepts such as 'shaped roofs', to increase the access to sunlight, airflows and views on top of the building, and 'urban niches' to provide spaces that were both open, but also protected from undesirable features such as rain or midday sun.

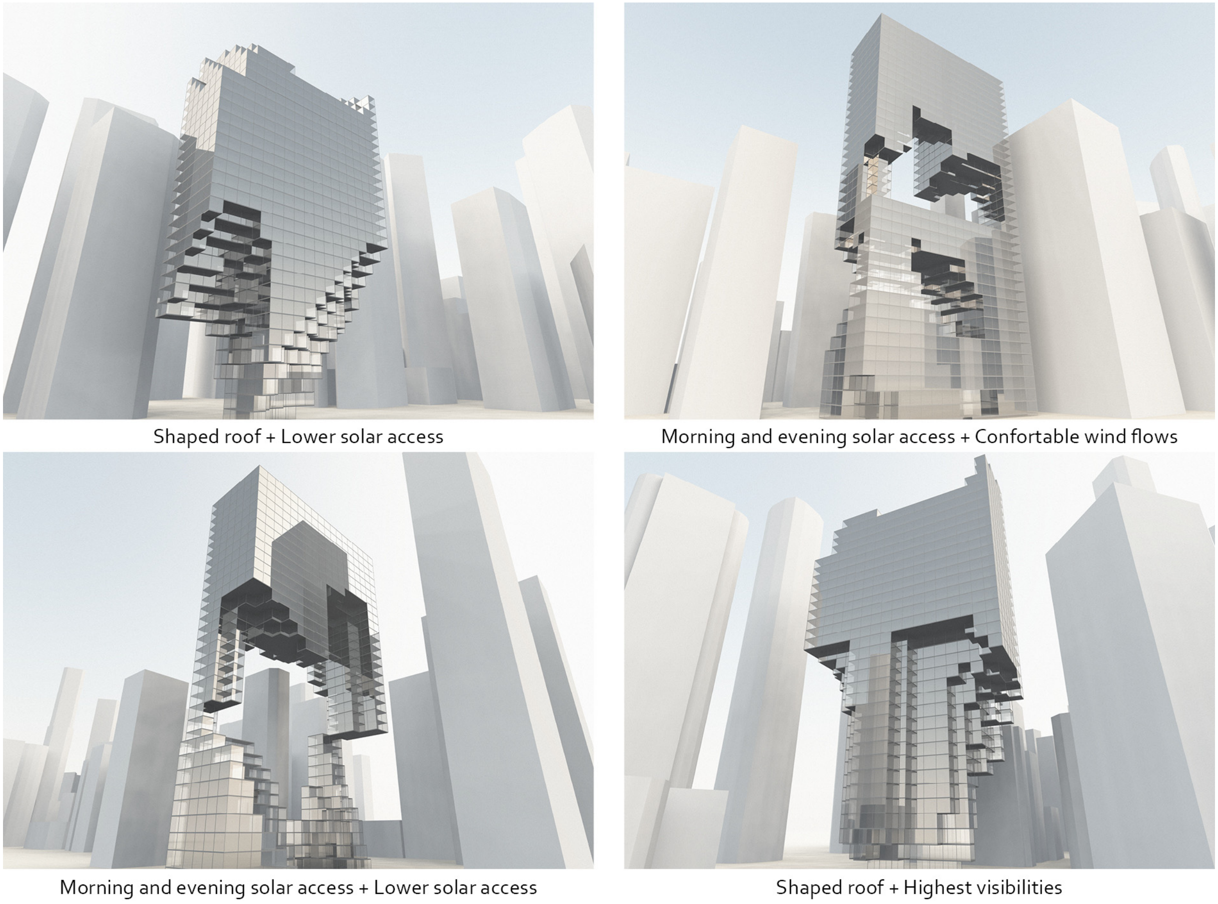
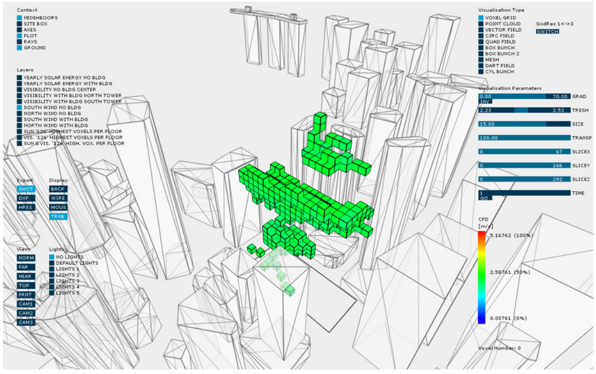


Figure 59: Massing study for a mixed-use building according to different environmental strategies (Image: T. Doan, M. Leidi).

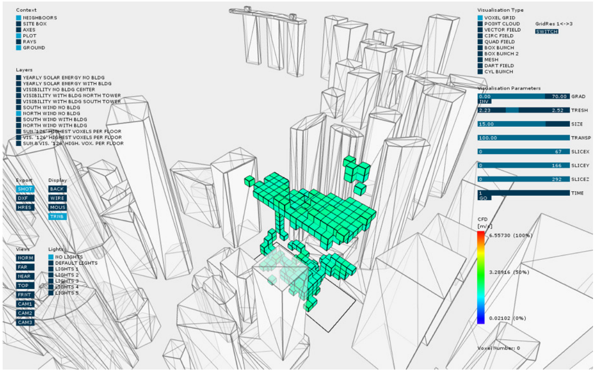
4.1.2 Experimentation by Ran Tateyama

Excerpt from the Observation Record

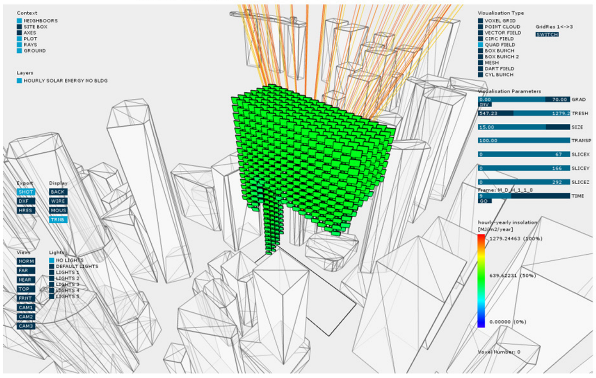
In this experiment, the user observed the presence of variables such as airflows, solar radiation, and visibilities having specific comfort values or specific occurrences during the day, as illustrated in Figure 60.



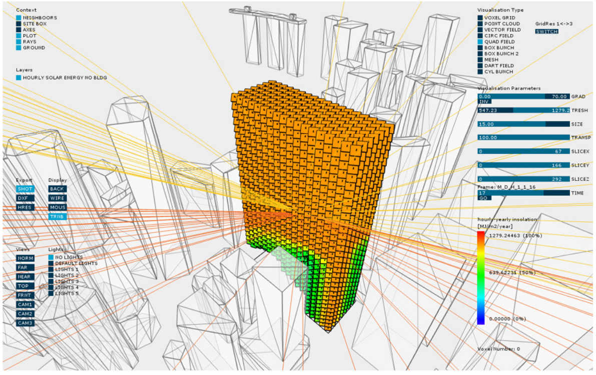
Comfortable South Wind (2.2-2.5 m/s)



Comfortable North Wind (2.2-2.5 m/s)



Strong Solar Radiation 9th hour (>547 MJ/m²/y)



Strong Solar Radiation 17th hour (> 547 MJ/m²/y)

Figure 60: Comfortable wind, and morning and evening solar radiation in the site (Image: R. Tateyama, M. Leidi).

Design Scheme

Inspired by the visualized data, the user decided to compose a building with different types of 'space-cells' using different types of forms. The simplest cell had the shape of a cube with four vertical faces, and the most elaborate one, the shape of an octagonal prism with eight vertical faces oriented in different directions. These cells got their specific shape according to their location in the site and to the consequent presence or absence of certain environmental resources. In turn, the faces of each cell were then be set as transparent, opaque, or green (covered with vegetation), depending on their orientation towards certain environmental resources.

This formal system was designed to be able to generate facades that, depending on the configuration, would be capable of providing both, access, for example to daylight and visibility, or protection, for example from glare and solar heat. In addition to that, the user remarked that the two prevailing winds flowing through the site were of comfortable speeds at similar positions as shown by the Green and Blue voxels in the image with the superposition of the resources in Figure 61. She therefore removed the corresponding cells to create a mid-height open-space that allowed the occupants to take advantage of the comfortable breezes while also enjoying the shade, rain protection, and views to the surrounding district. Finally, she used the formal language of the building to shape a terraced rooftop augmenting the access possibilities to the environment by increasing the spaces having horizontal and vertical adjacencies as illustrated in Figure 62.

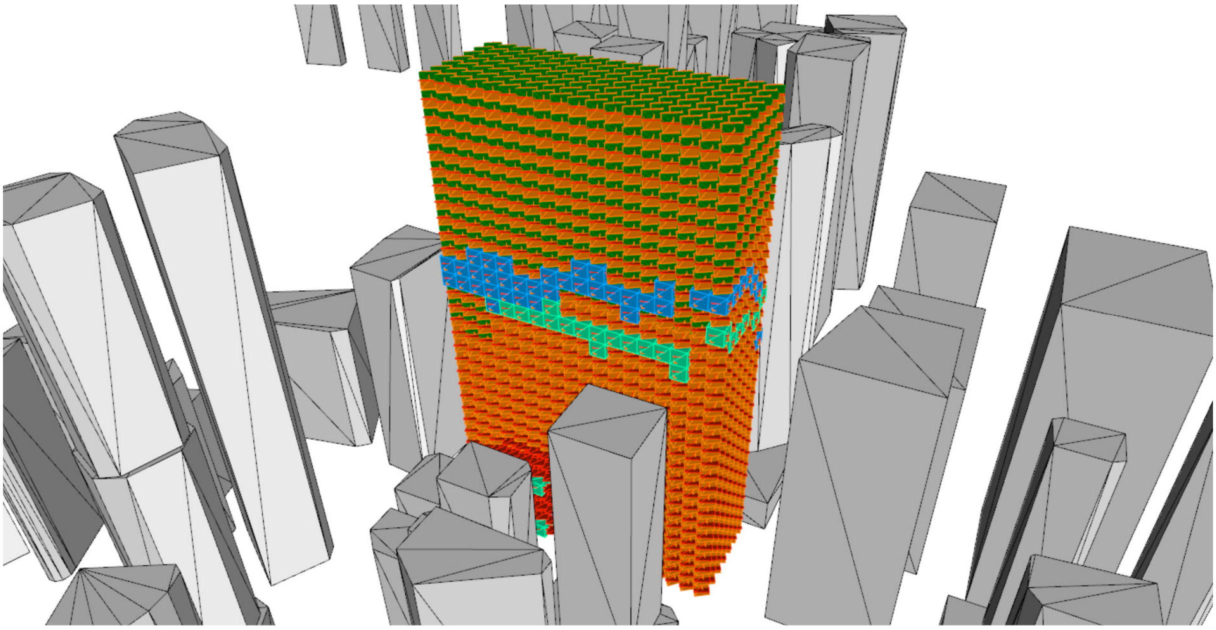


Figure 61: Superposition of the selected environmental information (Image: R. Tateyama, M. Leidi).

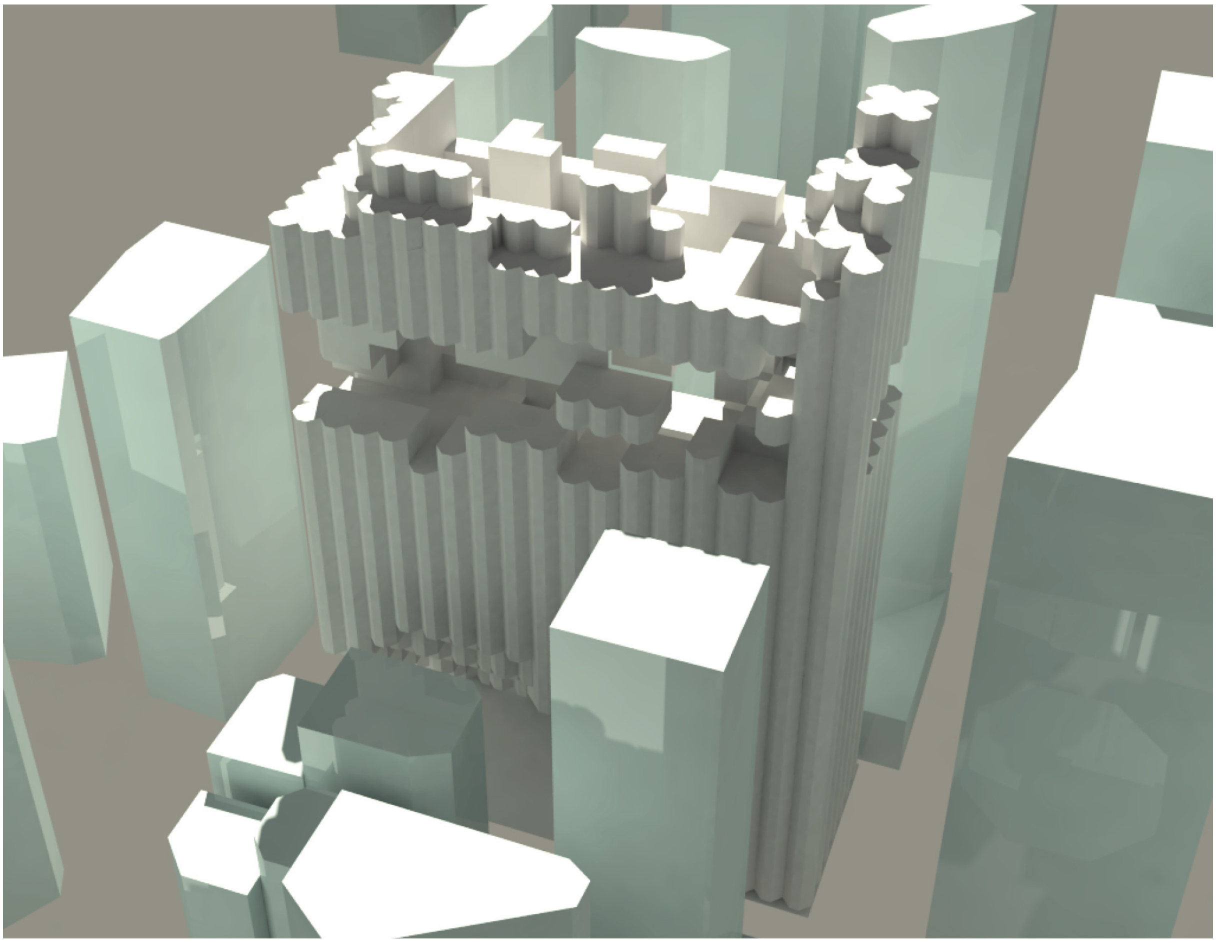
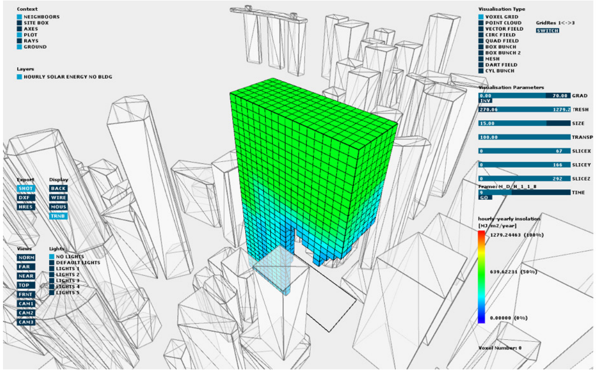


Figure 62: Design scheme resulting from the aggregation of vertically chamfered space cells (Image: R. Tateyama, M. Leidi).

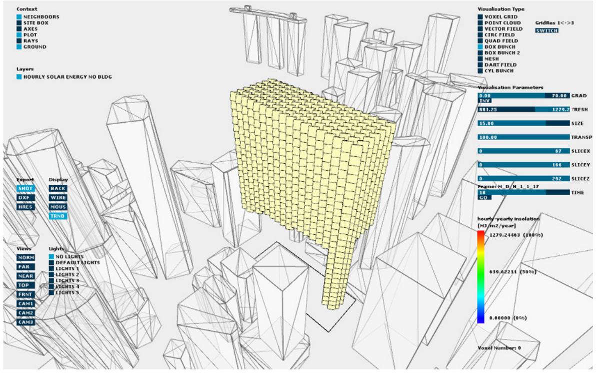
4.1.3 Experimentation by João Lopes

Excerpt from the Observation Record

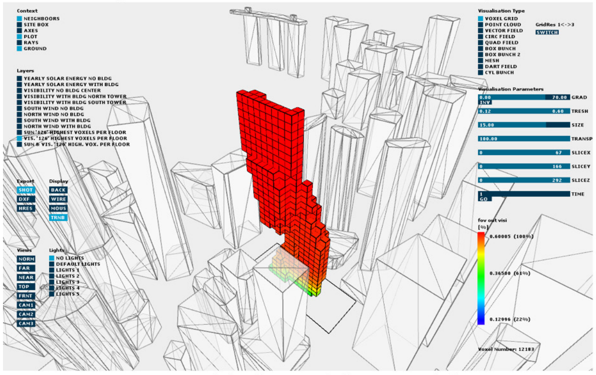
The user employed several filters to isolate portions of space of the site according to different specific constraints as illustrated in Figure 64.



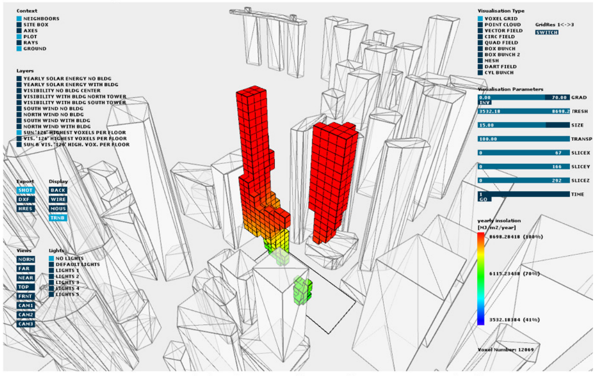
High solar radiation at 9th hour (> 270 MJ/m²/y)



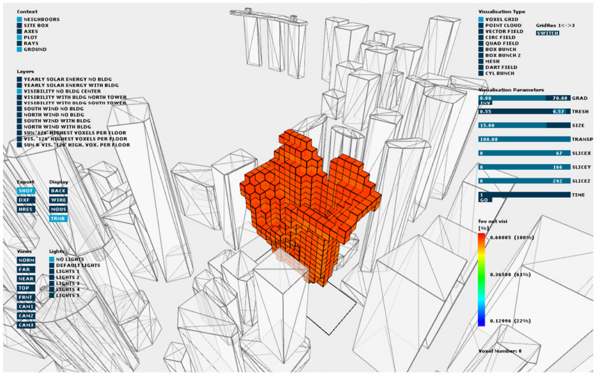
High solar radiation at 18th hour (> 880 MJ/m²/y)



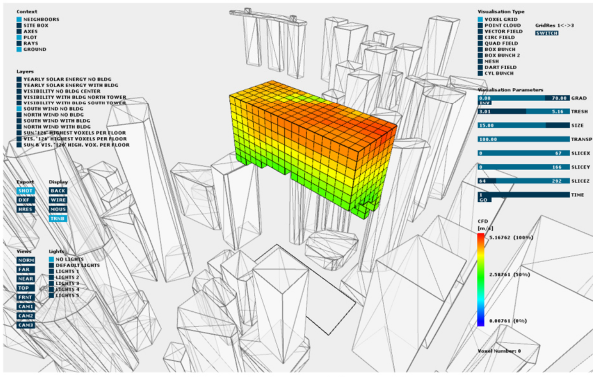
1'000 m² with highest visibility on each floor



1'000 m² with highest solar radiatio on each floor



High visibility (55-57%)



High wind speed (> 3 m/s)

Figure 63: Observation Record with a series of properties subject to specific constraints (Image: J. Lopes, M. Leidi).

Design Scheme

After having observed that the lower floors of the site featured weak environmental conditions, the user decided to liberate the bottom part of the tower to facilitate the penetration of daylight, air circulation, and views in that space. This allowed creating a space connected with the city plane, where people could access the building or gather for different open-space activities. Successively, after having observed that the best environmental conditions were distributed in different locations of the site, he decided to connect all these places of interest with a peripheral path around the facade of the tower. The goal of this pathway was to provide all building occupants with the possibility to reach and enjoy the best views and sunlight at the desired time, while staying sheltered from strong winds along the way. Finally, the texture of the top part of the building was shaped in order to maximize the production of solar power according to the evening demand peak of the tower.

By employing visual programming software (see Figure 64), the user created a procedure to read the geometries imported from VSA and use them as a source of information for further parametric modeling operations. Through this procedure he could generate a series of designs, according to different combinations between the input geometries and several formal rules, and he could finally select the design illustrated in Figure 65. The overall building design resulted thus as a combination of a lower open-space, a mid-height pathway, and an upper solar facade.

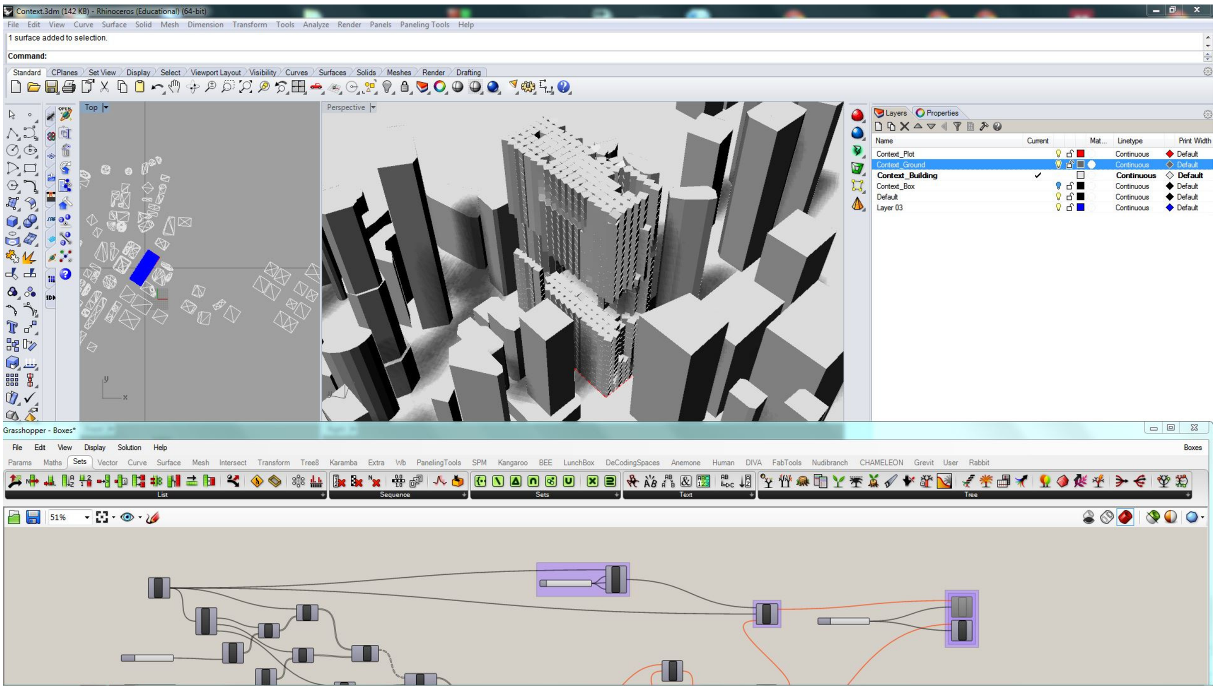


Figure 64: Use of visual programming for parametric operations on data exported from VSA (Image: J. Lopes, M. Leidi).

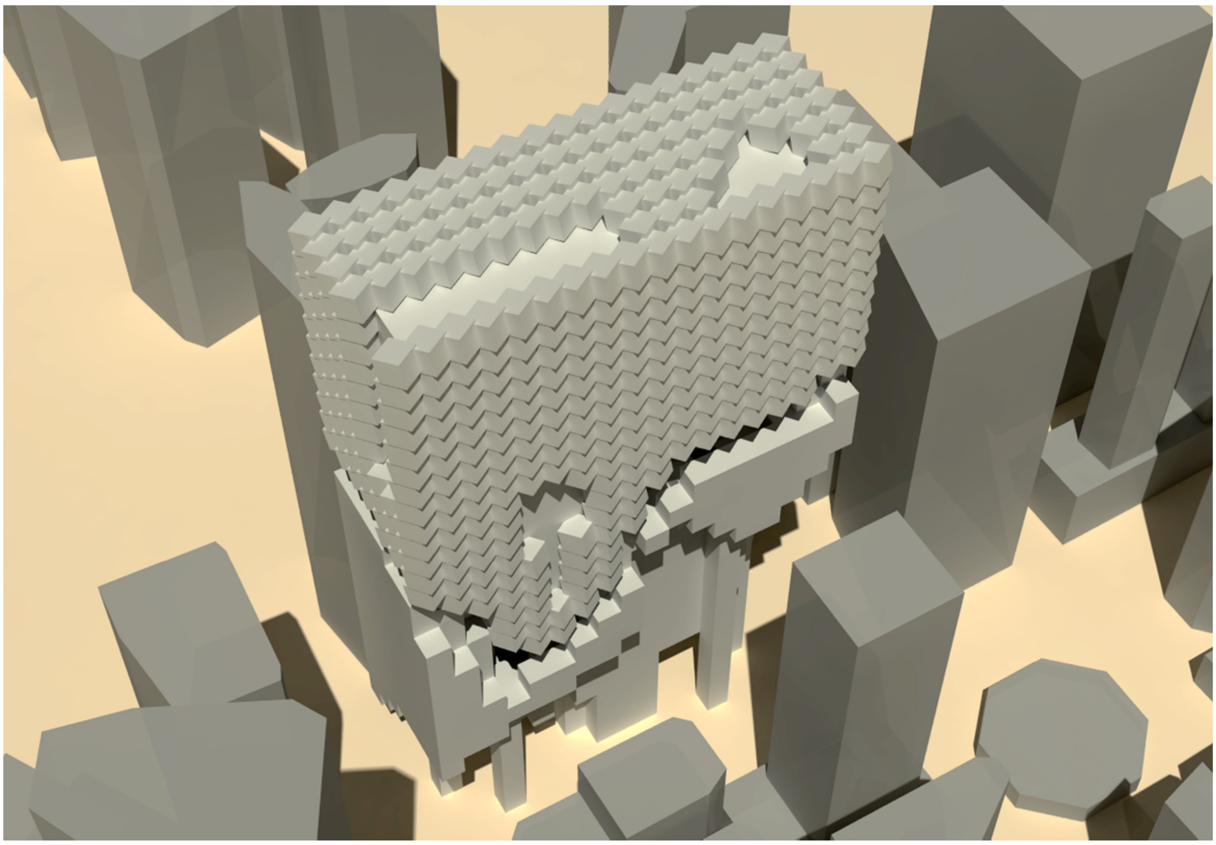


Figure 65: Final sketch composed by a lower open-space, a mid-height pathway, and an upper solar facade (Image: J. Lopes, M. Leidi).

4.1.4 Experimentation by Tomoya Senoh

Observation Record

In this case, the user observed the site resources in the presence of the two existing towers. He rapidly noticed that all properties presented high magnitudes around the same region, spanning from the top of the smaller tower to the top of the higher tower, as highlighted by Figure 67 (see next page). This consistency suggested to him the possibility of adding a new construction superstructure built on top of the existing towers, to exploit the resources available in that space.

Design Scheme

To draft his concept, the user employed the last mesh shown in the Observation Record (at the bottom of Figure 67), which presented a good compromise in terms of spatial distribution and continuity. Guided by this mesh, and by the hypothesis that the structure of the two towers could carry additional load, he sketched a structure with an elevated park dedicated to restoration and recreational activities, as shown in Figure 66. This new construction connects the two otherwise isolated towers and creates a completely new circulation scheme across the towers and the city plane. This park was conceived as a public space accessible to the occupants of the two office towers but also to the population of the whole urban area.

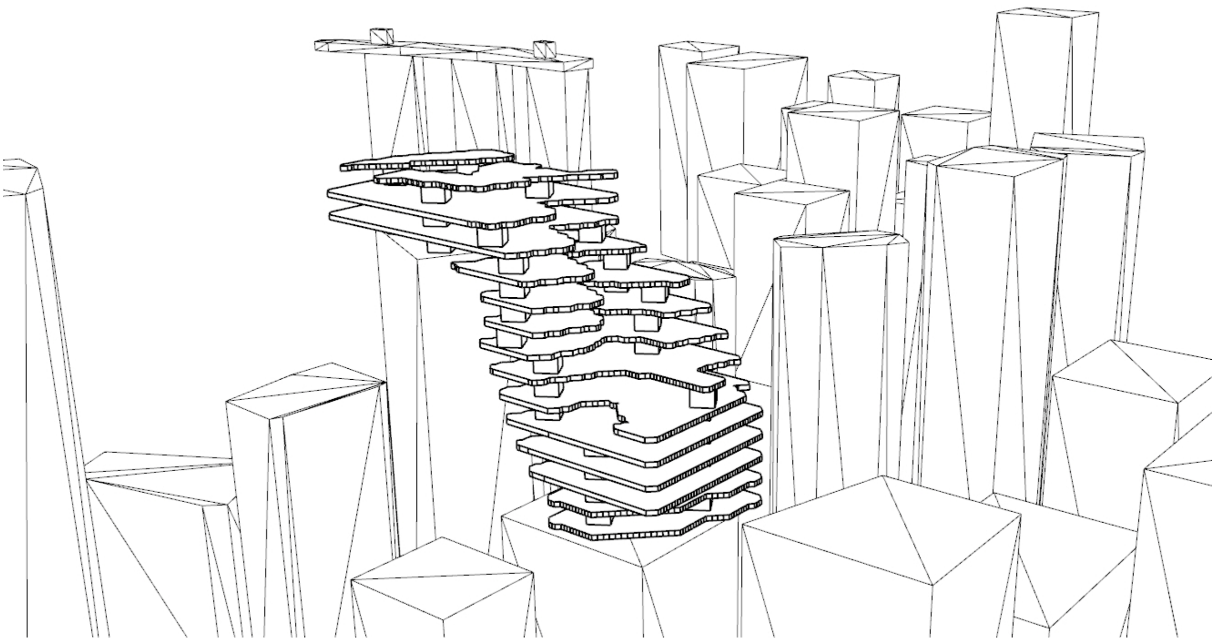


Figure 66: Superstructure with an elevated park connecting the two buildings (Image: T. Senoh, M. Leidi).

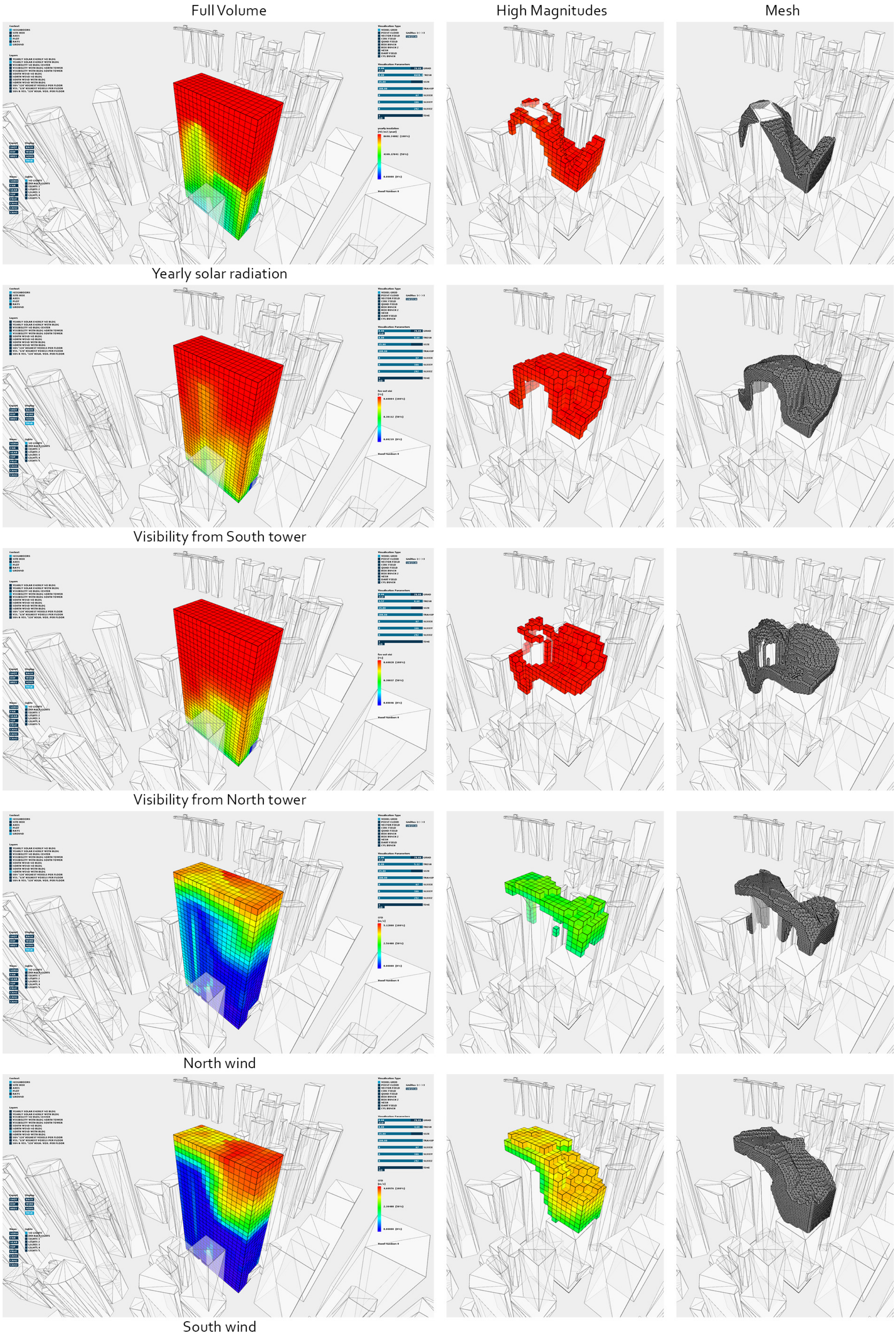


Figure 67: Many resources feature high magnitudes around the same region of the site (Image: T. Senoh, M. Leidi).

4.2 User Feedback

As mentioned, after their experimentations the users were asked to answer a questionnaire to evaluate their experience of using the VSA methodology.

4.2.1 Questionnaire Submitted to the Users

Volumetric Site Analysis (VSA) is a new technique that allows architects to explore environmental information of urban sites with the goal of retrieving conceptual design suggestions. Recently you used VSA in some conceptual design experimentations. In this questionnaire you are asked to evaluate your experience of using this new methodology.

Close-ended questions, please answer with Yes or No:

1. *Do you judge VSA as generally useful/beneficial for the conceptual design process?*
2. *Do you feel that VSA allows you to have a better perception of environmental resources in comparison with alternative methods you have used in the past?*
3. *Do you feel that the visualization and interaction possibilities make environmental resources more available and their integration in designs simpler and more intuitive?*
4. *Do you think that this technique could lead to the development of new design concepts that could not be achievable otherwise?*
5. *Would you be interested in using VSA in your practice/activity?*

Open-ended questions, please answer with a short comment. In your opinion:

6. *What are the main benefits provided by this technique?*
7. *What are the main technical or usability shortcomings of the technique?*
8. *What are the main conceptual or design shortcomings of the technique?*
9. *How do you define and judge the influence of the technique on your design results?*
10. *What do you suggest as further developments for this technique?*

4.2.2 Summary of the Answers

User 1	User 2	User 3	User 4
1. Do you judge VSA as generally useful/beneficial for the conceptual design process?			
Yes	Yes	Yes	Yes
2. Do you feel that VSA allows you to have a better perception of environmental resources in comparison with alternative methods you have used in the past?			
Yes	Yes	Yes	Yes, few tools offer analysis possibilities before the project is designed. VSA allows drawing concrete hypotheses on which initial project ideas can be established. The visualization is also very beneficial, as it is quite difficult to imagine these kinds of features through simple intuition.
3. Do you feel that the visualization and interaction possibilities make environmental resources more available and their integration in designs simpler and more intuitive?			
Yes	Yes	Yes	Yes, the only issue is the unsmooth transition of data to a 3D modeling tool.
4. Do you think that this technique could lead to the development of new design concepts that could not be achievable otherwise?			
Yes	Yes	Yes	Yes and no, the concepts will not be entirely new as the architectural field is already making steps towards sustainability, but the accuracy of VSA offers more possibilities than those given by guesses or intuition.
5. Would you be interested in using VSA in your practice/activity?			
Yes	Yes	Yes	Yes
6. What are the main benefits provided by this technique?			
It allows an easy evaluation of the environment.	We can see and consider the surrounding environment for design scopes.	A direct and intuitive analysis of the environmental potentials, an intuitive interface, dxf export capabilities.	The precision of the analysis and the mapping. The simultaneous visualization of all resources, which is quite hard to realize in a normal design process.

7. What are the main technical or usability shortcomings of the technique?			
-	During design, information has to be read from multiple non-integrated files (several 3D models and images).	The impossibility to import different contextual environments, the impossibility to export quantitative (numerical) data, the excessive computing power demand.	The difficult interpretation of the mappings, the abstract nature of the data points, the huge size of the model, the computational heaviness of the application, some issues navigating with the camera.
8. What are the main conceptual or design shortcomings of the technique?			
-	The design is not directly linkable (and reacting) to environmental information.	The impossibility to define a custom grid-unit (voxel), the difficulty to integrate the technique in a digital design workflow. It's hard to escape the compelling visualizations of VSA, and the user tends to stick to the first forms suggested by the analysis tool.	The difficulty in interpreting information through the depth of space. Changes due to future opaque objects are difficult to imagine, and precise information on their impact is not available. A 'dynamic' calculation would help: if there's a slab designed then the data is modified to reflect the change.
9. How do you define and judge the influence of the technique on your design results?			
The form has been defined according to the visualized data.	VSA brought me to conceive the building as a system of cells subject to operations of subtraction, addition and orientation.	Easy to use and intuitive. The technique permits enlarging the design possibility in an informed way, contributing to a more evidence-based urban design. The creative power it unleashes seems enormous and is very welcome.	This technique is useful to define volumes and balance voids and fills. It can also be used to define facades, but the rotation of the elements sometimes seems to deliver incoherent or monotonous expressions.
10. What do you suggest as further developments for this technique?			
To make it available. More people should use this tool and study the link between these environmental conditions and design.	Add the possibility to feedback the design sketch model to VSA.	The possibility to import new environments, less computing power demand, in a second stage a way of evaluating the influence of the design proposal in the immediate surroundings, more explanations regarding the analysis techniques, the meaning of units, etc.	I recommend a dynamic interaction mode: defining some points as opaque would change the data of other points. A more fluid export of the model to a regular CAD software would help.

Table 1: Summary of the answers to the questionnaire.

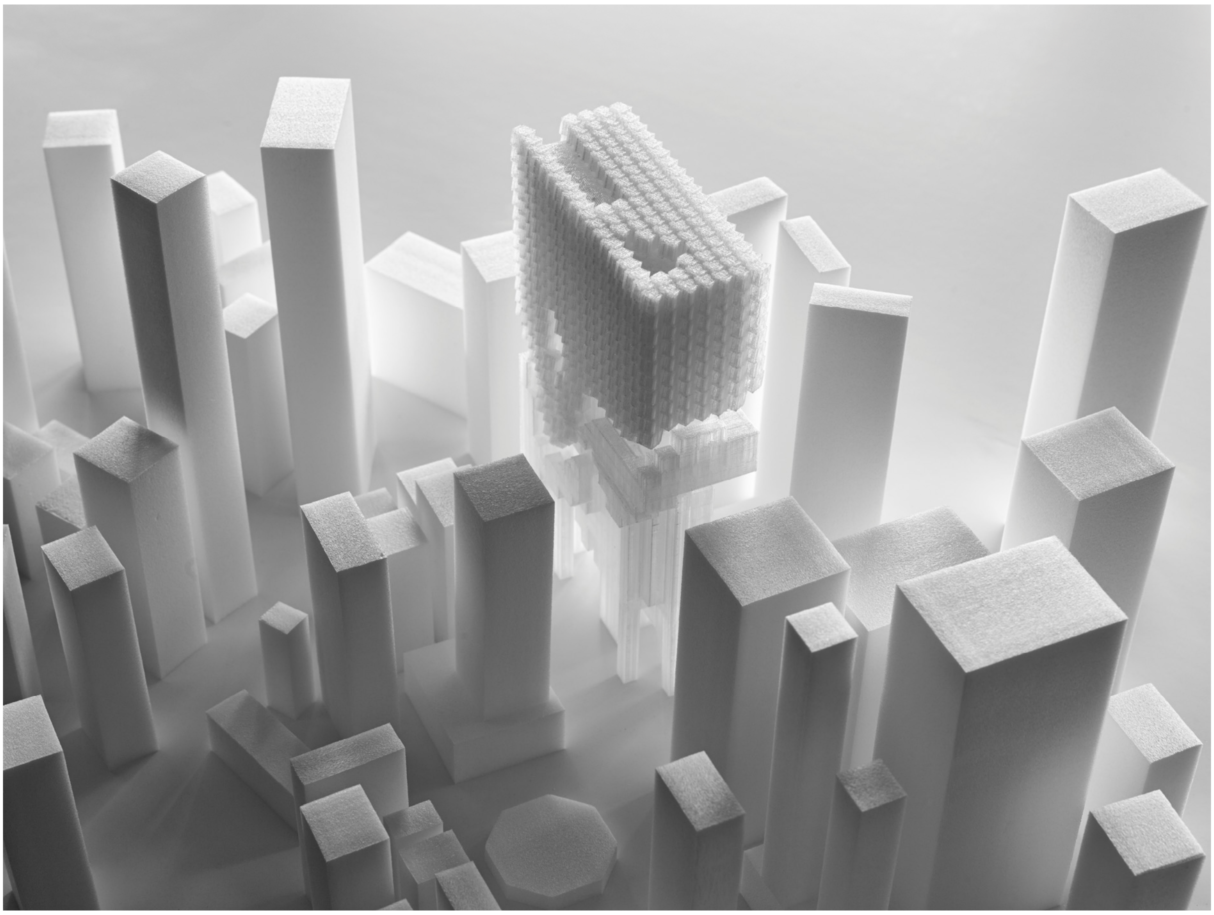
5 EXHIBITION

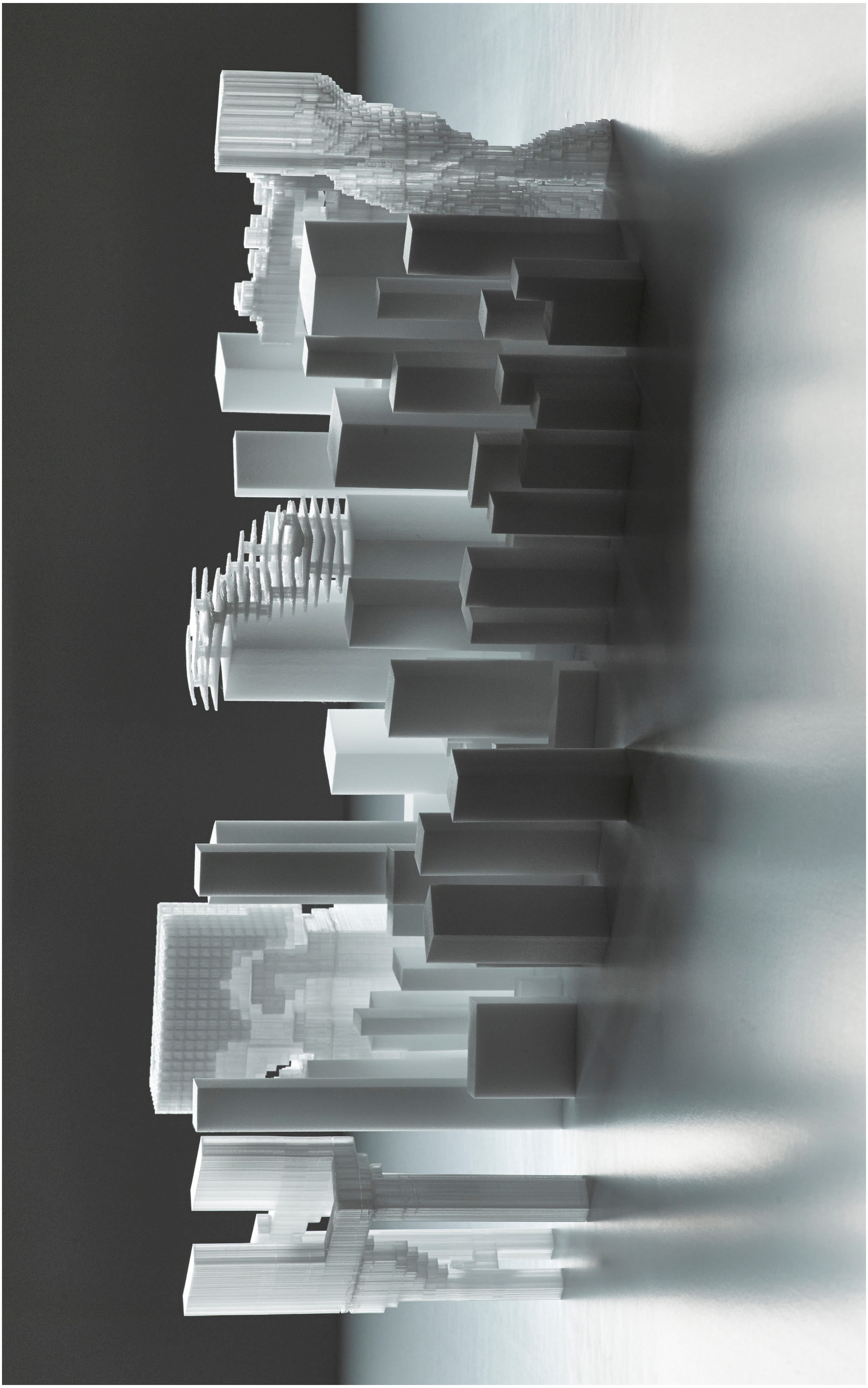
Five sketches from the case and user studies have been 3D printed and exhibited in a joint urban model during the CAADRIA conference in May 2014 at the Kyoto Institute of Technology. The following pages provide insight on the setup of this exhibition.

All printed models are related to the Singapore site (see Section 3.2.1). The models have been designed with spatial resolutions of 3 and 9 meters, and have been materialized using a scale of 1:1000.

These models represent the arrival point of the whole digital process that started by retrieving data from the physical world (see Section 2.2.1), continued by treating this information through a series of numerical steps of analysis, visualization and synthesis, to finally rejoin a conventional instrument of the architectural design process such as the physical model.

The captions of the images have been omitted to ameliorate the presentation. Models designed by M.Leidi, R. Tateyama, J. Lopes, and T.Senoh. Photographs taken by B.Noris and M.Leidi.





6 DISCUSSION

This section starts with a critical examination of the results of the case and user studies and continues with an evaluation of the whole VSA methodology. The discussion is then completed with the research conclusions, the future work, and an outlook to the broader impacts that this methodology could have on the conceptualization of urban architecture.

6.1 Examination of the Case Studies Results

The case studies experiments confirmed that VSA can be used to retrieve meaningful suggestions for the design process (see Section 3). The obtained results highlighted the existence of a huge diversity of possible approaches to transfer volumetric environmental information to the design process. The numeric validation of the design schemes also allowed confirming the legitimacy of the approach from a quantitative point of view, showing that the performance of some design schemes conceived with VSA can easily surpass the performance of conventional solutions (see Section 3.1.5). The developments of the case studies have also shown that VSA can be used with many different scopes. The next sections propose an evaluation and a classification of these different fields of application based on the results of the case studies.

6.1.1 Augmented Perception

The primary outcome that has been observed during the use of VSA is a phenomenon of 'augmented perception'. This novel phenomenon, which can clearly be perceived by observing the patterns of Figure 28, results from the combination of new means of analysis and visualization. The joint presence of multiple variables and the possibility to interact with their multiple dimensions (quantitative, volumetric, dynamic, directional) opens, in fact, new possibilities for the study of multivariate and multidimensional correlations over space and time. This augmented perception also facilitates the key possibility of coupling the environmental information of the site to the spatial and energy demands of the project (see Section 3.1.2). 4D layers consent, for example, to retrieve environmental information for specific time periods that correspond to peaks in the demand of energy, heat gains, daylight, or shading. By selecting the appropriate visualization settings, it is then also possible to obtain visualizations that directly suggest potential configuration of surfaces, with the details of the positions and directions that would be favorable for the envisioned goal. By combining these different possibilities the user can implement studies taking into account the mutual influence of several variables (see example in Figure 30), or evaluating the cause-effect relationships between the simulation results and the surrounding context. All these capabilities open new and interesting creative perspectives for the design process in relation to different application fields. In the next sections a distinction of these fields will be made between the distribution of uses and spaces, configuration of exterior surfaces, and development of new formal logics.

6.1.2 Distribution of Uses and Spaces

In the urban context the form of buildings is often highly constrained by external factors such as regulations or alignments, but the internal distribution of spaces and uses is usually less restricted. VSA provides new means for the perception of the volumetric diversities in the site and, thus, for the identification of specific positions or faces of the buildings, that could play relevant roles in relation to particular physical properties. The distribution of the spaces and uses of the buildings can therefore be made on a new informed basis.

Figure 68 illustrates two examples in which the distribution of spaces and uses has been defined according to environmental parameters. The first example (see details in Section 3.2.3) concerns a mixed-use building in which environmental information was used to define the spatial distribution of different commercial, office, hotel, technical or residential uses. In the second example (see details in Section 3.1.4), the apartments of a residential building were instead shaped in order to ensure access to daylight and sights to the highest possible number of living units.

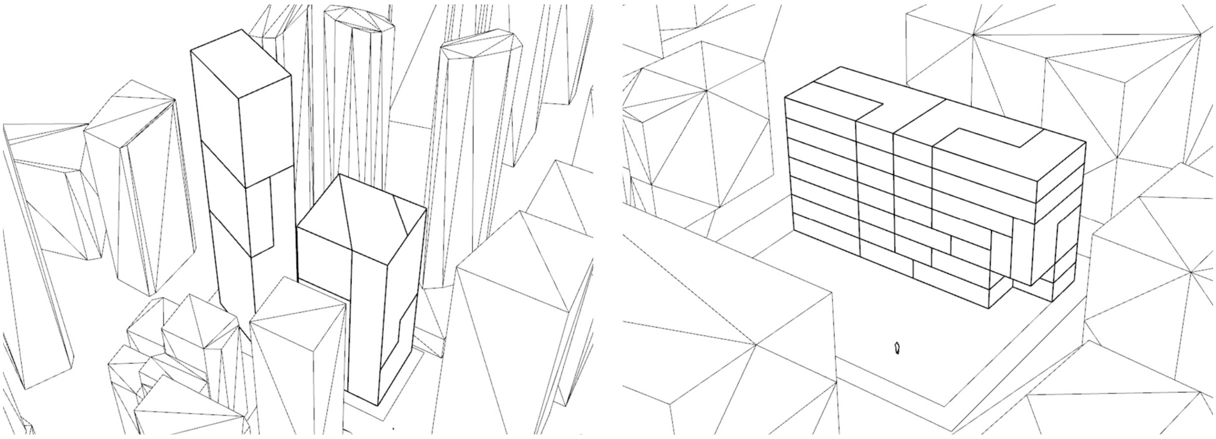


Figure 68: Example of design schemes in which spaces or uses have been distributed according to environmental properties.

In both examples, these external influences could be propagated further to lower levels of spatial configuration, influencing the definition of floor plans or the internal topology of the building. Additionally, at the discretion of the designer, these design schemes could become visible in the end design or even remain completely invisible to external observers.

6.1.3 Configuration of Exterior Surfaces

Exterior surfaces of buildings cover a crucial role in the interactions between inner and outer spaces. Similarly as for membranes in cells, building surfaces define a functional interface responsible for the exchanges of energy and matter from and to the surrounding environment. By using VSA, the exterior surfaces of buildings can be distributed and oriented according to a set of functional goals, and in combination with the quantitative, volumetric, dynamic and directional nature of the environmental resources.

The examples in Figure 69 illustrate how, through this process, it is possible to retrieve suggestions for novel configuration of exterior surfaces. These design schemes, which feature enlarged and better deployed exterior surfaces, offer new abilities for the joint modulation of solar radiation, airflows and views. In this way, simple items like openings, shadings, balconies, photovoltaic panels, thermal collectors, and wind shelters can be combined in extensive schemes that transcend the items themselves and are able to exploit and accommodate the complexities of the urban environment.

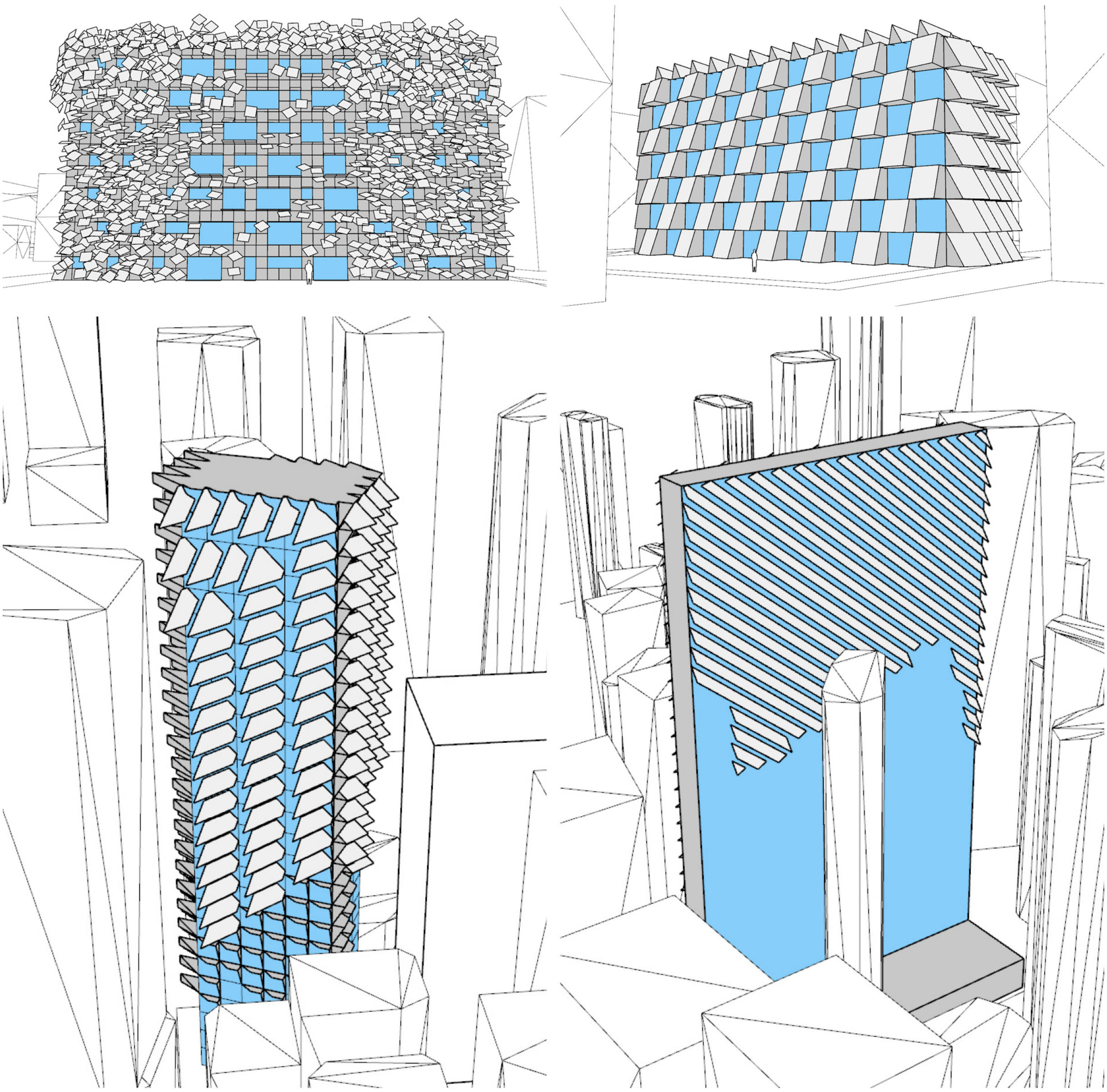


Figure 69: Example of design schemes that concern the configuration of exterior surfaces.

6.1.4 Development of New Formal Logics

Similarly, VSA can be used to retrieve suggestions to define new morphologies of buildings. By distributing units of architectural space according to single or multiple environment related objectives it is possible to visualize patterns that are directly shaped by the influence of different physical constraints on a selection of environmental resources. These volumetric patterns can then be used as a base for further conceptual thoughts and for the development of new formal logics.

Figure 70 illustrates instances of such design schemes that offer beneficial features in terms of access to daylight, penetration of heat gains, circulation of airflows, and access to sights.

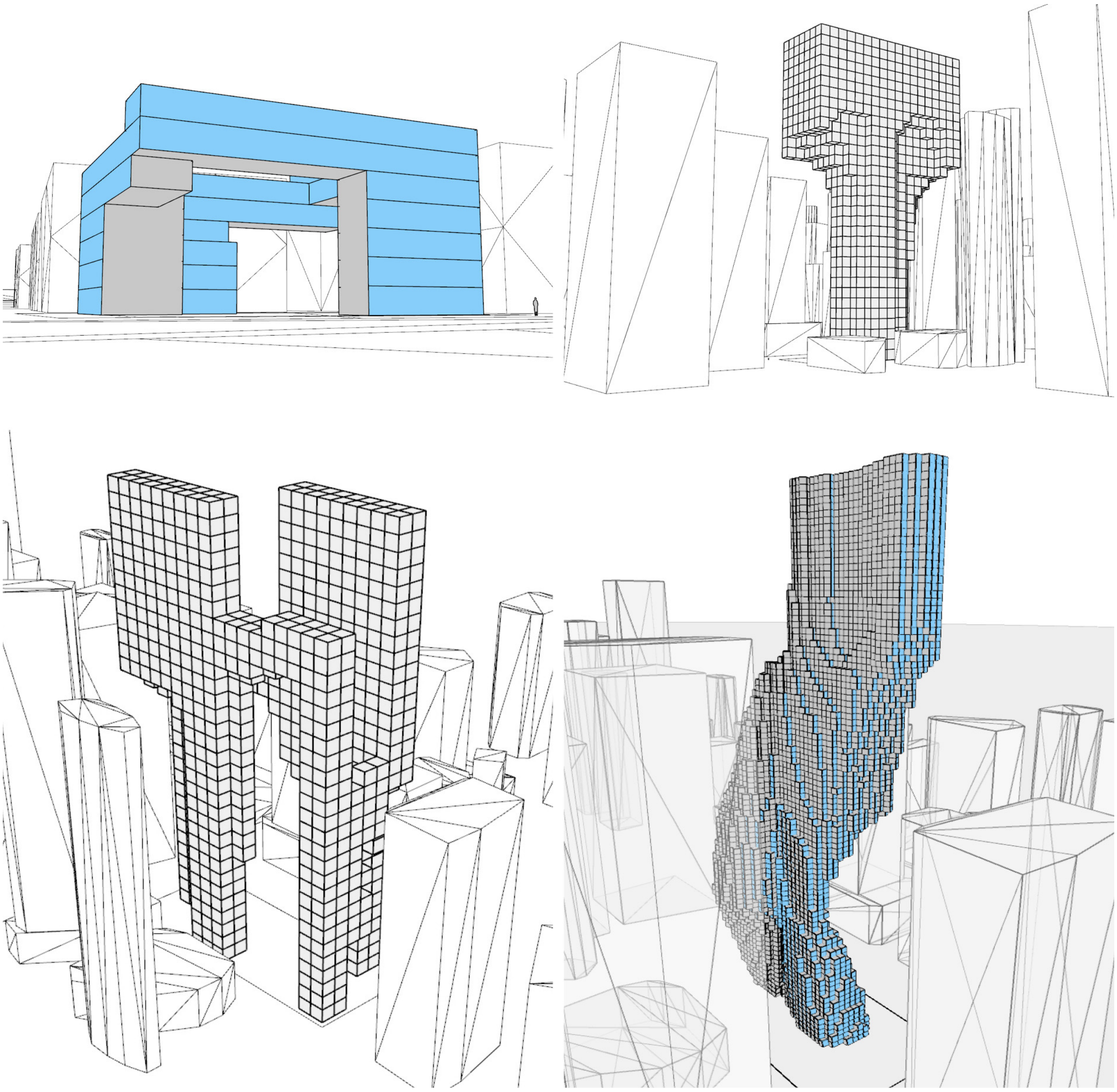


Figure 70: Examples of design schemes that involve new formal logics.

Finally, the conceptual possibilities of VSA can be multiplied by combining these new formal logics with the configuration of exterior surfaces (see Section 6.1.3) and the distribution of uses and spaces (see Section 6.1.2).

6.2 Examination of the User Studies Results

In turn, the design schemes developed by external users during the user studies confirmed the creative potential of VSA. Users' feed back also demonstrated a positive reception of the technique by the users.

6.2.1 Examination of User Experimentations

The users engaged VSA in different formal studies spanning from the balance of voids and fills to the orientation of facade elements. The developed design schemes (see Section 4.1) featured at the same time interesting diversities at the level of the approaches and similarities in terms of results.

A noticeable common characteristic is that design solutions seem to be guided toward systems composed by the aggregation of smaller elements. Even if this is partially endorsed by the analytic grid and the transition matrix (see Figure 4), the results seem to be bound to this logic deeper than expected. One of the reasons for this is the fact that the proposed solutions need a relatively small resolution in order to be able to react efficiently to the volumetric diversities present in urban sites. Simplifications on the resolution of designs would in fact automatically imply losses of accuracy in the use of the environmental resources.

Besides its application in formal investigations, VSA has also been additionally and interestingly used for the definition of materials. An example can be found in the faces of the octagonal prisms illustrated in Figure 62, where the envelope materials are attributed according to environmental criteria. In this example the final design results from a combination of this material variety with a formal porosity. This kind of design scheme allows developing semi-permeable solutions capable of combining opposing attitudes, such as protection and access, depending on local environmental conditions, allowing thus for a deeper integration of environment and architecture.

Another interesting aspect that arose from the work of the users is related to the reemergence of human and social factors. Essentially, the use of VSA concerns the combination of environmental resources with basic human needs in terms of space quality and energy. It is thus interesting to observe how the users relied on VSA to develop human and social topics also on a higher level. Several users have in fact developed the general principle of handling the environmental resources as a collective good. In this perspective, some proposed concepts concerned a big open-space that was located in a position presenting a good compromise among different important environmental resources. These spaces were then made accessible to all building occupants, or even to the whole population of the urban area (see Figure 59, Figure 62 and Figure 66). Others decided instead to identify multiple locations with the best conditions of several specific resources and make them all available to the public, creating several small urban niches connected through a pedestrian path. In this way, the occupants of the city could engage in a sort of 'urban hiking', accessing all these privileged locations, to enjoy a view or to savor a sunrise or a sunset at the corresponding moments (see Figure 65).

It is also interesting to observe how these public open spaces can be very different and sometimes have opposing character. Some are in fact located at the lower levels of the site, close to the circulation of the city, and are conceived as protection spaces, providing a shelter, mainly from rain and midday sun (see Figure 59 and Figure 65). Others are instead located at the top levels of sites, and are conceived as spaces oriented towards openness and the gathering of views, fresh air, and light through a direct contact with the sky (see Figure 62 and Figure 66).

6.2.2 Examination of User Feedback

The users also provided interesting feedback in relation to the use of the methodology (see Section 4.2.2).

On examination of their answers it can be clearly stated that the users perceived VSA as useful and beneficial for the design process. The evaluation of environmental information and its integration in the process was judged as direct and intuitive. The designers also confirmed that they would use VSA in their practice if it were available. They appreciated in particular the spatiotemporal accuracy of the data, the simultaneous presence of multiple variables, and the visualization and export capabilities of the interactive interface. Some users also had the impression that VSA was enlarging the design possibilities, allowing them to conceive design solutions that they would have not been able to imagine otherwise.

On the other side the users also encountered some difficulties. Critiques have been expressed in relation to aspects such as the elevated computing power necessary to run the visualization interface, the impossibility to run an analysis on a new site in a short time, and the impossibility to export numerical results from the user interface. Other aspects highlighted as negative were the sometimes difficult interpretations of the abstract volumetric information and the fact that during the design phase they had to read and import VSA information in 3D modeling programs from multiple non-integrated files. A user also reported the risk of becoming trapped by the appealing visualizations and being thus distracted from deeper design investigations. Finally, all users wished to have some means to verify the real effectiveness of the sketched solutions and the consequent alterations of the site resources.

6.3 Achievements and Limitations of the Methodology

Generally, it has to be considered that although this research was the product of considerable efforts, the whole process and the related methods have only been preliminarily sketched and have to be considered as prototypes at a proof-of-concept stage. Examination of the results of the case and user studies revealed stimulating possibilities as well as restrictive constraints at several levels. The causes of these possibilities and constraints can be traced back to the methods that were used for the design process. The next sections cover the evaluation of the achievements and the limitations of these methods in the same order as they were presented in Section 2.

6.3.1 Evaluation of the Analysis Methods

Several achievements have been gained in the analysis methods.

A new method for the evaluation of direct solar radiation of urban sites, capable of considering all quantitative, volumetric, dynamic and directional dimensions, and the effects of obstructions, has been successfully developed and tested (see Section 2.3.1). Among the different possible outcomes the vectorial variable $\overrightarrow{I_v}$ resulted in being the most useful for most applications because it allowed obtaining directional information for energy related investigations. The technique has been implemented with a streamlined approach and could thus be enhanced with more accurate and faster solar radiation models that may also include diffused and reflected components. For this purpose, the integration of a lighting simulation engine such as *Radiance* (Ward & Shakespeare, 2003) could be evaluated.

Similarly, a rough outline of methods for the volumetric analysis of urban visibility has been preliminarily sketched (see Section 2.3.2). In this case, the 'field-of-view vectorial outwards visibility' was the most applied, because of its balanced volume and of its capability to provide directional suggestions, however its effectiveness and meaning should be studied more in detail, especially in relation to concave sites, and in comparison with the 'scalar isotropic visibility'. Additionally it has to be remarked that in the developed methods visibility can be evaluated quantitatively but not qualitatively. The visibility analysis of specific objects of qualitative interest such as vegetation, lakes, mountains, squares, monuments, etc. could be explored in future developments.

Generally, further testing and developments of the solar and visibility analysis methods are necessary, especially in relation to the physical significance of the directional results obtained through vector addition. This, in particular is crucial in order to identify more accurately the values and the directions of interest in situations with discontinuous obstructions, involving multiple local maxima and minima.

Regarding CFD analysis, the employed proprietary tools have demonstrated to be appropriate to simulate the airflows, however a freely accessible solution would be preferable. The integration of one of the many existing open-source CFD engines (CFD Online, 2014) should be therefore evaluated. Among the observed variables (velocity, pressure, and turbulence intensity) velocity proved to be the most significant, therefore generic airflow investigations could be limited to this variable.

At the moment, the proposed methodology regards three physical properties and, even if more could be added (e.g. noise), this extension is limited to measurable properties only. This involves the risk of disregarding the non-quantifiable features of the conceptual design process.

At the current stage of developments, executing the Volumetric Site Analysis in a new site is not a simple and fast process. The preparation of data and models, the execution of simulations, and the post-processing of results takes about one month of work-time for an experienced user. Several optimization routines could be programmed to automate and accelerate certain analytic and procedural steps. An example is the use of a different neighborhood model for each of the different analytic simulations in order to reduce the models' triangles to the strict necessary, which varies between each simulation type.

Generally it would be also preferable to integrate and automate the 'Demand Assessment' and the 'Volumetric Site Analysis' steps, so that the user could simply launch the simulation and later retrieve all the results in the visualization framework, after having provided a series of inputs.

6.3.2 Evaluation of the Visualization Methods

The experimentations have also revealed the strengths and the weaknesses of the different visualization techniques. Concerning visualization elements (see Figure 19) points, arrows, darts and cyls were rarely used, while voxels proved to be the most applied elements and have been used in particular for the definition of volumes according to specific magnitudes. Meshes proved to be appropriate to visualize forms independently from the selected magnitudes and with some abstraction from the rigid pattern of the volumetric grid. Finally, directional elements such as circs, quads and boxes have also been widely used, but their physical interpretation and their transliteration into architectural solutions were less immediate than imagined.

The combined use of these elements with the visualization filters (see Section 2.4) proved to open new ways of investigation to identify patterns of architectural interest, like in the cases of multivariate correlations (see Section 6.1.1) and floor-based examinations (see Section 2.4.3). Additionally it also facilitated new ways of handling the dynamic and directional nature of environmental resources to study their reciprocal ties and to link them to the dynamic aspects of demand (see Sections 2.2.2 and 6.1.1).

Generally, visualization elements and filters had a huge impact on design results. The importance of these instruments goes in fact far beyond mere visualization. Their formal nature tends to already suggest design implementations that drive quite strongly the conceptual process.

In this perspective, the available elements and filters proved to be limited. More elaborated options, accessible from the interface, would have been beneficial. Examples of additional functions include the possibility to define a custom grid-step of the visualization or to visualize jointly multiple variables with different directions. These multi-layer visualizations would for example help designers to conceive architectural solutions that need to respond to several orientations, like in the case of openings that are concurrently influenced by sights, daylight, solar gains and ventilation.

In contrast, it would also be interesting to have the possibility to limit or to simplify some of the available visualizations. The spatial orientations of the visualization elements could be, for example, restrained to average values or to horizontal or orthogonal components. This would allow to rapidly picture simplified architectural suggestions without needing to post-process the original visualizations in 3D modeling programs. Other simplifications could be achieved by developing routines capable of proposing amalgamated visualizations in which the existing discrete elements could be combined in more cohesive representations according to physical similarities (as for example in the lamellar scheme in the last image of Figure 69).

Generally, the selection of both visualization elements and filters from a fixed list of possibilities resulted in a limited approach. Future developments should increase the flexibility of these options allowing users to script themselves custom visualization elements and custom visualization filters according to the specific needs of each project.

6.3.3 Evaluation of the Synthesis Methods

In relation to synthesis methods, Observation Records (see Section 2.5.1) and Directionality Graphs (see Section 2.5.2) have proven to be useful instruments, especially in the case of complex multidimensional and multivariate conceptualizations (see examples in Figure 47 and Figure 56). However, even if both tools demonstrated being valuable, they could also be deemed non-essential. At the current state of developments several manual operations are necessary to create them. Especially in the case of the Directionality Graphs, considerable efforts are required to export, import and assemble the related geometrical information in 3D modeling programs. These requirements thus reduce the likelihood that such tools would be adopted in normal conceptual design processes. Future developments should therefore consider an automated generation of these graphical tools, making them directly exportable from the visualization interface. In the case of the development of multi-layer visualizations, as envisioned in the previous section, a small Directionality Graph pictured directly in a corner of the user's interface could allow picturing the currently enabled layers and the associated volumetric and directional variabilities.

The notion of Design Schemes (see Section 2.5.3) has also appeared very useful to isolate the essence of design interventions and to handle, combine, and validate design ideas. However the transliteration of information from visualizations to design schemes turned out to be a delicate process not immune to mistakes. Physical misinterpretations and the misuse of visualizations have in fact sometimes driven non-expert users to wrong conclusions, leading them to design concepts that were not functioning as expected. Didactic explanations available from the interface, and new graphical objects explaining details concerning the analytic processes could be added. This would help designers to interpret visualizations for their real significance and to correctly predict the effects of their choices.

Additionally, a post-conceptual validation phase (see Sections 2.5.4 and 3.1.5) proved to be very profitable to exclude misinterpretations. Means of receiving feedback on the conceived design and on the site resources were also explicitly requested by the users. However, as mentioned in Section 1.8, VSA is not the adequate method to evaluate a surface-based design sketch. The ideal simulation engine for this purpose has however not yet been identified, or does not exist. Rapid evaluation tools (e.g. *Vasari*) provide a too scarce accuracy and do not support the necessary retrieval of information such as numeric results for specific surfaces. However, sophisticated energy simulation tools, like those used for the validation of this research (see Figure 7), have resulted in being very demanding in terms of user skills and simulation time. Future investigations should thus try to identify ideal validation tools that can appropriately balance accuracy and speed, developing the necessary interfaces to integrate them in the process. On the other hand, some predictive visual tools, like shading masks based on the directional information of the solar and visibility layers, could be integrated in the VSA methodology to assist the designers to anticipate the consequences of their actions in the site (see Section 1.8).

In terms of design results, the first experimentations of the case and user studies showed interesting creative potential, but also a series of limitations. The design schemes rising from VSA often have, for example, a more elaborated morphology than conventional design solutions. This highest formal complexity affects the requirements in terms of structure, construction, and materials, with a direct impact on costs and feasibility. The cost-benefit balance could therefore limit the applicability of certain solutions. However, the current advances in digital fabrication and construction processes demonstrate concrete and promising improvements concerning the realization of high-rise buildings with unconventional forms (Gramazio & Kohler, 2014).

The fact that the entire VSA approach relies on a strict Cartesian conception of space (see Figure 4) also has a direct influence on how design schemes are conceived. Even if this constraint is very common in architecture, and more generally in conceptual processes, it is a limiting factor for the design process. A possibility to obviate this issue would be to offer to the users a scripting environment to develop digital design schemes. These schemes could be independent from the Cartesian logic of the analysis grid while maintaining a link to the volumetric information through the interpolation of data or other techniques.

Besides this possibility, it would also be interesting to test further means of synthesis accessible directly from the user interface. These could comprise interactive techniques that would allow combining multiple primary layers of information using different weights on their importance. These new means of synthesis available from the visualization interface would allow for faster experimentation of concepts before the transfer to 3D modeling environments.

6.4 Conclusion

Through this research, it was possible to establish a comprehensive methodology for the volumetric analysis of environmental resources of urban sites and their integration in the conceptual design process. In particular, it was possible to verify the research hypothesis (see Section 1.5), proving that new means of analysis, visualization, and synthesis, tailored to the physical properties of urban sites (see Section 2), can augment the possibilities of the conceptual process, and catalyze the conception of design solutions that pre-empt environmental performance (see Section 3.1.5).

Like every other design technique, VSA proved to have its own strengths and limitations. However, the positive aspects largely outweigh the identified limitations that are mostly of a technical nature and amendable in further developments.

The main strength of the technique is the new ability to explore the environmental resources in a pre-design stage. This stimulates the reflection of the designer, leading him to acquire important information on the site and to develop an understanding of the rules that govern environmental resources.

The second strength is the new and simpler handling of environmental complexities. Information is made available in a three-dimensional interactive formal setting avoiding more complex graphical intermediations (see Section 1.3.1). This allows using it in a more direct way and facilitates the exploration of new conceptualizations that combine multiple variables and multiple dimensions. Through these abilities, the designer can fuse active, passive and expressive aspects into cohesive design conceptualizations that are based on the site-specificity of the environmental resources.

Generally, these means tend to reinforce the functional and aesthetic influence that environmental information can have on the design of urban architecture. VSA relies on a relatively objective and systematic logic, but it encloses a huge potential in terms of the diversity and richness of the design results.

The first reason is combinatorial. From the beginning of the process the designer can in fact select the environmental variables of interest, and choose the related dimensions to be used in the design process. The selected resources and dimensions can then be combined in a huge amount of different ways. First by selecting the primary layers of information, then by generating compound layers through scripted filters, and finally by combining the different design schemes.

The second reason is contextual. Identical design rules would in fact generate completely different solutions if applied to different sites. The reason is the dependency of the outcome from many site-related factors such as the shape of the parcel, its size, the project program, the local regulations, the built and topographic environment, and the different climatic, solar, and wind conditions. For this reason, some design schemes could turn out to be very successful under certain urban or climatic conditions, but could be completely inadequate in different contexts where other solutions would be more suitable.

Finally, it is important to highlight that, even if for a reasoning purpose, the conceptualization of VSA was presented in contrast to the classic surface-based simulation processes (see Section 1.4), this technique is in reality very complementary to them. As mentioned, after having used VSA to conceive a design scheme, that design scheme, or further developments of it, can be validated through a classic surface-based simulation process, or can be used to define the starting conditions of performance-based generative design processes (i.e. the parametric models and their initial values, see Figure 3).

6.5 Future Work

Future research activities can regard different actions that can be divided into the following groups.

1. Make Available

The first step of future work should concentrate on improving the usability and the accessibility of the existing VSA methods. Ideally, this should be done by releasing them as an open-source library, freely available to the public. Required actions comprise the review and upgrade of the whole software-architecture, the data structure, and the import/export functionalities. These technical ameliorations should also reduce the simulation time of the analysis phase and the computational power required by the visualization interface. This would allow non-expert users to apply the methodology to new sites in a reasonable amount of time.

2. Develop Methods

Most of the limitations of the methodology described in Section 6.3 could be amended by the development of new or ameliorated methods. These ameliorations include the improvement of the existing solar and visibility analysis methods, the integration of an open-source CFD engine, didactical explanations to the interface, tools to facilitate the predictions of alterations, new visualization elements, filters, and synthesis methods, and new scripting techniques to create custom visualization elements and to develop non-Cartesian design schemes linked to the volumetric data.

3. Ameliorate Interoperability

The interoperability of VSA with other tools should also be ameliorated. The development of a more fluid interconnection integrating the exchange of geometries images and numerical data with architectural 3D modeling programs is a necessity. Additionally, links for validating the design schemes in fast, surface-based simulation programs, and to develop complex geometries in algorithmic design environments (see user example in Section 4.1.3), would contribute to better integration of VSA in the design process.

4. Expand to More Complex Scenarios

The capabilities of this methodology could also be expanded to more complex cases such as non-rectangular or concave sites, multi-site studies, or the analysis of larger areas.

5. Apply

Regarding application, the surface of possibilities has only been scratched. A whole world of new functional and aesthetic opportunities, given by the translation of design schemes into finite architectural designs, remains to be explored. Additionally VSA could also be used as a means for higher-level investigations. As for example studies on the role of environmental resources on phenomena like urban growth and self-regulation.

6.6 Outlook: Broader Impacts on the Conceptualization of Urban Architecture

This research work stimulates some reflections on the broader impacts that this process could have on the conceptualization of urban architecture.

As highlighted by Koolhaas (2008, p. 2), the most widespread urban formal typology is given by towers that 'are nothing more than the constant and monotonous repetition of a piece of land in the vertical direction'. These banal boxed-shaped tower typologies have established themselves over time due to advantages in terms of structure, vertical mobility, standardization and scalability. In order to allow access to environmental resources and to limit mutual obstructions, the design of these volumes is then generally controlled by a few key parameters related to the urban grid, like height, depth, and distance to other buildings. The Manhattan *Commissioner's Plan* of 1811 is probably the most known model of such organizational structures, but, also here, reactions have always been very divided between the praise of balance and order (Burrows & Wallace, 1999) and the critique to rigidity and monotony (Gray, 2005). Despite the robustness of the 'box-grid' system, the increasing elevation and densification of the built environment due to urbanization (UN, 2011) has started to undermine this fundamental setting. Self and mutual obstructions are in fact increasingly hindering access and penetration of environmental resources in the urban space. As a consequence, some of the most densely inhabited areas on the planet are starting to feature highly degraded conditions of sustainability and livability (Loh, et al., 2010).

Through history, architects and planners, aware of these issues, have always dreamed of better and different cities through the development of utopic urban proposals (MVRDV, 2005) (Klanten & Feireiss, 2011). Many of these visionary projects have also addressed the issue of achieving urban density while preserving access to light, air and nature. However, as highlighted by Maas (2005), in the last decades the architectural discipline has essentially failed in successfully transposing any of these large-scale visionary concepts of sustainable urbanity into practice.

Figure 71: Example of a neighborhood containing buildings based on volumetric design schemes (Image: T. Doan, M. Leidi).

One of the difficulties in the development of these concepts can be identified in the absence of accurate means to assist architects and planners in understanding and interpreting complex environmental phenomena in urban settings (Srivastav, et al., 2009). Volumetric Site Analysis wants to contribute towards filling this gap. Additionally, by addressing environmental issues at the root, before the conceptual phase, VSA wants to focus on the genesis of new architectural ideas rather than on the improvement of existing schemes. This regained conceptual liberty combined with augmented means of environmental perception opens new architectural possibilities. Essentially, they empower a return to nature in the urban context. With new means, but with the same fundamental spirit of vernacular architecture (see Section 1.2), a new kind of sustainable vertical urbanity could thus start making its way forward. In this process, the conceptualization of buildings could literally be turned upside-down, shifting from a ground-up to a sky-down ideology. The sharp building boundaries of the current urban setting could thus start to gradually dissolve in favor of a new three-dimensional inhabitable landscape capable of accommodating the environment (see Figure 71).

In this landscape, existing constructions would behave comparably to organisms that extract their resources from their environment. As organisms, they would relate to each other according to symbiotic rules. Some would ameliorate their access to the environment, retracting themselves from close neighbors, according them in this way the equivalent benefits (see example in Figure 57). Others would instead approach or even overtake surrounding buildings, acquiring resources at the detriment of their neighbors (see example in Figure 66). Mutualistic, parasitic and commensalistic rules could thus become conceptual devices to develop new architectural experimentations, focusing on relationships among buildings rather than on buildings themselves.

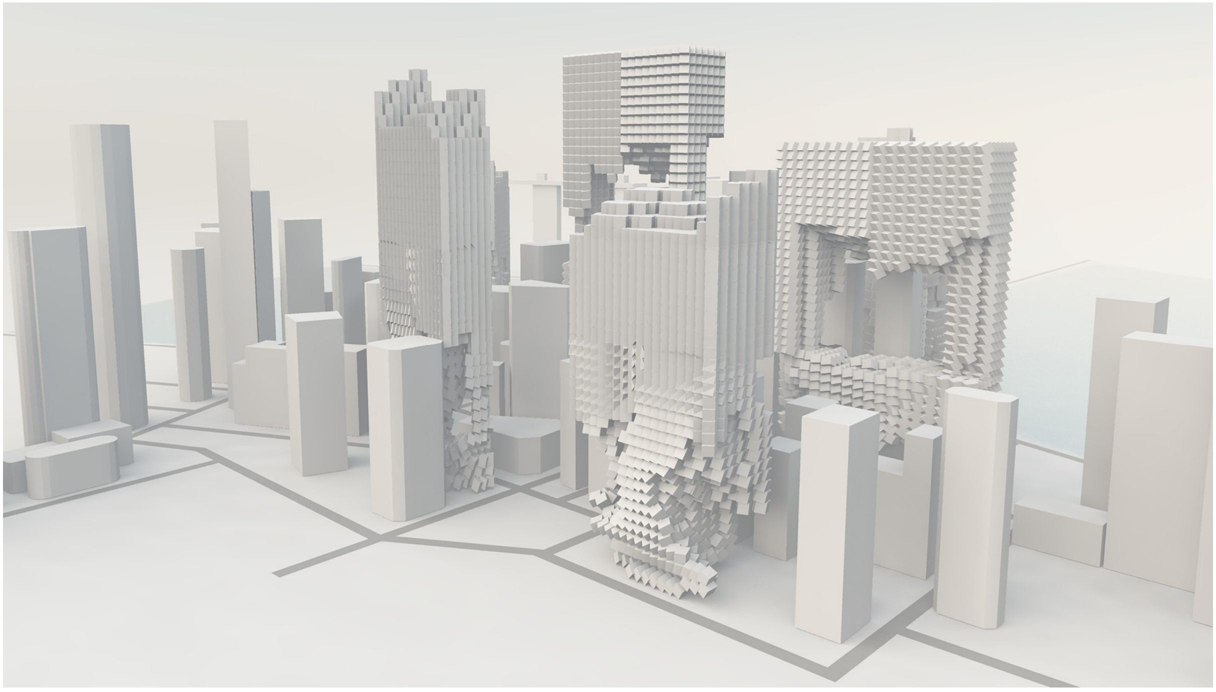


Figure 72: Example of neighborhood containing buildings based on directional design schemes (Image: T. Doan, M. Leidi).

The conceptual principles that ensue from this methodology are in fact not those of new omnipotent and universal design solutions but, inversely, those of a bottom-up approach based on an accurate observation of the local resources and constraints of each single urban site. From this perspective, similarly to the growth of a little plant in an obstructed underbrush, high-rise buildings would become capable of extracting the best from their specific environment. New flexible urban solutions like 'shaped rooftops', 'urban niches', 'elevated public spaces', 'architectural canopies', and 'environment-receptive forms' could start populating the urban landscape, adapting to local specificities and capturing features of space, time and direction (see Figure 72). In this context, Volumetric Site Analysis does not want to be another technological utopianism, but rather a useful method that, when implemented in the right measure, could expand the possibilities of the design process and catalyze the conception of new and beneficial design solutions that would be hardly conceivable otherwise (see Figure 73).

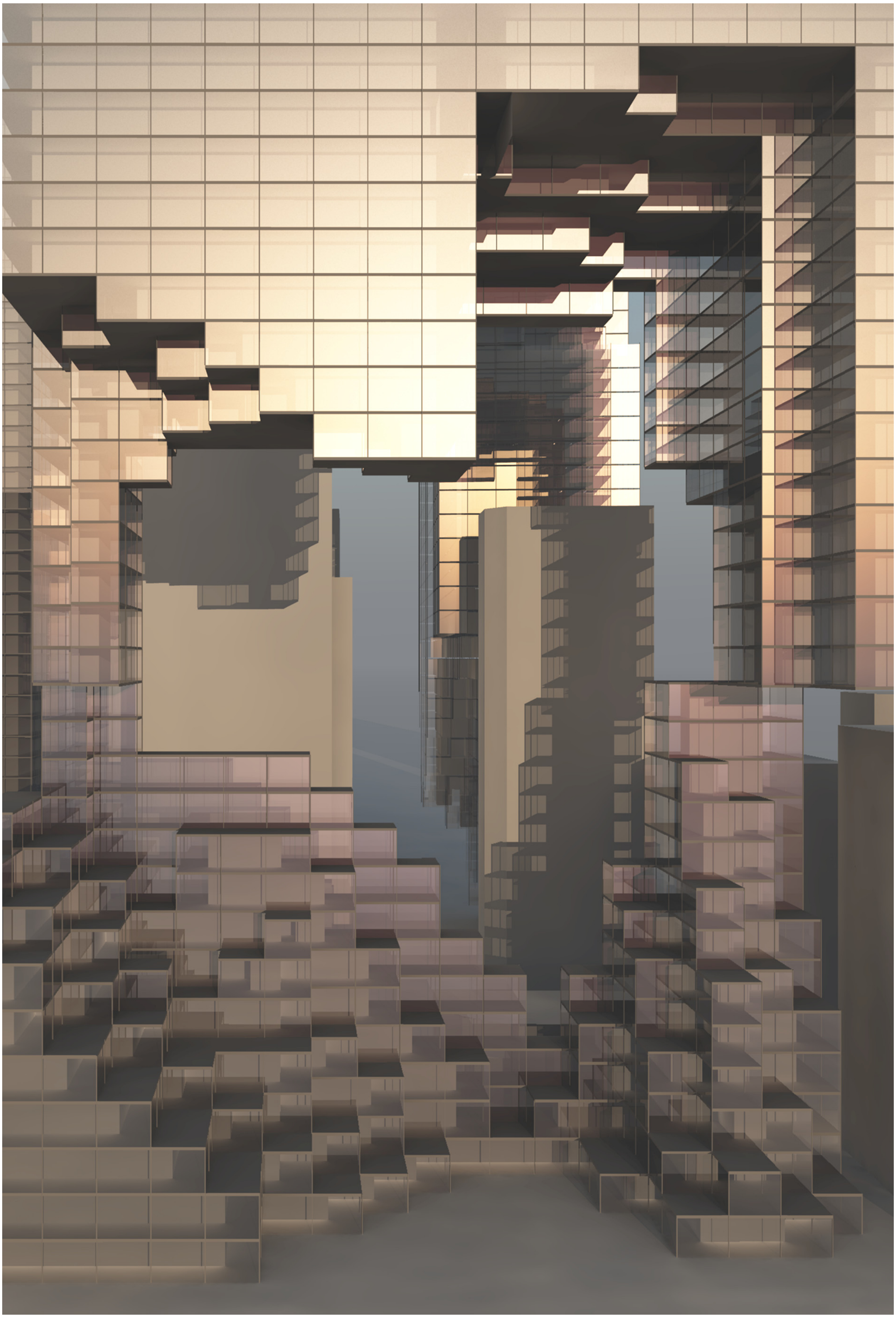


Figure 73: Example of a design scheme for a mixed-use urban complex, that offers protection from midday sun and from rain, admission of morning and evening daylight, good air circulation, and intriguing sights (Image: T. Doan, M. Leidi).

References

Aksoy, T. & Inalli, M., 2006. Impacts of some building passive design parameters on heating demand for a cold region. *Building and Environment,* pp. 1742-1754.

Ansys, 2014. *Ansys website.* [Online]
Available at: http://www.ansys.com/
[Accessed 03 03 2014].

Arens, E. et al., 1980. *A New bioclimatic chart for passive solar design.* Amherst, 5th National Passive Solar Conference.

Ascomp, 2014. *Ascomp website.* [Online]
Available at: http://www.ascomp.ch/
[Accessed 03 03 2014].

Attia, S., 2011. *State of the Art of Existing Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools,* Louvain La Neuve: Université catholique de Louvain.

Benedikt, M., 1979. To take hold of space: isovists and isovist fields. *Environment and Planning B,* Volume 6, p. 47–65.

Bennett, T., 2013. *Sunpath diagrams showing shading on site.* [Online]
Available at: http://myth-esis.blogspot.ch
[Accessed 28 06 2014].

Bernaek, W., 1984. Wind environment around single buildings of rectangualr shape, and, Wind environmeent around building configurations. *Heron Magazine, Institute for Building Materials and Building Structures,* 29(1), pp. 30-70.

Blocken, B., Stathopoulos, T., Carmeliet, J. & Hensen, J. L. M., 2014. Application of computational fluid dymanics in building performance simulation for the outdoor environment: an overview. *Journal of Building Performance Simulation,* 4(2), pp. 157-187.

Brown, G. Z., 1985. *Sun, Wind, and Light, architectural design strategies.* 1st ed. New York: John Wiley & Sons.

Burrows, E. & Wallace, M., 1999. In: *Gotham: A History of New York City to 1898.* New York: Oxford University Press, pp. 419-422.

Caldas, L., 2007. Generation of energy-efficient architecture solutions applying GENE_ARCH: An evolution-based generative design system. *Advanced Engineering Informatics,* 22(1), pp. 59-70.

Castorina, G., 2012. *Performative Topologies, An evolutionary shape optimization framework for daylighting performance coupling a particle-spring system with an energy simulation tool.* San Francisco, Synthetic Digital Ecologies, International Conference of the Association for Comuter Aided Design in Architecture (ACADIA).

CFD Online, 2014. *List of software related to CFD.* [Online]
Available at: http://www.cfd-online.com/Links/soft.html
[Accessed 21 03 2014].

Chantrelle, F. P. et al., 2011. Development of a multicriteria tool for optimizing the renovation of buildings. *Applied Energy,* Issue 88, p. 1386–1394.

Cheng, S., 2009. *Curved Photovoltaic Surface Optimization for BIPV: An Evolutionary Approach Based on Solar Radiation Simulation,* London: University College.

Choo, T.-S. & Janssen, P., 2014. Evolutionary Optimisation of Semitransparent Building Integrated Photovoltaic Facades. *International Journal of Architectural Computing,* 12(1), pp. 81-100.

Compagnon, R., 2004. Solar and daylight availability in the urban fabric. *Energy and Buildings,* Issue 36, pp. 321-328.

DeKay, M. & Brown, G. Z., 2014. *Sun Wind & Light, architectural design strategies.* 3rd ed. Hoboken NJ: Wiley.

DeKay, M. & Moir-McClean, T., 2003. *GreenCenter: Planning for Environmental Quality in Chattanooga,* Knoxville: City of Chattanooga.

Denzer, A., 2013. *The Solar House: Pioneering Sustainable Design.* New York: Rizzoli.

Donald, P. G., 2004. Psychrometric Chart Celebrates 100th Anniversary. *ASHRAE Journal,* Issue November, pp. 16-20.

Donn, M., Selkowitz, S. & Bordass, B., 2009. *Simulation in the service of design - asking the right questions.* Glasgow, 11th International Building Simulation Association Conference.

Dubois, M.-C. & Horvat, M., 2010. *State-of-the-art of digital tools used by architects for solar design,* Toronto / Québec City: IEA SHC Task 41.B.

Duffie, J. A. & Beckman, W. A., 2006. *Solar engineering of thermal processes.* Hoboken, New Jersey: John Wiley and Sons.

ERM, 2009. *Parameters of Human Vision and Viewshed Definition,* Environmental Resources Management Australia: Annexure A of the Stockyard Hill wind farm landscape & visual assessment.

Franke, J., Hellsten, A., Schlünzen, H. & Carissimo, B., 2007. *Best practice guideline for the CFD simulation of flows in the urban environment,* Brussels: COST Action 732, Quality assurance and improvement of microscale meteorological models.

Fry, B. & Reas, C., 2014. *Processing.* [Online]
Available at: http://processing.org/
[Accessed 10 03 2014].

Geyer, P. & Schlüter, A., 2014. Automated metamodel generation for Design Space Exploration and decision-making – A novel method supporting performance-oriented building design and retrofitting. *Applied Energy,* Issue 119, p. 537–556.

Gramazio, F. & Kohler, M., 2014. Made by Robots: Challenging Architecture at the Large Scale. *Architectural Design - Wiley Editing Services,* 84(April).

Gray, C., 2005. Are Manhattan's Right Angles Wrong?. *The New York Times,* Issue 23.10.2005.

Hillier, B. & Hanson, J., 1984. *The Social Logic of Space.* Cambridge: Cambridge University Press.

Hindrichs, D. U. & Daniels, K., 2007. *plus minus 20°/40° latitude, Sustainable building design in tropical and subtropical regions.* Stuttgart: Edition Axel Menges.

Horvat, M. & Wall, M., 2012. *Solar design of buildings for architects: Review of solar design tools,* Toronto / Lund: International Energy Agency.

Hottel, H. C., 1976. A simple model for estimating the transmittance of direct solar radiation trough clear atmospheres. *Solar Energy,* Volume 18, pp. 129-134.

IRAP, 2006. *Institut für Raumentwicklung IRAP HSR - Lichte Höhe Geschosshöhe,* Rapperswil: Hochschule für Technik Rapperswil.

Janssen, P., 2004. *A design method and computational architecture for generating and evolving building designs,* Hong Kong: Pao Yue-kong Library, The Hong Kong Polytechnic University.

Janssen, P., 2009. *An evolutionary system for design exploration.* Montreal, Joining Languages, Cultures and Visions - International Conference CAADFutures.

Kaftan, E. & Marsh, A., 2005. *Integrating the cellular method for shading design with a thermal simulation.* Santorini, Proceedings of the International Conference on Passive and Low Energy Cooling for the Built Environment.

Kaijima, S., Bouffanais, R. & Willcox, K., 2013. *Computational fluid dynamics for architectural design.* Hong Kong, Proceedings of the 18th International Conference of the Association for Computer-Aided Architectural Design.

Kämpf, J. et al., 2010. Optimization of buildings' solar irradiation availability. *Solar Energy,* 84(4), pp. 596-603.

Klanten, R. & Feireiss, L., 2011. *Utopia Forever.* Berlin: Gestalten.

Knight, I. & Ribberink, H., 2007. *European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems,* s.l.: Annex 42 of the International Energy Agency, Energy Conservation in Buildigns and Community Systems Programme.

Knowles, L. R., 2003. The solar envelope: its meaning for energy and buildings. *Energy and Buildings,* Issue 35, p. 15–25.

Koolhaas, R., 2008. *Challenging Preconceptions of the High-Rise Typology.* Dubai, CTBUH 8th World Congress.

LaBelle, G., Nembrini, J. & Huang, J., 2008. *Simulation-Driven Design System.* Antwerpen, International Conference eCAADe, Architecture 'in computero', Integrating Methods and Techniques.

Leibundgut, H., 2011. *LowEx Building Design, für eine Zero Emission Architecture.* Zürich: vdf Hochschulverlag AG.

Leidi, M. & Schlüter, A., 2011. *Volumetric Insolation Analysis.* Lausanne, CISBAT international conference, Ecole Polytechnique Fédérale de Lausanne.

Leidi, M. & Schlüter, A., 2012. *Formal and Functional Implications of Dynamics-Related Solar Design Schemes.* San Francisco, Synthetic Digital Ecologies, International Conference of the Association for Comuter Aided Design in Architecture (ACADIA).

Leidi, M. & Schlüter, A., 2013a. Exploring Urban Space, Volumetric Site Analysis for Conceptual Design in the Urban Context. *International Journal of Architectural Computing,* 11(2), pp. 157-182.

Leidi, M. & Schlüter, A., 2013b. *Exploring Urban Space - Video.* [Online]
Available at: http://suat.arch.ethz.ch/en/research/posip or http://vimeo.com/66668317
[Accessed 21 03 2014].

Leidi, M. & Schlüter, A., 2014a. *Conceiving Design Schemes of Urban Architecture through Volumetric Site Analysis - Short Papaer.* Kyoto, 19th International Conference on Computer-Aided Architectural Design Research in Asia.

Leidi, M. & Schlüter, A., 2014b. *Conceiving Design Schemes of Urban Architecture through Volumetric Site Analyisis - Poster.* [Online]

Available at: http://suat.arch.ethz.ch/research/posip
[Accessed 12 06 2014].

Leidi, M. & Schlüter, A., 2014c. *Conceiving Design Schemes of Urban Architecture through Volumetric Site Analyisis - Video.* [Online]
Available at: http://suat.arch.ethz.ch/research/posip or https://vimeo.com/94337116
[Accessed 12 06 2014].

Leonardo, M. & Oscar, J., 2013. Multi-Objective Heuristic Computation Applied to Architectural and Structural Design: A Review. *International Journal of Architectural Computing,* 11(3), pp. 363-392.

Libbey-Owens-Ford, 1951. *First sun angle calculator tool for determining solar geometry variables for architectural design.* Toledo: LOF.

Loh, C., Kilburn, M. & Chau, J., 2010. *HOT, STACKED, AND CROWDED, Improving the Livability of Hong Kong's Urban Environment One Building at a Time ...?,* Hong Kong: Hong Kong Civic Exchange.

Maas, W., 2005. "68-...". In: *KM3: Excursions on Capacity.* Barcelona: Actar, pp. 476-481.

Manwell, J., McGowan, J. & Rogers, A., 2003. *Wind Energy Explained: Theory, Design and Application.* Chichester: John Wiley & Sons.

Marin, P., Bignon, J.-C. & Lequay, H., 2008. *A Genetic Algorithm for Use in Creative Design Processes.* Minneapolis, Silicon + Skin: Biological Processes and Computation, International Conference of the Association for Computer Aided Architectural Design (ACADIA).

Marsh, A., 2006. *The Interaction of Radiance and Ecotect,* Leicester: 5th Annual Radiance Workshop.

Marszal, A. et al., 2011. Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings,* Issue 43, p. 971–979.

Meadows, H. D., Meadows, L. D., Randers, J. & Behrens, W. W., 1972. *The limits to growth : a report for the Club of Rome's Project on the Predicament of Mankind.* New York: Universe Books.

MeteoSwiss, 2014. *Free tables with metereological Norm Values.* [Online]
Available at: http://www.meteoswiss.admin.ch/web/en/climate/swiss_climate/tabellen.html
[Accessed 15 07 2014].

Miguet, F., 2007. *A further step in environment and bioclimatic analysis: the software tool SOLENE.* Beijing, Proceedings of the IBPSA conference, pp. 1630-1637.

Möller, T. & Trumbore, B., 1997. Fast, minimum storage ray-triangle intersection. *Journal of Graphics Tools,* 2(1), pp. 21-28.

Montavon, M., 2010. *Optimization of Urban Form by the Evaluation of the Solar Potential,* Lausanne: EPFL.

Moore, F., 1991. Concepts and Practice of Architectural Daylighting. In: New York: Van Nostrand Reinhold Company.

MVRDV, 2005. Chronology. In: *KM3: Excursions on Capacity.* Barcelona: Actar, pp. 482-501.

NF, 2014. *Natural Frequency / Sun-Path Diagrams.* [Online]
Available at: http://wiki.naturalfrequency.com/wiki/Sun-Path_Diagram
[Accessed 28 06 2014].

NREL, 2014. *OpenStudio Energy Simulation Software.* [Online]
Available at: https://openstudio.nrel.gov/
[Accessed 5 3 2014].

Olgyay, V., 1963. *Design with Climate, bioclimatic approach to architectural regionalism.* Princeton: Princeton University Press.

Oliva, A., Park, S. J. & Konkle, T., 2011. Representing, perceiving and remembering the shape of visual space.. In: H. L. R. & M. Jenkin, eds. *Vision in 3D Environments.* s.l.:Cambridge University Press.

Reichel, A. & Schluz, K., 2012. *HEAT | COOL - energy concepts, principles, installations.* Basel: Birkhäuser.

Robinson, D. & Stone, A., 2004. *Irradiation modelling made simple: the cumulative sky approach and its applications.* Eindhoven, Proceedings of the 21st Conference on Passive and Low Energy Architecture (PLEA).

Rullán-Lemke, C., 2009. *ArchitekturForm & SolarEnergie.* Hamburg: Cuvillier Verlag Göttingen.

Rutten, D., 2007. *RhinoScript for Rhinoceros 4.0,* s.l.: Rober McNeel & Associates.

Sargent, J., Niemasz, J. & Reinhart, C. F., 2011. *Shaderade: Combining Rhinoceros and Energy Plus for the design of static exterior shading devices.* Sydney, Proceedings of the Buildings Simulation Conference.

Simon, G. & Moore, S. A., 2004. Introduction: The paradoxes of sustainable architecture. In: *Sustainable Architectures: Natures and Cultures in Europe and North America.* London: Spon.

Srivastav, S., Lannon, S., Alexander, D. & Jones, P., 2009. *A review and comparison of data visualization techniques used in building design and in building simulation.* Glasgow, Proceedings of the Eleventh International Building Simulation Conference.

Straube, J., 2006. *Historical Development of the Building Encolsure,* Westford: Building Science Press.

Suleiman, W., Joliveau, T. & Favier, E., 2012. *A New Algorithm for 3D Isovist.* Liege, s.n., p. Proceedings of the Sageo conference.

SwissTopo, 2014. *Digital height model DHM25.* [Online]
Available at:
http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/height/dhm25.html
[Accessed 15 07 2014].

Tandy, C., 1967. *The isovist method of landscape survey, Symposium: Methods of Landscape Analysis,* s.l.: Landscape Research Group.

Teller, J. & Azar, S., 2001. Townscope II - A computer system to support solar access decision-making. *Solar Energy,* 70(3), p. 187–200.

Turner, A., Doxa, M., O'Sullivan, D. & Penn, A., 2001. From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B,* 28(1), p. 103–121.

Turrin, M., von Buelow, P., Stouffs, R. & Kilian, A., 2010. *Performance-oriented design of large passive solar roofs, a method for the integration of parametric modelling and genetic algorithms.* Zürich, Future Cities, International Conference eCAADe.

UN, 2011. *United Nations World Urbanization Prospects, the 2011 Revision.* [Online]
Available at: http://esa.un.org/unup/index.html
[Accessed 07 03 2014].

Van Bilsen, A. & Poleman, R., 2009. *3D Visibility analysis in virtual worlds: the case of supervisor.* Sydney, Proceedings of the 9th International Conference on Construction Applications of Virtual Reality.

Van Maren, G. & Ma, J., 2012. *3D Analyst – Feature & Volumetric Analysis.* San Diego, Technical workshop presentation at the Esri International User Conference.

Voss, K. et al., 1996. The Self-Sufficient Solar House in Freiburg - Results of 3 Years of Operation. *Solar Energy,* 58(1-3), pp. 17-23.

Ward, G. & Shakespeare, R., 2003. *Rendering with Radiance.* Davis: Space & Light.

Watson, D. & Labs, K., 1983. *Climatic design : energy-efficient building principles and practices.* New York: McGraw-Hill.

White, T. E., 1983. *Site Analysis: Diagramming Information for Architectural Design.* Tallahassee: Architectural Media Ltd.

Yi, Y. K. & Malkawi, A., 2012. Site-specific optimal energy form generation based on hierarchical geometry relation. *Automation in Construction,* Volume 26, p. 77–91.

Zarzycki, A., 2010. *Intuitive Structures: Applications of Dynamic Simulations in Early Design Stages.* Orlando, Spring Simulation Multiconference.

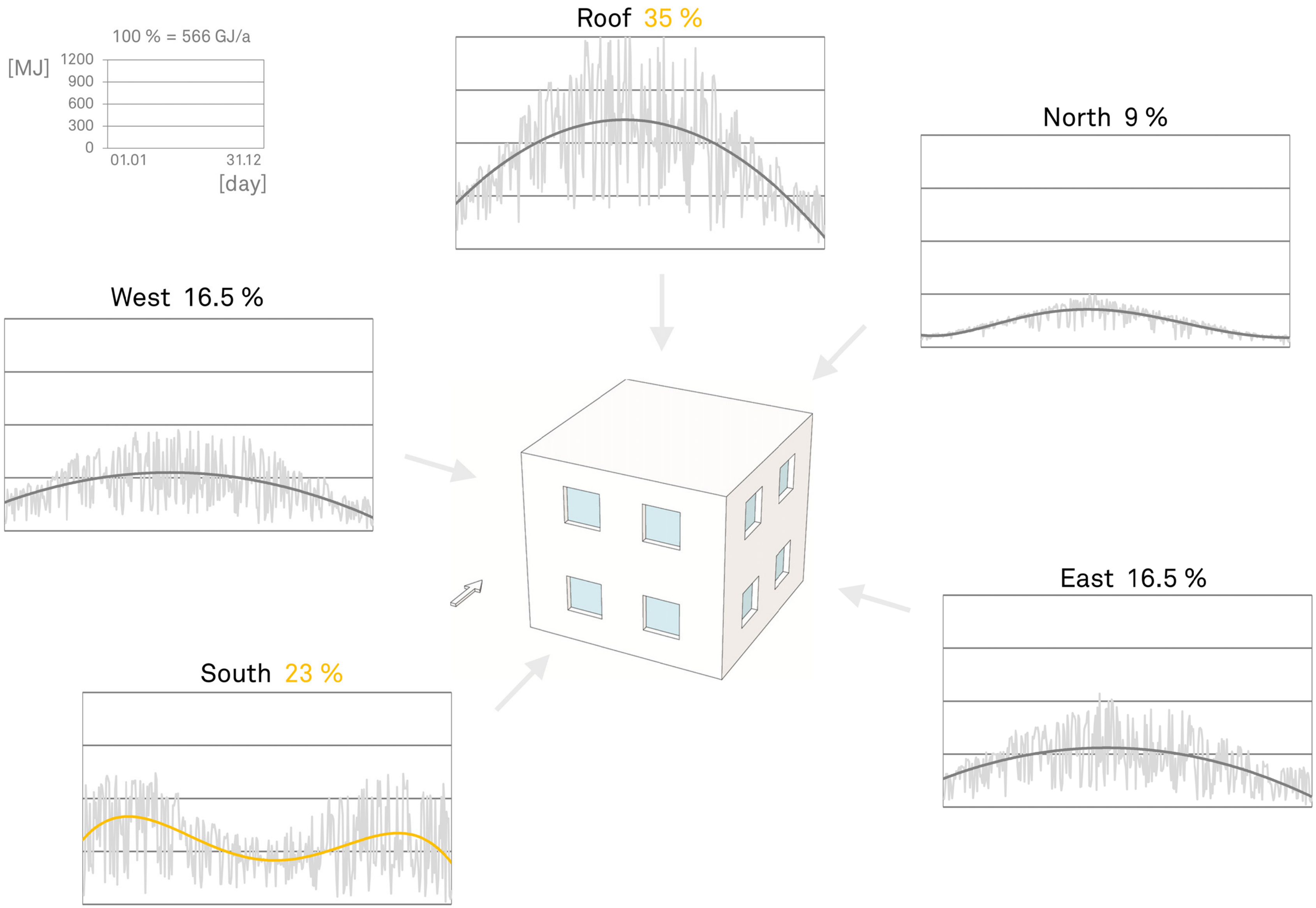
Zhai, Z., 2006. Application of Computational Fluid Dynamics in Building Design: Aspects and Trends. *Indoor and Built Environment,* Issue 15, pp. 305-313.

Figures Credits

Front Cover	Tom T.D. Doan and Michele Leidi
Fig. 1	Adapted from DeKay and Brown (2014, pp. e.283, e.285, e.289, e.290)
Fig. 2	Adapted from Bennett (2013)
Fig. 54	Michele Leidi, contents adapted from Hindrichs and Daniels (2007, p. 276)
Fig. 58, 59, 71, 72, 73	Tom T.D. Doan and Michele Leidi
Fig. 60, 61, 62	Ran Tateyama and Michele Leidi
Fig. 63, 64, 65	João V. Lopes and Michele Leidi
Fig. 66, 67	Tomoya Senoh and Michele Leidi
Section 5	Models by Michele Leidi, Ran Tateyama, João V. Lopes, and Tomoya Senoh
	Photographs taken by Basilio Noris and Michele Leidi
All other Figures	Michele Leidi

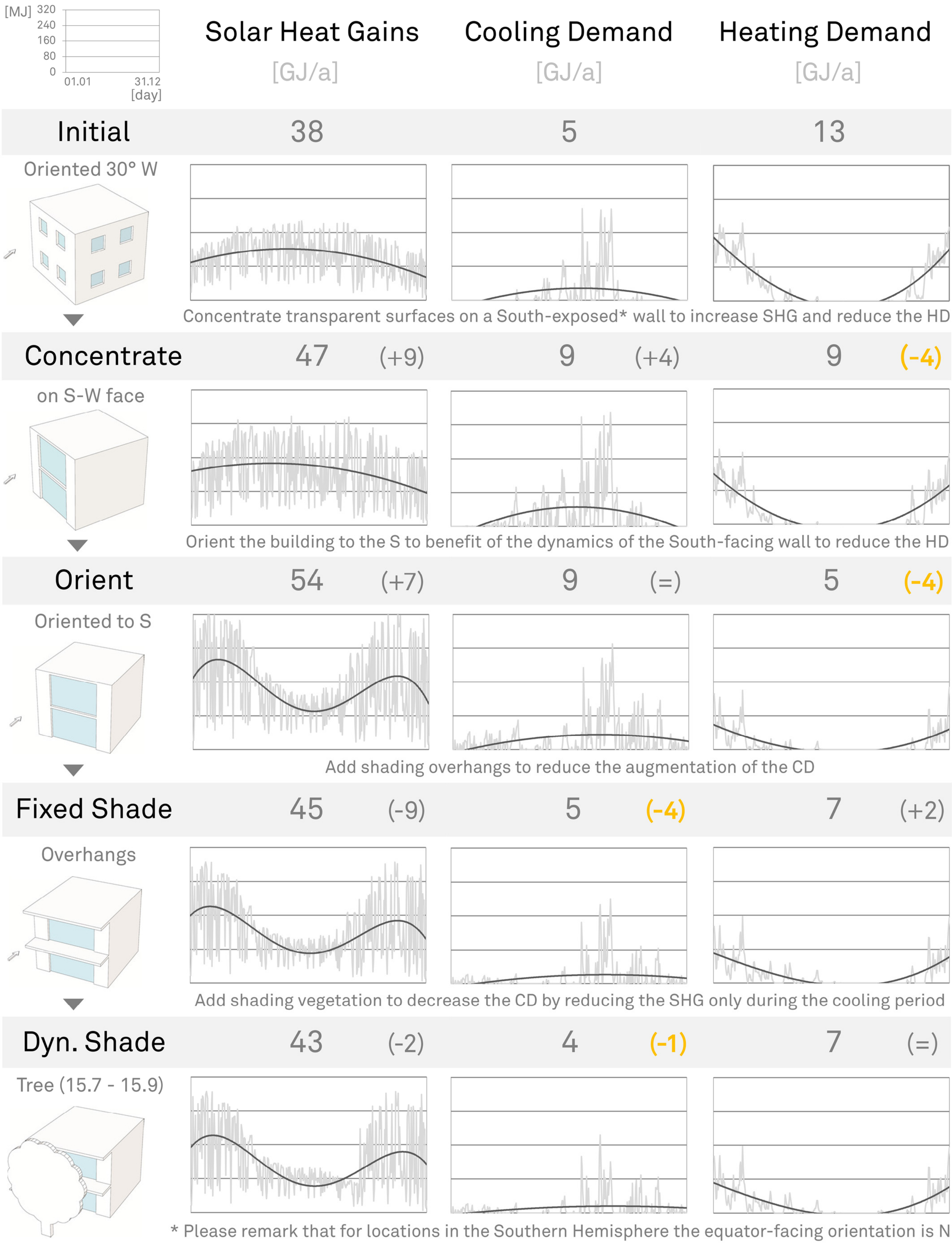
Curriculum Vitae

Name	Michele Leidi
Date of birth	6 November 1981
Nationalities	Swiss and Italian
Languages	Italian, French, English, German, Spanish
Education & Work	2000 High school certificate in Lugano
	2000-2005 Undergraduate studies at EPFL in Lausanne
	2005 MSc EPFL degree in engineering
	2005-2007 Project engineer at Philip Morris Products SA in Neuchâtel
	2007 Scientific assistant at EPFL-LSRO and EPFL+ECAL Lab in Lausanne
	2008 Military service
	2009 Visiting researcher at FHNW-i4Ds in Windisch
	2009-2010 Postgraduate studies at ETHZ-CAAD in Zurich
	2010 Start of activities in the architectural practice
	2011 MAS ETHZ degree in architecture
	2010-2014 Research and doctoral studies at ETHZ-SuAT in Zurich
	2014 DSc ETHZ degree in architecture



Incident Solar Energy

Example of annual magnitude and dynamics of the solar energy incident on the opaque surface of different sides of a cardinal-oriented house at 42° of latitude.
More details in: *Formal and Functional Implications of Dynamics-Related Solar Design Schemes*, Michele Leidi & Arno Schlüter, ACADIA 2012.



Archetypical Interventions of Passive Solar Design

Example of the annual magnitude and dynamics of solar heat gains, cooling demand and heating demand at 42° of latitude.
More details in: *Formal and Functional Implications of Dynamics-Related Solar Design Schemes*, Michele Leidi & Arno Schlüter, ACADIA 2012.