Optimisation of Urban Form by the Evaluation of the Solar Potential

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What's past is prologue.

William Shakespeare, The Tempest

Version abrégée

Quel sera le visage de la ville de demain? Il s'agit d'une question cruciale car, au cours des quatre milliards et demi d'années de son existence, la Terre n'a jamais été aussi menacée qu'elle l'est aujourd'hui. Depuis 2008, la moitié de la population du globe vit en ville – plus de 70% dans les pays riches. Or c'est en milieu urbain que sont produits plus des trois quarts des émissions de CO_2 et qu'est consommée 75% de l'énergie mondiale. La bataille du climat pour la poursuite de notre espèce et de toute autre vie se jouera donc dans les villes. Sera-t-il possible de créer une ville écologique idéale ?

L'objectif de cette thèse est de comparer des formes urbaines existantes et théoriques pour explorer les divers effets de la densité construite sur la lumière naturelle et sur le potentiel solaire. En effet, la recherche d'orientations idéales relatives au solaire a été et reste une problématique persistante du 19ème siècle et ceci jusqu'au début du 20ème siècle. Encore aujourd'hui, malgré nos connaissances scientifiques et pratiques de l'énergie solaire, établir le bon choix n'a pas encore franchi la frontière de l'énigme, art délicat dans le champ d'une science exacte.

Dans un premier temps, six sites urbains existants, quatre en Suisse, deux au Brésil et deux projets dans le Royaume-Uni, ainsi que quelques formes urbaines génériques et une ville utopique, ont été modélisés et analysés. Le véritable enjeu se situe non seulement dans la construction de nouveaux quartiers exemplaires, mais aussi dans la transformation de villes existantes. La méthode d'analyse utilisée permet d'évaluer le potentiel du chauffage solaire actif et passif, la production d'électricité photovoltaïque ainsi que l'éclairage naturel en façade et en toiture des immeubles. Les résultats obtenus par l'analyse de ces différents cas ont révélé de grandes variations du potentiel solaire sur l'enveloppe des bâtiments. Idéalement, ces investigations pourront aider les architectes et les urbanistes à optimiser le potentiel solaire dans la phase conceptuelle de leurs projets.

Une étude comparable a été effectuée sur la Ville contemporaine de trois millions d'habitants imaginée par Le Corbusier. Selon ce dernier, la Ville contemporaine aurait pu accroître la capacité urbaine tout en améliorant, en même temps, l'environnement bâti et le fonctionnement de la ville. Ce travail a ainsi permis de déterminer le potentiel solaire de cette ville utopique en vue de vérifier les hypothèses de Le Corbusier. En effet, depuis 1922, les écrits de Le Corbusier influencent les architectes et urbanistes dans leurs choix des orientations et des formes urbaines. Il était donc important de vérifier si cette influence a raison d'être.

Des valeurs de rayonnement solaire et d'éclairement par la lumière naturelle obtenus par simulations numériques constituent le cœur de cette procédure d'évaluation. La méthode générale, adoptée pour l'ensemble des simulations numériques, a consisté – via le dessin assisté par ordinateur, à savoir AutoCad – en la modélisation tridimensionnelle et spatiale de chaque bâtiment ou groupes de bâtiments avant de les exporter vers un logiciel d'analyse de performances urbaines (logiciel PPF/RADIANCE). Les distributions statistiques d'irradiation et d'éclairement des façades et des toitures ont été calculées à l'aide d'une méthode de ray-tracing, en vue de déterminer les surfaces appropriées aux différentes technologies solaires (énergie solaire passive et active, photovoltaïque et éclairage naturel). Des indicateurs de performance ont été utilisés pour évaluer le gisement solaire disponible et exploitable dans un contexte urbain (par exemple, les diagrammes polaires, les statistiques de facteur de vue du ciel et de lumière naturelle) et cela, en vue de déterminer des stratégies solaires optimales en zone urbaine.

Les différents travaux et recommandations en rapport avec l'énergie solaire, apparus surtout depuis la fin du XIXème siècle, de même que les divers modèles scientifiques et logiciels se rapportant à ce thème, sont aussi présentés dans ce document.

Mots clés: Architecture, Quartiers durables, Recommandations solaires, Densité, Tissu urbain, Simulation numérique, PPF RADIANCE, Modèle 3D, Etude de cas, Analyse énergétique, Eclairement, Solaire actif, Solaire passif, Photovoltaïque, Le Corbusier, la Ville contemporaine de trois millions d'habitants.

Abstract

What will the cities of tomorrow look like? This is a crucial question because in the four and a half billion years of its existence, the Earth has never been so threatened, as it is today. Since 2008 half of the world's population has lived in towns – more than 70% in rich nations. Three quarters of CO_2 emissions are produced in towns, 75% of the world's energy is consumed in towns. The battle for our climate, for the continuation of our species and all other life, will be largely waged in cities. Will it be possible to create the ideal ecological town?

The objective of this study is to compare actual and theoretical urban forms in order to explore the diverse effects of daylighting and solar potential on densely built-up sites. Indeed, the search for ideal solar orientations has been a persistent problem from the 19^{th} century until the beginning of the 20^{th}. Even today, for all our scientific knowledge and empirical experience of solar energy, making the correct choice has still not crossed the boundary from an enigmatic, tricky art into the field of an exact science.

As a first step, six existing urban sites in Switzerland and Brazil, as well as two projects in the United Kingdom, a few generic models and a utopian city, were modelled and analyzed. The goal was not merely the construction of new, exemplary districts but also the transformation of existing towns. The findings have been used to assess the potential of façades and roofs located in urban areas for active and passive solar heating, photovoltaic electricity generation and daylighting. The results obtained from these different case studies revealed large variations of the potential for solar energy collection on the buildings' façades and roofs. Ideally, these investigations are expected to help architects and town planners understand how to optimise solar collection on buildings design.

In addition, a study was made of the Contemporary City of Three Million Inhabitants created by Le Corbusier. According to the latter, the Contemporary City could increase the urban capacity and at the same time improve the urban environment and the efficiency of the city. Therefore the present study extracted the solar potential of this utopian city in order to assess Le Corbusier's propositions. Since 1922, Le Corbusier's studies have influenced architects and town-planners in their choice of orientations and urban forms: it was therefore crucial to discover if this reliance on Le Corbusier was justified.

Solar irradiation and illuminance values obtained through numerical simulations form the core part of the method. The method adopted for the entire set of computer simulations consisted in modelling — via a computer-aided drawing piece of software, namely AutoCAD — the digital model of each building or group of buildings prior to exporting them to an urban performance analysis software (PPF/RADIANCE software package). Spatial distributions of solar irradiation and daylight fluxes over the overall building façades and roofs were calculated using ray-tracing simulation techniques to determine the appropriate placement of different solar technologies (passive and active solar, photovoltaic and daylighting). Performance indicators were used to assess the solar utilisation potential of the urban sites (e.g. statistics of sky view factors and daylight factors) in order to determine the optimal solar strategies for a given urban context.

In addition, various works and sun-related recommendations that have appeared mainly since the end of the nineteenth century, together with the various scientific models and software tools pertaining to this topic, are presented in this study.

Key words : Architecture design, Sustainable districts, Sun-related recommendations, Density, Urban fabric, Numerical simulation, PPF RADIANCE, Three-dimensional model, Case study, Energy analysis, Daylighting, Passive solar, Active solar, Building-integrated photovoltaics, Le Corbusier, The Contemporary City of Three Million Inhabitants.

Contents

Chapter 1: Introduction

1.1 Context of study

The World is a rapidly changing and transforming place, so is the City. What will be the ecological nature of the City of the Future?

Architectural design and urban planning are becoming more and more complex, both from a technological and conceptual point of view. They involve numerous and different procedures and demand new qualifications. The number of specialists required is growing: in the short term and in the long term completely new occupations will be created. This is mainly due to the growth and the transformation of the cities in the developed countries but also concerns, on a larger scale, their expansion in the developing countries.

According to Joel Cohen[1], the World will have to build one city of one million people every week for the next 43 years to absorb the growth of world urban population. An immense rural exodus is transforming the face of the planet. At the turn of the 19th century only 3 percent of the World was urbanized. Since then, more than half of the 6.7 billions of human inhabitants has been living in towns, as opposed to a mere third in 1950. Between now and the year 2030 this proportion will be approaching two thirds. In 2009, a total of 20 cities are hosting more than 10 million inhabitants. Today, cities like London, Paris, Berlin, São Paulo, New York, Tokyo, Beijing and Hong Kong each have several million inhabitants (see Figure 1 and Figure 2). How is it possible to control their energy consumption, the movement of people, the sewage, the waste processing, and above all the phenomenon of urban sprawl? The problem is even more exacerbated by the fact that two thirds of the World's urban population are concentrated in the developing countries.

From the point of view of sustainable development, the model of the compact city is considered a desirable goal. However, for a large part of the population, this density has a negative connotation and has become synonymous with large, cramped, built-up areas that have produced significant numbers of overshadowed spaces. There are also the attendant evils of noise and air pollution plus a lack of visibility due to obstructions. The idea of the compact city is also frequently associated with the huge blocks constructed during the 20th century which have been severely criticised for their lack of security, their monotony and the feelings of anonymity which they provoke (Marchand, Montavon et al. 2008).

Grégoire Allix (Allix 2009) declares that in the area of climate change the cities are not the problem but the solution. A compact city which combines housing and activities and which is served by public transit is less polluting than secluded individual housing which relies to a large extent on the automobile. The correlation between weak urban density and the elevated emissions of CO_2 per inhabitant has been demonstrated by Professor René Frey (see Figure 3). The lighting and heating of buildings produces a quarter of the World's greenhouse effect gases, according to the estimates of the World Bank, transportation counts for a third of the waste of built-up areas. Transportation is responsible for 60% of the CO_2 emissions in São Paulo as opposed to 20% in London or New York, which are both well served by the underground rail system. In the United States, a country of residential sprawl, the dense city remains a challenge, while the total area of the hundred largest built-up spaces in the country has increased by 82% between 1970 and 1990.

[1] Head of the Laboratory of Populations at the Rockefeller University and Columbia University.

Figure 1: Hong Kong, Architecture of density (Picture by Michael Wolf).

Source: [online] URL: http://www.photomichaelwolf.com/hongkongarchitecture/(Consulted on June 22nd, 2009).

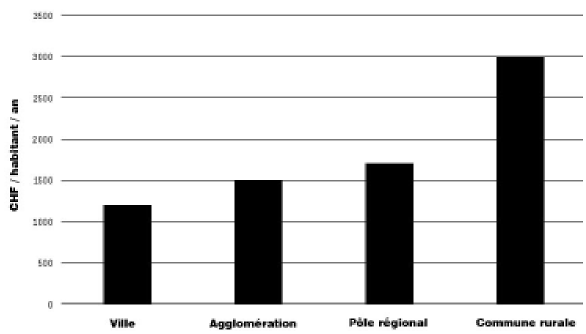
Figure 2: Resident in his flat in Hong Kong's oldest public housing estate, a room of 100 square feet in size (Picture by Michael Wolf).

Source: [online] URL: http://www.photomichaelwolf.com/100x100/index.html (Consulted on June 22nd, 2009).

Demographic expansion and centralization of economic activities, in conjunction with the automobile boom, determined the new urban rationales. Although certain cities, like Paris, Barcelona and Chicago for instance, were radically transformed in order to adapt to the constraints of industrial modern society, most of them evolved according to other circumstances: this often explains their chaotic nature. Land-related pressures gave birth to speculation, leading to buildings in which accommodations lacked fresh air and sunlight, as well as to the construction of skyscrapers (in New York a zoning law has regulated their volume since 1916). Their multiplication was made possible principally because the island of Manhattan sits entirely on granite. In addition, thanks to all kinds of technological progress: the resort to materials such as steel and reinforced concrete, the eradication of load-bearing walls, the introduction of fireproof metallic frameworks and hydraulic elevators, the flourishing of increasingly mightier skyscrapers has been reassured (Eaton 2001).

Overall, the growth of cities is basically due to commonplace proliferation or through the rather mediocre execution of building projects. The main problems are due to poor construction materials, unrealistic construction deadlines, an obsession with economic profitability and the lack of modesty of their designers: the latter often forget that the quality of a city is the result of collective work. Not least are the shortcomings of urban and architectural culture (Allain 2004). Famous authors such as Pierre Lavedan[2], Michel Ragon[3], Leonardo Benevolo[4] and Charles Delfante[5] have described, through the different human civilisations and eras, the progressive development of cities.

In ancient times, the importance of climate in the course of urban planning was a serious consideration (Harzallah 2007). Despite this, the cities were nor really sustainable. Ruano wrote for instance that "*Nobody knows what a sustainable human settlement looks like or how it functions. Some people say that small European towns in the Middle Ages, or prehistoric hamlets for instance, were "sustainable". Both models, however, were based on the same non-sustainable paradigm: resources were extracted from the environment, while waste [was] thrown back. The fact that they were small is what made such settlements "apparently sustainable", since disruption to the natural environment was minor. The best proof, though, that those early human settlements were not truly "sustainable" is that through an endless and increasing accelerated growth spiral they eventually evolved into today's urban civilization, which is most certainly not sustainable*" (Ruano 1999) (see Figure 4).



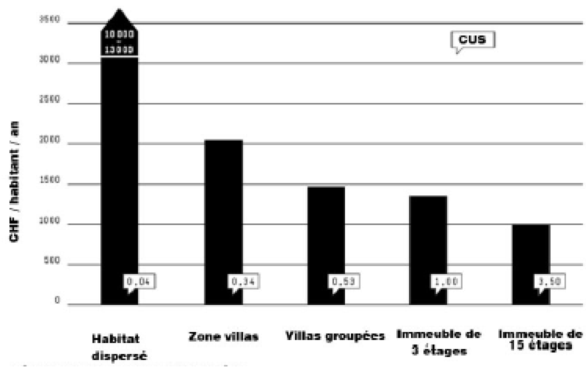


Figure 3: Medium cost of the infrastructures (fresh water and waste water, roads, electricity) in CHF/Inhabitants pro year of a town, of a built-up area, of a regional centre and a rural community (left to right, Figure on left) and of a dispersed settlement, of a detached bulding habitat, of a cohousing community, of a 3-storey building, of a 15-storey building (left to right, Figure on right).

Source: Frey, René L. (2004). Städtewachstum in die Breite oder in die Höhe? Überlegungen und Standtpunkte der Stadt und Regionalökonomie, March 2004.

[2] Lavedan, P. (1926). *Histoire de l'urbanisme*. Paris, H. Laurens.
[3] Ragon, M. (1986). *Histoire de l'architecture et de l'urbanisme modernes*. Paris, Points/Essais.
[4] Benevolo, L. (2000). *Histoire de la ville*. Marseille, Editions Parenthèses.
[5] Delfante, C. (1997). *Grande histoire de la ville de la Mésopotamie aux Etats-Unis*. Paris, Armand Colin.

Figure 4: Barcelona. The engineer Ildefons Cerdà (1859) produced a one-of-a-kind city in the hope of inventing an urban ideal. Stifling and restricting as it is, the squared framework of 130m interaxial per module is adapted to the pedestrian scale. Yet within it, it is difficult to find one's way around. In spite of the various architectural styles (populating Cerdà's framework took nearly a year), its urban uniformity comes close to boredom and seems to scorn topography as well as Barcelona's environment.

Source: [online] URL: http://www.sagaplanet.com/modules/smartsection/item.php?itemid=156 (Consulted on June 22nd, 2009).

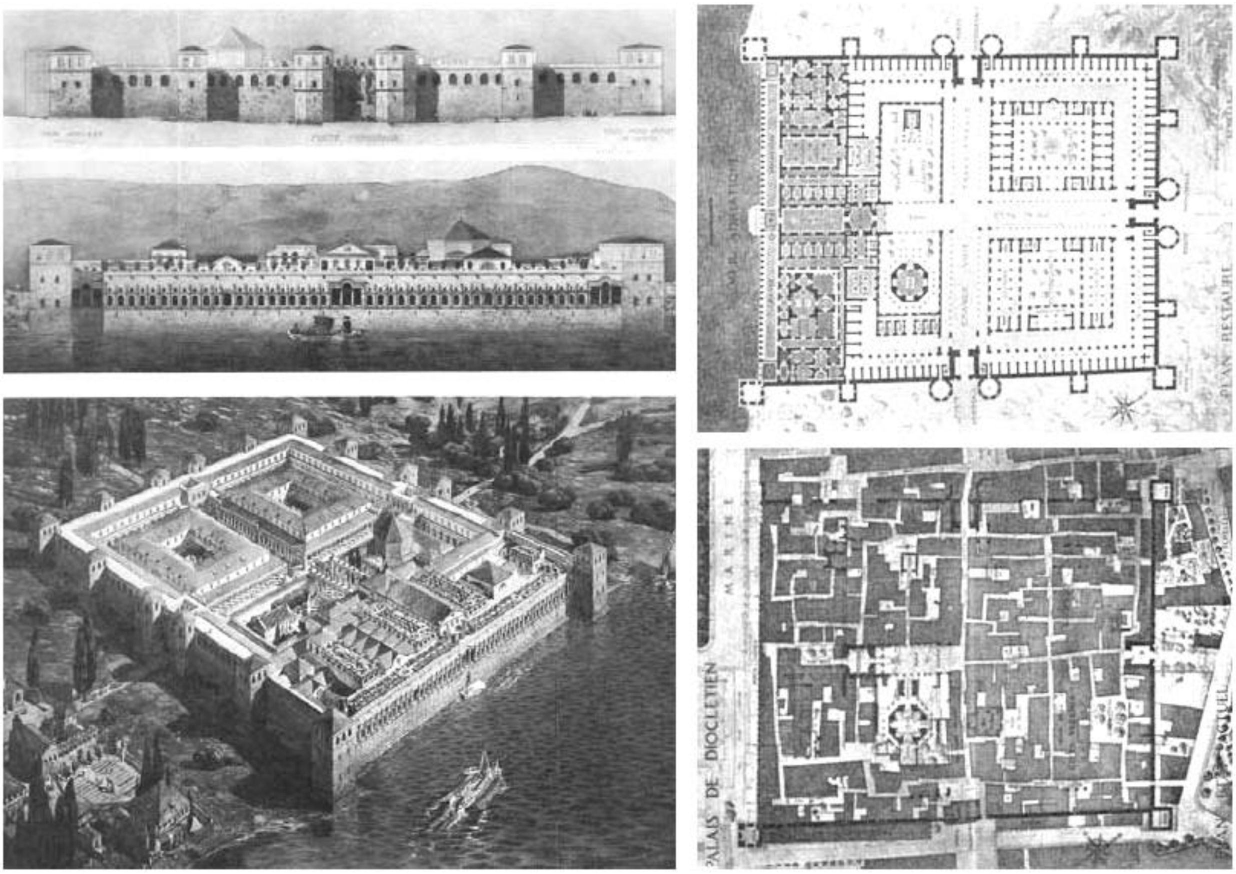


Figure 5: Densification of Diocletian's Palace and the surrounding area in the historic centre of Split in Croatia.

Source: Marchand, B., Montavon, M., Bossy, K. (2008). Ville de Genève. Les enjeux qualitatifs de la densification par surélévation. Geneva, DeLaMa Urbanisme et aménagement du territoire - Service d'urbanisme de la ville de Genève.

On the other hand, according to Professor Bruno Marchand (Marchand, Montavon et al. 2008), the ancient arenas of Arles (France) as well as the town centre of Split (Croatia) are beautiful examples of the densification of successful, existing infrastructures. The historic centre of Split is remarkable for having been built on the inside and then around the Diocletian's Palace (see Figure 5). This case is an important reference point in the histiography of urbanism and of architecture, especially during the period of modernity in the 20th century. It has often illustrated the famous motto of the Italian architect, Leon Battista Alberti[6], that: "*One's house is a small city, and a city has the qualities of a big house*". However, in Alberti's day, towns were very different from ours at the present time.

Before the 18th century, medieval cities suffered from the noxious atmosphere of intramural districts, due to a "passive attitude" towards the urban microclimate, but also because of military constraints. By the Enlightenment, these constraints turned into an "interventionist attitude" reflected by the transformation of urban planning. The Enlightenment's philosophers and writers often viewed the city as a sick body (urban pathology attracted illness, begging, prostitution, filth and bad air). Medieval districts, with their narrow, twisted streets, flanked by towering edifices, were notorious for retaining noxious air and blocking out the sunlight. The medical findings of the French chemist-biologist Louis Pasteur and the German physician-biologist Robert Koch demonstrated the impact of the human environment on the tuberculosis bacillus: they showed how sunlight could kill the germs. Housing thus became part of a social prophylaxis of tuberculosis, described as the illness of darkness. In this specific context, architects and urban planners began to take account of solar radiation in their architecture and urban design. Therefore, an emphasis on the sun took place in these two areas (Harzallah 2007).

Solar visualisations became as a consequence the object of numerous investigations undertaken by builders as soon as they became interested in the effect of sunlight on their buildings. Egyptian temples, the Parthenon in Athens, the Pantheon in Rome, as well as the shadow tracings of Leonardo da Vinci are examples of these novel attitudes. The military need for observation points from or through their edifices was certainly another reason: medieval loopholes, lookout towers, stone curtain walls on castles, etc. Famous architects and engineers have even designed buildings using solar ray tracings although it is difficult to ascertain whether these tracings, found on certain technical drawings were used before the design stage or after the completion of the project (Houpert 2006). Even in the literature of the last century, the *Techniques and Architecture* journal (Massé 1943) devoted the entire double issue 7th-8th of July-August 1943 to solar ray tracing. A description of methods known in the middle of the twentieth century is given in the latter; the state of the art in this field was already very advanced at that time. For that reason, a new and better adapted organisation of the city was progressively developed, which seeks to reach a genuine symbiosis between the natural and urban environment of the future.

1.2 Thesis objectives

This thesis aims to promote sustainable urban architecture by allowing a better direct use of solar technologies in the urban environment: this includes passive and active solar technologies, buildings which integrate photovoltaic (BIPV) and daylighting design. The increasing development of cities and metropolises is a key factor in the energy consumption of housing in Switzerland as well as in the rest of the World. Recent developments in the use of energy in rational building, such as in energy efficiency and, the use of renewable energy, cannot easily be applied in the urban context: high-density land use, urban-related constraints (building regulations) and socio-cultural constraints (protection of the architectural heritage) impose limits on urban-specific conditions, which tend to reduce the possibilities for the direct use of solar energy (buildings that cast shadows, inappropriate surface orientation, etc). Solar radiation control is related to urban geometry: it concerns the key players from the building sector who deal with urban forms (architects, engineers, urban planners). If one wishes to preserve the natural environment and cope at the same time with the continuing demand for housing, it

[6] Leon Battista Alberti (February 18, 1404 – April 20, 1472) was an Italian author, artist, architect, poet, priest, linguist, philosopher, and cryptographer, and general Renaissance humanist polymath.

is essential to demonstrate that there are possibilities to build more compact cities which are guided by the principles of sustainable development.

The main objective of this study is the evaluation of the gross and useful solar radiation and daylight flux in representative urban environments (Switzerland, the United Kingdom and Brazil). Several building technologies employing a direct use of solar energy for heating, daylighting and/or electricity generation were taken into account. In this way, novel building shapes as well as new ways to arrange groups of buildings in order to improve the solar energy collection were expected to be devised. It is not a matter of describing the physical mechanisms of the complex phenomena involved in an urban context but rather of identifying simple rules and relationships for the designers. This involves outlining the buildings and their envelopes, on district and street scales (urban canyons). From a morphological point of view, it means that the three-dimensional shapes of buildings and building groups as well as open spaces must be taken into account. The main reason for working via this geometrical representation of urban objects is that it enables building designers and urban planners to cope with the consequences of planning choices without setting aside architectural design. As a matter of fact, urban morphology is of primary importance for indoor microclimate.

The second objective of this study is the comparison of theoretical urban planning and design in order to explore the impact of two different indicators of building density in an urban context – i.e. the plot ratio and the site coverage (ratio of building footprints to site area) – for their solar and daylight potential. In many studies, the urban density is simply monitored by means of the plot ratio (ratio of total floor area to site area) and/or urban canyon aspect ratio (ratio of height of buildings to street width), which only represent two possible indicators of urban density. By examining urban density from a slightly different perspective, attempts were made to demonstrate that one can build more compact cities which obey the principles of sustainable development, especially in regards to their solar and daylighting potential.

Finally, the third objective of this study was to address some of Le Corbusier’s original architectural concepts, which are an integral part of his theoretical work. The latter is still influencing today’s architects and urban planners in their day-to-day practice. An important task was to revisit Le Corbusier’s sun theories by the way of scientific methods: using modern computer simulations, the conclusions of the *Contemporary City of Three Million Inhabitants* (designed in 1922) were examined along with some Parisian street blocks decried at that time by Le Corbusier.

To this end, the method adopted for the entire set of computer simulations consisted in modelling—via a computer-aided drawing piece of software, namely AutoCAD— the digital model of each building or group of buildings prior to exporting them to an urban performance analysis software (PPF software package). The PPF simulation package was developed for that purpose by Professor Raphaël Compagnon at the University of Applied Sciences of Western Switzerland (HES-SO). Important modifications were made however to the software package in its first version which aimed more at the computer rendering of urban sites. One main concern was to achieve an optimal combination of the building digital data with topographical data in order to be able to assess the solar potential of an urban site by means of a ray-tracing technique. The latter was used in several research studies, as well as in several urban projects, which confirm the validity of the simulation approach. (Compagnon 2000; Steemers, Raydan et al. 2000; Compagnon 2004; Montavon, Scartezzini et al. 2004; Montavon, Scartezzini et al. 2004; Nikolopoulou 2004; Robinson, Scartezzini et al. 2005; Cheng, Steemers et al. 2006; Cheng, Steemers et al. 2006; Montavon, Steemers et al. 2006; Kaempf, Montavon et al. 2007; Steemers, Montavon et al. 2007; Marchand, Montavon et al. 2008; Kaempf, Montavon et al. 2009).

1.3 Statements of thesis

Three distinct hypotheses are put forward below making up the main statement of this thesis. Although they are thoroughly interconnected, they differ as follows:

Hypothesis 1: ***The shape and spatial layout of the buildings can considerably improve their solar energy incomes.***

Environmental issues tend to be increasingly taken into consideration in architectural practice. Nevertheless, these do not necessarily provide the most suitable solutions for solar design. Institutions, policies and other interested parties favour a rational use of energy without questioning the urban layout.

Hypothesis 2: ***High density does not always reduce the utilization potential of solar energy in an urban context.***

The environmental impact is always a concern when urban densification is envisaged, because the densification of the urban fabric is generally supposed to impair the daylighting and solar energy use within buildings.

Hypothesis 3: ***The Contemporary City of Three Million Inhabitants would not offer the expected quality of solar exposure claimed by Le Corbusier at that earlier time.***

Beyond his thoughts focussed on the energy of the Sun, Le Corbusier seemingly aspired to a thorough and global reform of the urban fabric. This implied the definition of a new urban texture, opposing the existing one, and putting forward some hygienist concepts (or dictates), in compliance with the urban ideas of his day, but lacking scientific rationality.

A series of case studies chosen from around the World will be used to support these hypotheses and to demonstrate their validity.

1.4 Structure of thesis

The current thesis report is made of three main parts, at the end of which a conclusion appears.

Chapter 2 presents the main solar-based approaches that appeared in the 18th and the 19th centuries during the development of architectural processes. These prescriptions dealt with façade exposure, street orientation, building outlines, building shape and devices. Moreover, relevant studies that have been published as late as 2009 are classified. Also presented are the various models, developed in order to integrate solar and visual constraints within the framework of architectural and urban studies.

Chapter 3 is devoted to the presentation of the research methodology. In particular, it sets out an overview of the most frequently used techniques in computer graphics and in the simulation of urban sites. The different approaches recently developed in order to decide the geometrical features of architectural and urban residential projects are also explained.

Chapter 4 sets the scene for the thesis work by describing the Swiss, British and Brazilian urban sites used within this study. Details of the computer 3D digitizing methods used for the urban sites considered in this thesis are also provided, as well as the renderings generated and the analysis of results carried out with the use of the PPF software package. There is a discussion of the results of the various city models and generic forms of urban sites. In addition, for an investigation of urban design, the *Contemporary City of Three Million Inhabitants* is described in order to assess Le Corbusier's propositions and to question whether the *Contemporary City* could in fact increase the urban capacity and at the same time improve the urban environment and the efficiency of the city. A summary of lessons learnt from the comparison of the different urban designs is presented in conclusion.

Chapter 5 concludes the thesis by summarizing the main achievements. It suggests different application fields and alternative directions for a further development of this study.

Chapter 2: Overview of recommendations related to solar radiation

2.1 Introduction

Which urban form is the healthiest and which offers the best all-season access to the sun?

Since the early19th century the answers to both of these questions have been considered as one and the same – by many architects, by medical practitioners and above all by the *hygienists*. The movement called *Hygienism* began in England which also witnessed the birth of the Industrial Revolution. The workers who operated the “dark Satanic mills” described by the poet William Blake[7] were housed in conditions not much healthier than the “mills” themselves. The *hygienists* would advocate social protection laws and also emphasize the importance of sunlight in urban planning. Guided by their principles, architects, scientists, physicians and experts in many fields would struggle to produce urban designs which offered the best exposure to solar radiation.

This chapter examines various architectural designs and gives concrete examples of architectural design bases that have appeared since the nineteenth century and which were especially supported by medical practitioners and *hygienists*.

The study works have been gathered into five categories presented chronologically, following the detail below:

- Theory of façades exposure;
- Theory of orientation of streets;
- Theory of building outlines and streets;
- Recommendations for courtyards;
- Buildings: establishment and density questions.

The approach adopted is not comprehensive, it does not follow the chronological manner of the historian, and it is not the present writer’s own invention. For this particular approach, a debt is owed to the Ph.D. work of Dr Amina Harzallah, who has generously allowed her own method for listing the great contributors in this field to serve as a guide. This chapter in the present thesis contains a drastically briefer summary than Dr Harzallah's of those authors who have developed theories about architecture design and health from 1753 until 1954.

The great milestones have been grouped by Harzallah into the period of one century. For example, the scientific interest in the solar exposure of buildings is at its most intense at the very beginning of the twentieth century. The second milestone is the discovery of penicillin in 1928 and its mass production by the late 1940’s. There is also the era of a rapid reconstruction after the First World War. All of these crucial events have been condensed into a period which corresponds to the *hygienist* movement which is a phenomenon of the late 19th and the early 20th centuries. History is not tidy and compartmentalized and the writings and ideas of experts on architecture and engineering do not follow a straight line. Moreover, the approach taken by this work makes it possible to examine and classify relevant studies that have been published as late as 2009. The various scientific models and pieces of software implemented in order to appraise a given urban or architectural design are included in Section 2.7.

2.2 Theory of façade exposures

The different and frequently recommended façade exposures theories varied from east to south because of the confusion and contradictions pertaining to sun-related ideas.

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[7] William Blake (28 November 1757 – 12 August 1827) was an English poet, painter, and printmaker.

2.2.1 East façades exposures

East exposure supporters referred to Vitruvius' ideas and to Dr Adolphe Vogt's works (1885). Vitruvius feared heat waves and stated that cities "*in the Summer, in south-exposed locations, the Sun is especially hot the minute it rises, and burning hot at noon [...] so that health is highly affected by these sudden changes from hot to cold*" (see Figure 6). Table 1 gives a chronological list of the authors of east façade orientation theories, together with the mentors[8] who guided them in their choices.

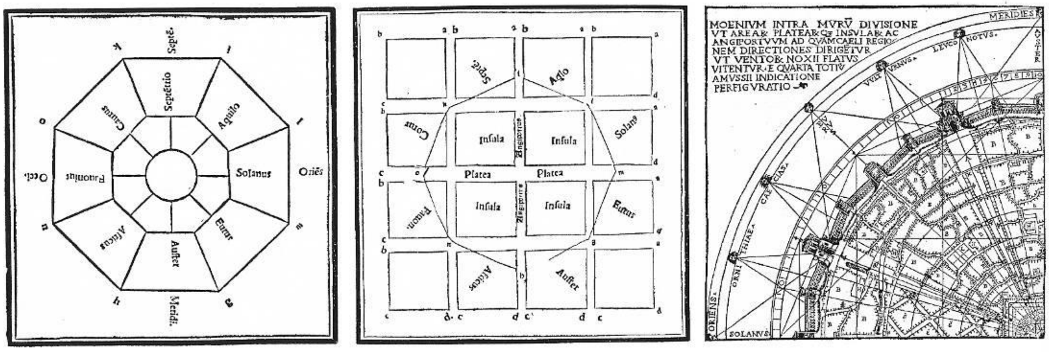

Figure 6: Fra Giocondo (attr.). Vitruvian city.

Source: Eaton, R. (2001). *Cités idéales, L'utopisme et l'environnement (non) bâti*. Anvers, Fonds Mercator.

Table 1: East façades exposure authors

Theories	Years		Authors
	4th Century B.C.	–	Hippocrates
East Exposure mentors	1st. Century B.C.	–	Marcus Vitruvius Pollio
	1844/1897	–	Isidore Bourdon
	1846	–	Jean-Baptiste Monfalcon
	1846	–	Isidore-Augustin-Pierre de Polinière
	1869	–	Michel Lévy (+ west exposure)
	1885	–	Adolphe Vogt
East Exposure authors	1886/1887/1905/1887	–	Emile Trélat (east + west both in moderate countries)
	1887	–	Emile Clément (+ south and west)
	1838	–	Pierre-Adolphe Piorry
	1897	–	Achille Bourbon
	1911	–	M. Bousquet
	1913	–	Cloquet & Cobbaert (+ south-east)

Piorry's recommendations (1831) are vague, but reflect Vitruvius' precepts. According to Bourdon (1844), openings must be exposed in an eastern direction to take advantage of the first sunrays and the cleanest air. Monfalcon and de Polinière (1846) relate this exposure to moods and healthiness. Bourbon (1897) recommends this exposure as a trade-off between health factors, drying and heat. Bousquet (1869) reports that Lévy (1911), after having studied the advantages and shortcomings of each exposure, finally advised east and west exposures. Trélat (1886), who relied on Vogt's works (1885), considered east and west to be the most favourable exposures for temperate climates. He also recommends an east-west orientation for northern countries and a north-south orientation for southern countries. Arguments put forward by Trélat announce the new concerns related to sunlight and heat, thought of as microbicide elements. Vogt (1885) ascertains that an east-oriented façade receives more heat than a west-oriented façade, which in turn receives more heat than a south façade. He proves that the south façade captures sunbeams very obliquely, which hit the ground vertically. Clément (1887) is reservedly inspired by Vogt's works. He explains that the results obtained by Vogt do not take seasons into account and that in Winter he probably would have come to different conclusions. Clement deems

[8] Mentor, a wise and trusted counselor or teacher.

all orientations as suitable except north. Cloquet and Cobbaert advocate east orientation, which they rank equal to south-east.

2.2.2 South façades exposures

Table 2 gives a chronological list of the authors of south façade orientation theories, together with the mentors who guided them in their choices. Those authors who do recommend south-orientated façades were influenced by the plan of the baths of Vitruvius, by Socrates and by the German pioneer on health research, Dr Bernhard Faust (1824). Faust's[9] doctrine, the origin of which von Camerloher (1829) attributes to Socrates, advised the orientation of housings toward southern light. Various housings were built in Germany following this principle thanks to Dr Vorherr (1823). South exposure supporters relied on a more scientific basis, via the measurement of the quantity of heat received by a surface as a function of its orientation by means of the use of the actinometer[10]. In the 19th century, Dr Knauff of Heidelberg was the first to reveal mathematically and physically the quantity of solar heat received by a south façade (see Table 3). Knauff does not specify for what latitude he made the experimentation; Harzallah (Harzallah 2007) assumes that it is for the city of Heidelberg (49°25'0" north) in Germany.

However, these planners reveal more subtlety of thought than a mere "blanket" acceptance of southern exposure. Renaud (1863) generally supports the south orientation with the qualification that room occupancies might determine a different orientation. Garnier (1905), one of the great trailblazers of urban planning, devises a project with an original pecked-line-building layout enabling proper daylighting and proper ventilation. Barde (1891), a Swiss architect, shows a deeper reasoning with his study of street orientation in an urban context, where common houses have two exposed faces. He also recommends that only the main rooms of a housing located in Central Europe should be exposed to the south.

More emphatically, Marboutin (1910) uses the evidence of nebulosity and radiations of the sky vault to prove that façades facing streets, as well as main façades of isolated buildings, must face south to provide optimal housing conditions: heat in Winter and cool in Summer. In Marboutin's view, the most favourable exposure is at an angle between 60° and 75° with the meridian (see Figure 7).

In fact, Marboutin's name is constantly mentioned by the supporters of the south exposure, particularly by Deschamps (1930), Dourgnon (1936), Hermant (1934/1943), Bardet (1941), Lebreton (1945) and Leroux (1952). Leroux, in particular, gives a general overview of Marboutin's works in relation to the insolation of buildings in temperate climates.

In addition to Marboutin's studies, Hermant (1934/1935/1943) reported other investigations carried out in Copenhagen by Wolmer, in the United States by the A.S.H.V.E[11] and by the John B. Pierce Foundation (1936). Lebreton (1945) refines Figure 8 drawn by Hermant and indicates orientation angles that must not be exceeded at 42° north to benefit from a proper sunshine upon bright weather.

[9] Instigator of the *Sonnenbau*, doctrine that advocates the search for sunshine in dwellings.
[10] Term of physics. Instrument invented by M. Becquerel to measure intensities of different rays of the spectrum.
[11] American Society of Heating and Ventilating Engineers (now part of American Society of Heating, Refrigerating and Air-Conditioning Engineers).

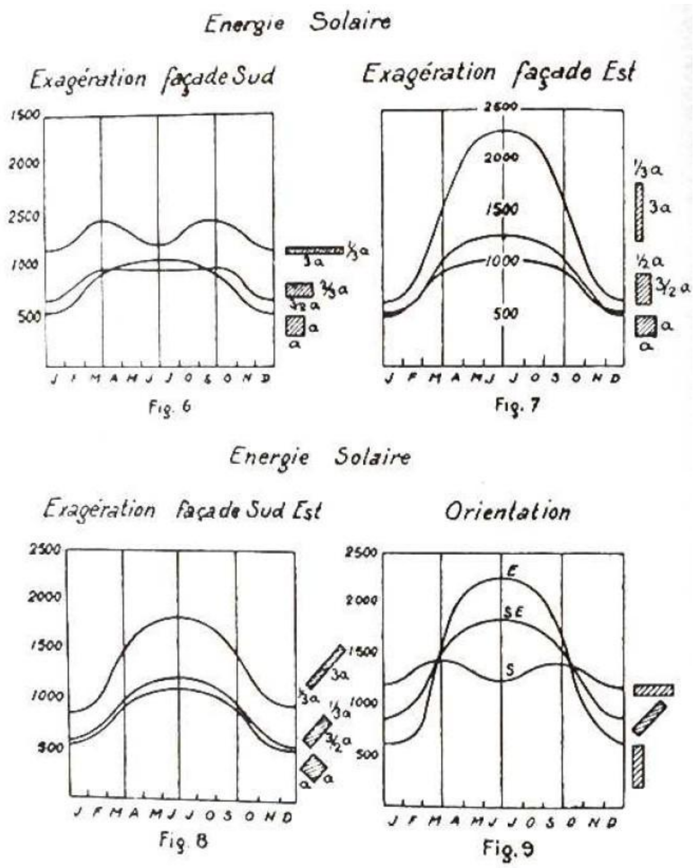

Figure 7: Félix Marboutin. Study of the influence of façade orientation on solar energy. Annual energy variations are low for the case of the south exposure, intermediate for the south-east exposure and high for the east exposure.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

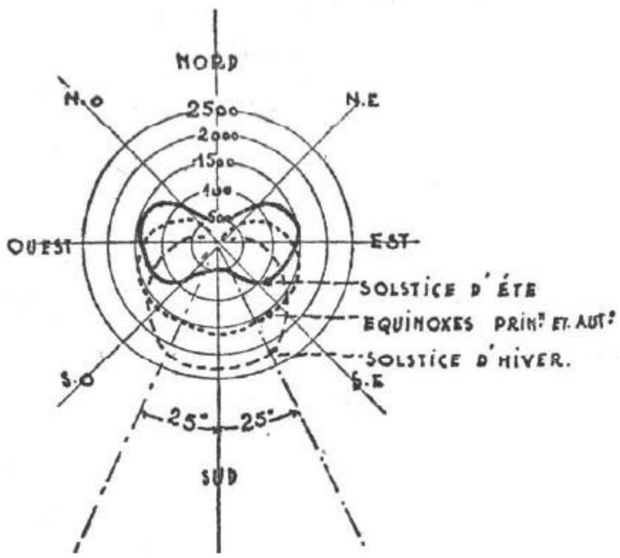

Figure 8: Jean Lebreton. Luminous intensity received by vertical walls, for all orientations, upon bright weather, at 42° north (according A.S.H.V.E and the John B. Pierce Foundation).

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

Table 2: South façades exposure authors

Theories	Years		Authors
South Exposure mentors	4th Century B.C.	–	Socrates
	1st. Century B.C.	–	Marcus Vitruvius Pollio (baths)
South Exposure authors	1624	–	Louis Savot (Winter accommodation)
	1755	–	Abbé Laugier
	1785	–	Francesco Milizia
	19th Century	–	M. Knauff of Heidelberg
	1823	–	Dr Vorherr
	1824	–	Bernhard Christoph Faust
	1829	–	Anton von Camerloher
	1844	–	Bourdon (east in Paris; north countries: south exposure)
	1863	–	Léonce Reynaud
	1885	–	F. Putzeys & E. Putzeys
	1891	–	Charles Barde
	1896	–	Léon Duchesnes
	1898	–	D. Spataro
	1902	–	Achille-Adrien Proust
	1905/1917	–	Tony Garnier
	1905	–	Emile Trélat (north countries: south and north exposure)
	1910	–	Félix Marboutin
	1923	–	E. Joyart
	1925	–	Jules Courmont (based on the work of J. Arnould)
	1929	–	Ludwig Hilberseimer
	1930	–	HenriDeschamps
	1934/1936/1943	–	André Hermant
	1935	–	Henning Wolmer
	1936	–	Jean Dourgnon
	1941	–	Gaston Bardet
	1943	–	G. Ghilardi
	1945	–	Jean Lebreton
	1952	–	Robert Leroux

Table 3: Knauff. Number of calories received for various façade exposures

Periods	East or West	South	North
Summer Solstice (June 24)	2600	1904	467
Equinox (March 20 or Sept. 20)	1534	3375	0
Winter Solstice (Dec. 21)	358	1965	0

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

The German architect Ludwig Hilberseimer is usually mentioned in connection with Mies van der Rohe and the Bauhaus[12]. For political reasons, Hilberseimer fled Germany in 1933 and continued his work in urban planning at the Illinois Institute of Technology. He is mentioned by Hermant, who ranks him amongst the south exposure supporters with differentiation of indoor room orientations as a function of existing activities (see Figure 9). Ghilardi (1943) evolves the concept of sunshade that appeared in the 1930s, by recommending south orientation of the main façades, because they receive more heat in Winter and less in Summer than east and west façades.

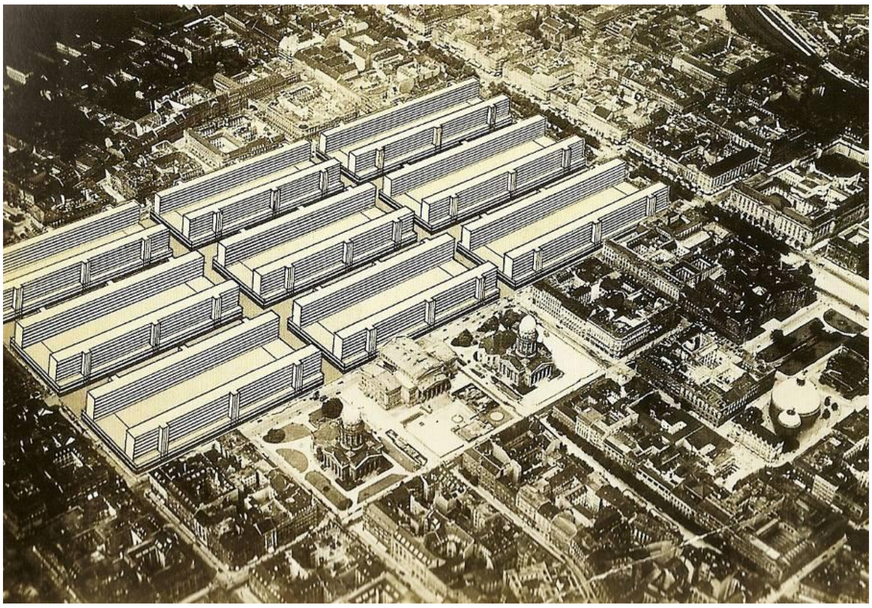

Figure 9: Ludwig Hilberseimer. Application of the principles, project development of Berlin: Friedrichstadt district.

Source: Eaton, R. (2001). *Cités idéales, L'utopisme et l'environnement (non) bâti*. Anvers, Fonds Mercator.

Not all the opinions about the exposure of north façades were based on data that would pass muster in today's scientific community. With various degrees of validity, early medical pioneers attributed all manner of evils to northern façades' exposure. Pierre Adolphe Piorry (1831), Monfalcon and De Polinière (1846), Dr Etienne Clément (1887), Bourbon (1897), Juillerat (1904) listed their many objections: northern exposure was cold, produced fatigue and melancholy, was particularly unhealthy for nervous women with delicate breasts, etc.

2.3 Theory of street orientations

The various theories of buildings or streets axes orientation can be classified in two groups: on the one hand the hygienists' and on the other hand the climatistes (so designated by Barraqué (1998) (Harzallah 2007). Table 4 gives a chronological list of the authors of the various street orientations' theories.

[12] Bauhaus ("House of Building" or "Building School") is the common term for the Staatliches Bauhaus, a school in Germany that combined crafts and the fine arts, and was famous for the approach to design that it publicized and taught. It operated from 1919 to 1933.

Table 4: Chronological list of authors of various street orientations' theories

Theories	**Years**		**Authors**
North-South axis	1876	–	Benjamin Ward Richardson (Hygeia city)
	1885	–	Adolphe Vogt
	1885	–	Félix and Emmanuel Putzeys
	1887	–	Etienne Clément
	1887	–	Emile Trélat (moderate countries)
	1891	–	Charles Barde
	1896	–	Léon Duchesne
	1904	–	Paul Juillerat & Louis Bonnier
	1905/1908	–	Henri Provensal
	1909	–	Raymond Unwin
	1925	–	Jules Courmont
	1930	–	Edmond Marcotte
	1934	–	Jean Raymond
	1947	–	Albert Besson
	1948	–	Robert Leroux
East-West axis	1891	–	Charles Barde
	1896	–	Léon Duchesne
	1902	–	Achille-Adrien Proust
	1943	–	André Hermant
	1948/1951	–	Robert Leroux (hot countries)
East-West axis objectors	1890	–	Joseph Stübben
	1921	–	Emile Juillerat
	1933	–	Jean Raymond
45° axis	1885	–	Joseph Stübben
	1887	–	Etienne Clément
	1894	–	William Atkinson
	1901	–	Georges Handly Knibbs
	1901	–	R. Henson Broadhurst
	1902	–	Achille-Adrien Proust
	1908	–	Henri Provensal
	1909	–	Inigo Triggs
	1912	–	A. J. Macdonald
	1925	–	Jules Courmont
	1922	–	Raymond Unwin
	1943	–	André Hermant
58° axis	1943	–	Gaetano Vinaccia (Paris, Rome)
19° Heliotermic axis	1908/1928	–	Augustin Rey, J. Pidoux & C. Barde (19° Paris)
	1930	–	Le Corbusier (1887-1965)
	1930	–	Edmond Marcotte & André Gutton
	1941	–	André Gutton
19° Heliotermic axis objectors	1943	–	Gaston Bardet
	1943	–	Gaetano Vinaccia
	1943	–	André Hermant
	1946	–	Robert Leroux
15°< To <20°	1887	–	Etienne Clément (latitude 0 to 30°)
15°< To <35°	1904	–	Léon Jaussely (Barcelona) a
-5°< To <45°	1928	–	Augustin Rey
0°< To <45°	1904	–	Paul Juillerat
	1945	–	Jean Lebreton
0°< To <60°	1921	–	Paul Juillerat
	1925/1934	–	Jean Raymond
60°< To <70°	1910/1937	–	Félix Marboutin
	1941	–	Gaston Bardet

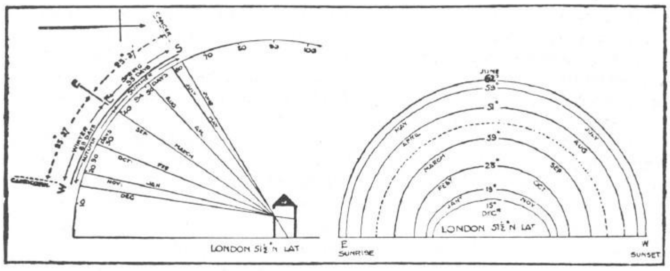

Figure 10: Raymond Unwin. Various Sun positions during seasons, latitude of London.

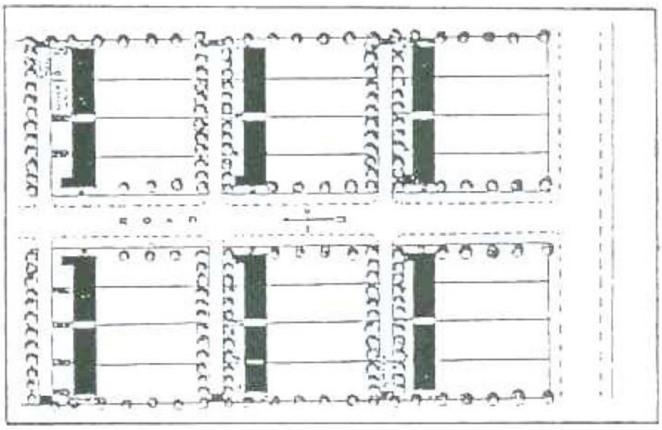

Figure 11: Raymond Unwin. Plan with main north-south main ways.

Source Figure 10 and Figure 11: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

Figure 12: Letchworth, England. First Garden City.

2.3.1 North-south orientation of roads (east-west exposure of façades)

The first group to advocate the above orientation and exposure appears towards the second half of the nineteenth century and is made up of physicians, engineers and a few architects. They espouse the ideas of Dr Adolphe Vogt (1885) of Berne, who claimed that "solar heat" would be uniformly distributed in homes as a result of the north-south orientation of roads (east-west exposure of façades). This particular orientation and exposure would, he insisted, provide a solar optimum with antimicrobial properties.

Vogt (1885) is cited in their research works by the Putzeys Brothers (1885), Dr Clément (1887), Trélat (1887) and Duchesne (1896) in support of their choice of the north-south axis. Dr Richardson (1876), in his utopia city model, Hygeia City[13], also lays out north-south-oriented streets.

Several French authors are equally enthusiastic supporters of this view, writers such as Juillerat & Bonnier (1904) for instance. The architect Provensal (1905/1908) notes that sunbeams are almost horizontal in Winter, oblique in Autumn and in Spring, whereas they are nearly vertical in Summer. According to him, the almost horizontal beams are the most valuable since they are penetrating and not very frequent in winter. Harzallah (Harzallah 2007) writes that Provensal, even though he claims to have a scientific approach, ignores the shading of these low beams by buildings, whose height must be studied. He also condemns the chequered American street system which would produce secondary roads perpendicular to north-south roads and consequently lead to an inadvisable exposure to the north. To him, buildings must be directed north-south axis in a way that allows the sun to scan destructively all bacteria-infested zones.

Courmont (1925) considers that this axis (north-south) would provide the maximum of sunlight and heat. The north-south axis is also favoured by Barde (1891), Juillerat & Bonnier (1904), Marcotte (1930), Raymond (1934), Besson (1946) as well as Leroux (1948). Leroux bases his preference on the study of the daily thermal alternation between both façades, tangible if the house is lightweight and lessened if the house is of heavier construction. The east-west axis would induce an unpleasant thermal imbalance all year long, whether the building is lightweight or heavy. On the other hand, Marcotte, even though he prefers the south façade for an isolated house, deplores the disadvantages connected with the north façade and recommends as a trade-off the north-south axis of lanes.

Vogt (1885) notes that in Berne (Switzerland) east-west streets have a lower mortality rate on the sun-exposed side. To create new districts, he recommends drawing main roads from the north to the south, whilst scaling their width in proportion to the height of the houses. Furthermore, transversal or equatorial ways must be very short and very wide. Trélat (1887), Clément (1887) and Besson (1947) agreed with Vogt's views.

Courmont (1925) also mentions the supporters of the north-south street orientation and those supporting the east-west axis. The latter seek the south façade for its larger sunbeam intensity. The English urban planner Unwin[14] (1909) highlights the disadvantages of the north exposure by creating a diagram showing London's latitude in order to defend his preference for east-west exposures (see Figure 10). He also presents a diagram of French origin, which illustrates main north-south ways, perpendicularly cut out by secondary ways (see Figure 11) and translates Howard's[15] ideas into reality (see Figure 12).

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[13] Richardson, B. W. (2006*). Hygeia: A City of Health*. Paris, Editions de la Villette.

[14] Unwin, R. (1909). *Town Planning In Practice : An Introduction To The Art Of Designing Cities And Suburbs*. London, Unwin.

[15] Sir Ebenezer Howard (1850–1928) is known for his publication Garden Cities of To-morrow (1898), which influenced urban planning throughout the world. During his lifetime two garden cities were founded, both in Hertfordshire: Letchworth (1903) and Welwyn Garden City (1920). They served as prototypes of the new towns organized by the British government after World War II. ©Encyclopaedia Britannica

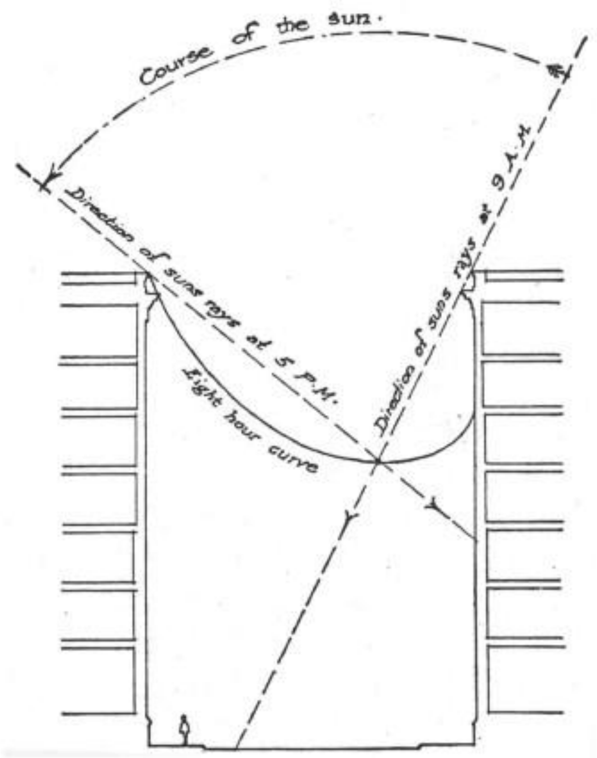

Figure 13: William Atkinson. Profile of a south-east–north-west oriented street facing north-west. The sunbeam directions are drawn for the summer solstice, latitude 42°0’ north.

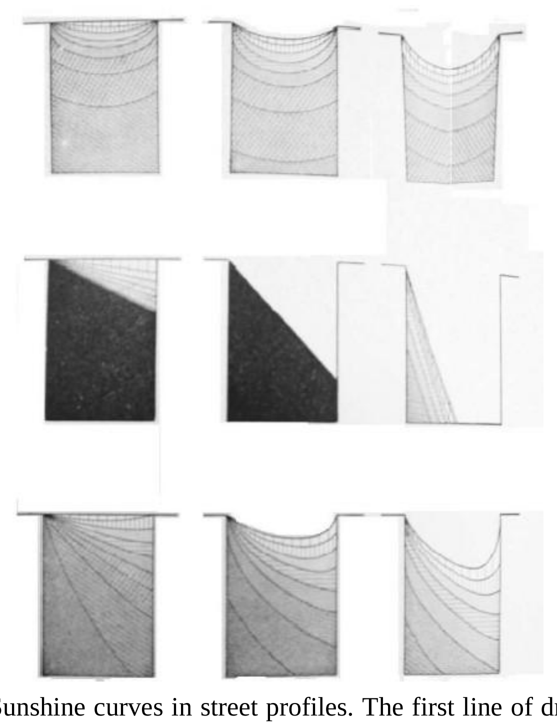

Figure 14: William Atkinson. Sunshine curves in street profiles. The first line of drawings represents north-south oriented streets; the second line corresponds to east-west oriented streets and the last line to streets oriented at a 45° angle starting from north; left-hand diagrams are given for the Winter Solstice, those in the middle for Equinoxes and right-hand ones for the Summer Solstice; values in grey shades are proportional to sunshine durations.

Source Figure 13 and Figure 14: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

2.3.2 East-west orientation of roads (Exposure of south façades)

The physicians, architects and engineers who supported the east-west orientation of roads (exposure of south facades) tend to be active at the beginning of the 19th century. In their experimentations to discover the benefits of north exposure, this second group finally concluded that the south exposure offered the best advantages.

Barde (1891) recommends this axis for the most imposing of Europe's buildings: first-class hotels, public buildings or high-scale Civil Service buildings. They would have a main façade (reception desks, important offices, elegant reception rooms) and another secondary one (kitchens, staircases, outbuildings, secondary offices). For very hot countries, Barde advocates the north exposure for the main façade. Duchesne (1896) advises south and north-exposed façades solely in southern countries.

Proust (1902) advises this axis to avoid the inconveniences of north exposure. He also points out that the north orientation would be preferable if direct sunlight was not desired. Hermant (1943) relied heavily on Marboutin's works (1910/1937). He concludes that east-west-axed streets are the most properly sunlit. André Hermant was also the first architect to restore the north façade. Hermant presents, according to each space's function, and in order of preference, the proper orientation:
- bedrooms : south to east ;
- toilets : south to east ;
- kitchens : south, south-east, east, north-east, north ;
- dining rooms : south, west, north ;
- storerooms, pantries : north-east, north, north-west ;
- living rooms : south to south-east, alternatively south-west.

Leroux (1948) supports south and north exposures for hot climates; in cold climates of the boreal zone, south-oriented façades. However, Leroux also notes that in temperate climates, it is humidity that makes the rooms unhealthy, rather than the lack of sunshine. He explains that a room facing north is desirable as long as it is dry and properly heated in winter.

Stübben (1890), Juillerat (1921) and Raymond (1933) totally reject the east-west axis because of the disadvantages of the north façade. Raymond adds that in temperate climates, one has to avoid east-west roads because their south sides would receive insufficient sunlight.

2.3.3 Diagonal orientation of roads

Finally, some authors put forward less radical solutions that allow for differing orientations and compromise. They generally show a preference for an orientation of 45 degrees. However, some of them, such as Besson (1946), have suggested the possibility of a "turning house" in order to solve the problem of the "correct" façade orientation.

Clément (1887), Stübben (1890), Atkinson (1894, cited by G. H. Knibbs in 1901) or Unwin (1922) propose an orientation of 45° to uniformly distribute direct sunlight over all façades. Whereas Proust (1902), Provensal (1908) and Courmont (1925) recommend this direction to avoid at all costs the deep cold that the north façade would provide and the west because of its rain and winds. For Hermant (1943), the point is to have equivalent façades from an heat point of view.

The Boston architect, William Atkinson (1894), sets out an original method for Boston's latitude (42° north) which makes it possible to estimate correctly the ratio between orientations and street outlines through the development of sunshine duration curves in various street profiles with various orientations. (see Figure 13 and Figure 14).

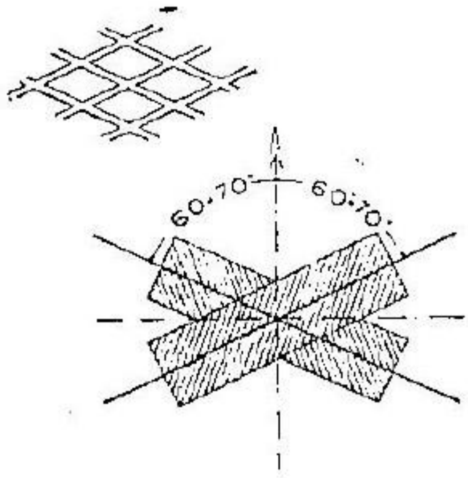

Figure 15: Félix Marboutin. Angle comprised between 60° and 70° on both sides of the north-south axis.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

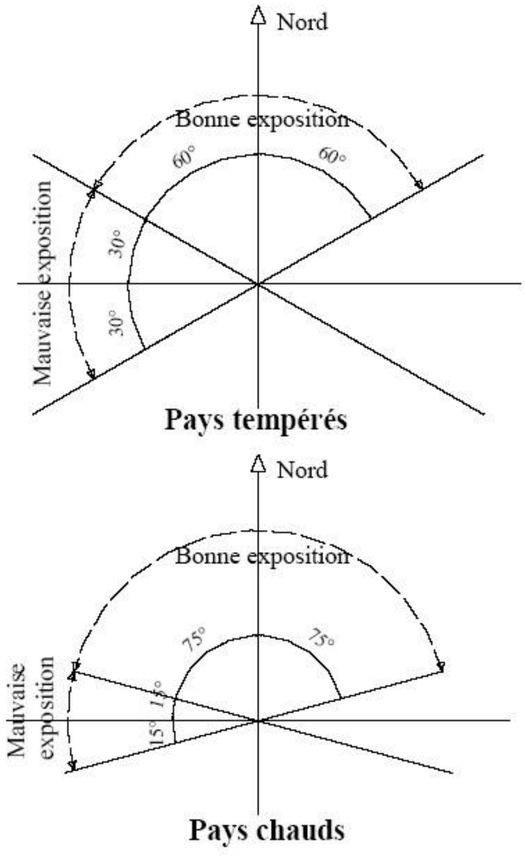

Figure 16: Amina Harzallah. Sketch reproducing Jean Raymond's diagram showing the best street orientations.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

2.3.4 Other orientation of roads

Some authors suggest different street orientations angles. Clément (1887) varies them from 15° to 20° as a function of latitudes between the Equator and 30°. His goal was to produce an insolation that was sufficient in Winter and not too excessive in Summer. De Souza (1908) notes that Jaussely (1904), in his extension plan of Barcelona, considered the best orientation would be north-south with a deviation left or right of the meridian from 15° to 35°.

These angles vary as a function of latitude and location. It seems that with a 30° deviation starting from the north-south axis, the sunlight will last at least an extra hour – an increase of 2 hours to 3 and a quarter hours. Juillerat (1904/1921), in his search for a maximal sun penetration and to avoid the north exposure, proposes a range of angles between 0° and 45°, later between 0° and 60°.

To Marboutin, the more beneficial exposure is at an angle between 60° and 70° of the meridian. Consequently, his street plans form a lozenge-shaped draughtboard (see Figure 15).

Having opted for an upper limit angle of 66 grades (approximately 60°), the engineer, Jean Raymond (1925/1934), suggests different orientation choices for temperate, hot and tropical climates. Figure 16 illustrates his views. Harzallah (Harzallah 2007) considers that Raymond's findings are sufficient to guide urban planners towards the optimal orientation of the city streets.

Lebreton (1945) gives a full range of orientations from 0° to 45° as a function of space use:
- 25° max. deviation toward south–south-east: best living rooms, including kitchen;
- 45° max. deviation toward south-east: all rooms;
- 45° max. deviation toward south-west: acceptable for daytime rooms, but unfavourable for bedrooms.

According to Lebreton, all other orientations must be avoided for daytime or nighttime residential rooms.

To conclude, Vinaccia (Vinaccia 1943-52) recommends adhering to the orientation he designated as *Equisolare*. The latter ponderates sunlight homogeneously for the four exposures (see Table 5 and Figure 17). To validate his results, he compared surface energy obtained with the heliothermic axis[16] to the *Equisolare* orientation, calculated at 48° for the city of Paris.

Table 5: Surface energy (calories/m²) received by exposed façades

Heliothermic orientations	**Winter solstice**	**Summer solstice**
Façade parallel to the axis	460	3000
Façade perpendicular to the axis	1200	1900
Total	**1660**	**4900**
Equisolare Orientation	1100	2000
Façade parallel to the axis	850	1600
Total	**1950**	**3600**

[16] See item 2.3.5

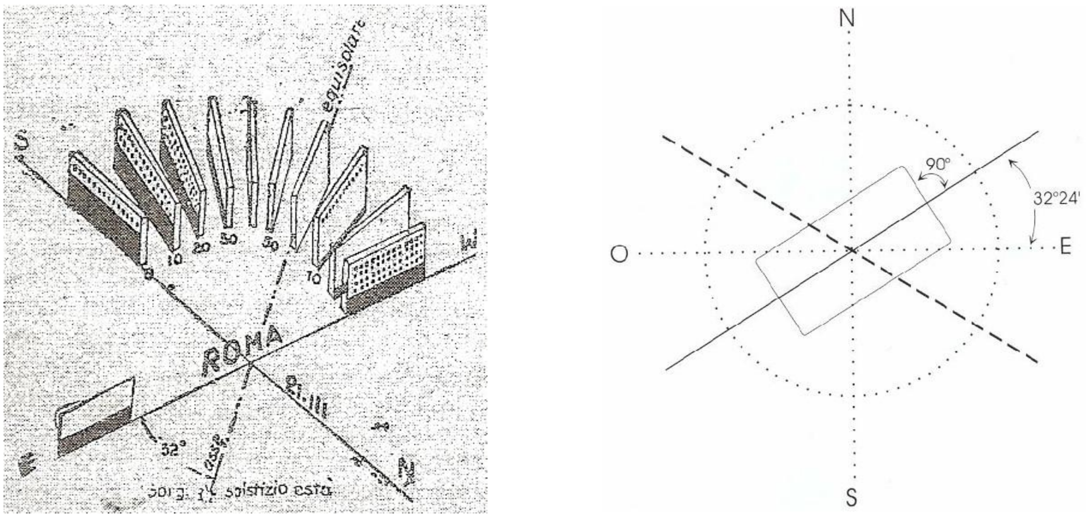

Figure 17: Gaetano Vinaccia. Study of facades in Rome according to orientation of roads (H = L, equinox); Equisolare orientation provides more sunshine.

Source: Vinaccia, G. (1943-52). *Per la Città di Domani, Volume I: Come il clima plasma la forma urbana e l'architettura -la sanità e l'igiene cittadina*. Roma, Palombi.

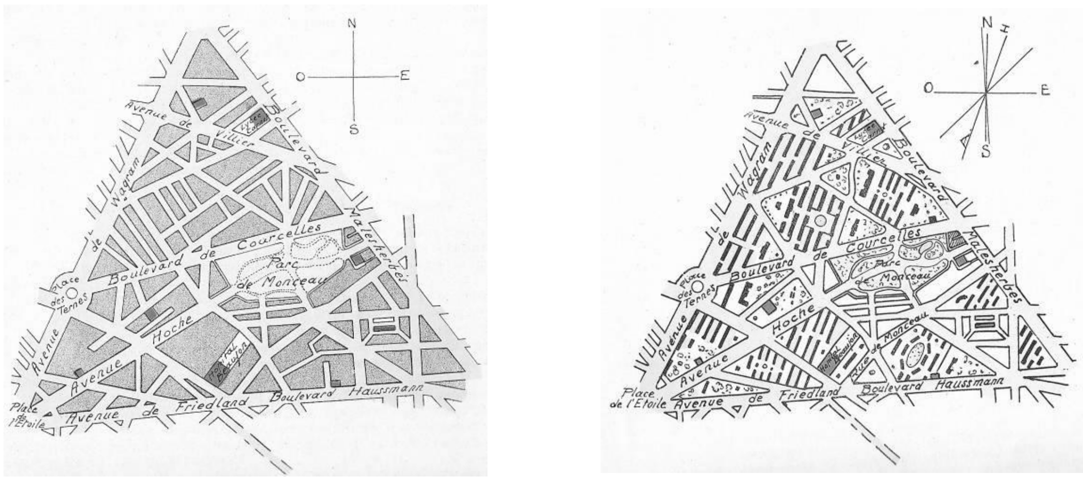

Figure 18 left and right: Augustin Rey. Heliothermic district reorganization in Paris. Main thoroughfares, squares, parks and all public buildings are unchanged. Lands are laid out following parallel bars directed on the heliothermic orientation. Closed courtyards are removed and garden surfaces are widened.

Source: Rey, A.-A., Pidoux, J., Barde, C. (1928). *La science des plans de villes : ses applications à la construction, à l'extension, à l'hygiène et à la beauté des villes : orientation solaire des habitations*. Lausanne, Payot.

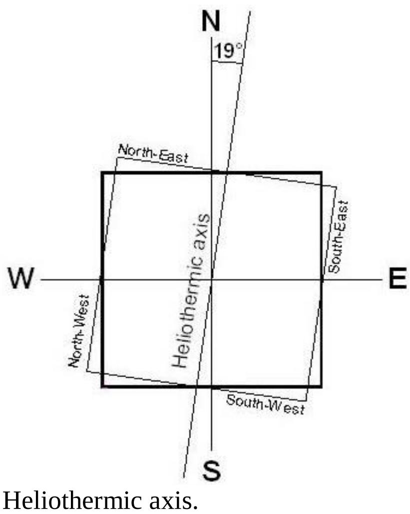

Figure 19: Heliothermic axis.

2.3.5 Heliothermic axis

Rey, Pidoux and Barde (Rey, Pidoux et al. 1928) suggested one of the most emblematic theories of the movement in their book La Science des plans de villes showing applications of city reorganization according to the heliothermic axis (see Figure 18).

The heliothermic unit was defined as the product of sunshine hours with thermal degrees. Gaston Bardet states, in the Revue Techniques et Architecture (Massé 1943), that this calculation is physically meaningless and that a temperature can be multiplied by a mass but not by a duration. The assessment of the heliothermic axis is made in the following way. The heat factor follows the light factor with a given delay, the thermal wave reaching its maximum in the afternoon, from 2 to 3 p.m., according to the season of the year. The thermal axis differs from the light axis by approximately 45° between these two extremes. The heliothermic axis, more or less at the bisecting line, is 19° north-east for Paris and varies moderately with the latitude and the climate of the location of interest (see Figure 19). According to its designers, this axis would bring a maximal annual solar radiation. The heliothermic theory caused intense controversy among urban planning theoreticians.

The engineer Marcotte (1930) as well as the architects Le Corbusier (1930) and Gutton (1941) fully adhere to the heliothermic axis. Certainly Le Corbusier contributed the most to Rey's theory by defining the heliothermic axis as "the framework of the city plan[17]" and by using it in some of his urban projects until 1945. During the third C.I.A.M in Brussels in 1930, he sets out his *La Ville radieuse* project: plates 3 and 4 were dedicated to building insolation. For building layout purposes, the principle he adopted is the heliothermic axis— incidentally, he never cited Rey, Pidoux or Barde. The "assessment principle" is given in plate 3. To Le Corbusier's mind, this plan should be the urban planner's first act and the first act of the authorities. A few years later, Le Corbusier sets this theory aside, without explanation. The first project for Marseille's housing unit in 1945 is directed according to the heliothermic axis, whereas in 1947, under Dourgnon's recommendation, the unit was directed exactly according the north-south axis.

Rey's theories were disputed by Bardet (1943), Vinaccia (1943), Hermant (1943) and Leroux (1946). Bardet in particular describes the disastrous influence that Rey had on his contemporaries in France and abroad, where numerous cities were directed according to the heliothermic axis appeared, and suffered from the highest temperature variations, precisely those of the east and west façades. Vinaccia (Vinaccia 1943-52) states that some naïve urban planners have wrongfully resorted to the heliothermic axis to justify "scientifically" their own urban design projects or simply to be "up to date". To conclude, Hermant and Leroux admit the relevance of the heliothermic axis, but outline the fact that it is not a "sine qua non" for urban planning.

2.4 Theory of building outlines and streets

An historic way of regulating building height is the proportion relative to street width. According to James Howard Kunstler (Kunstler 1996) the optimal aspect ratio based on human psychology lays between 1:1 to 3:1 (preferably closer to 1:1). With low buildings set far back from the street people feel isolated and vulnerable. With buildings that are too tall people feel uncomfortable surrounded by concrete, glass, and steel canyons.

Solar considerations played a crucial role in the definition of a street outline, as well as in the creation of the built front. There are two main methods leading to these recommendations: on one hand, through mathematical equations; on the hand, by the way of proportions derived from simplified building outlines, correspond to the aspect ratio in-between the heights of the façades and the width of the streets.

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[17] "*l'armature du tracé urbain*" in french in the text.

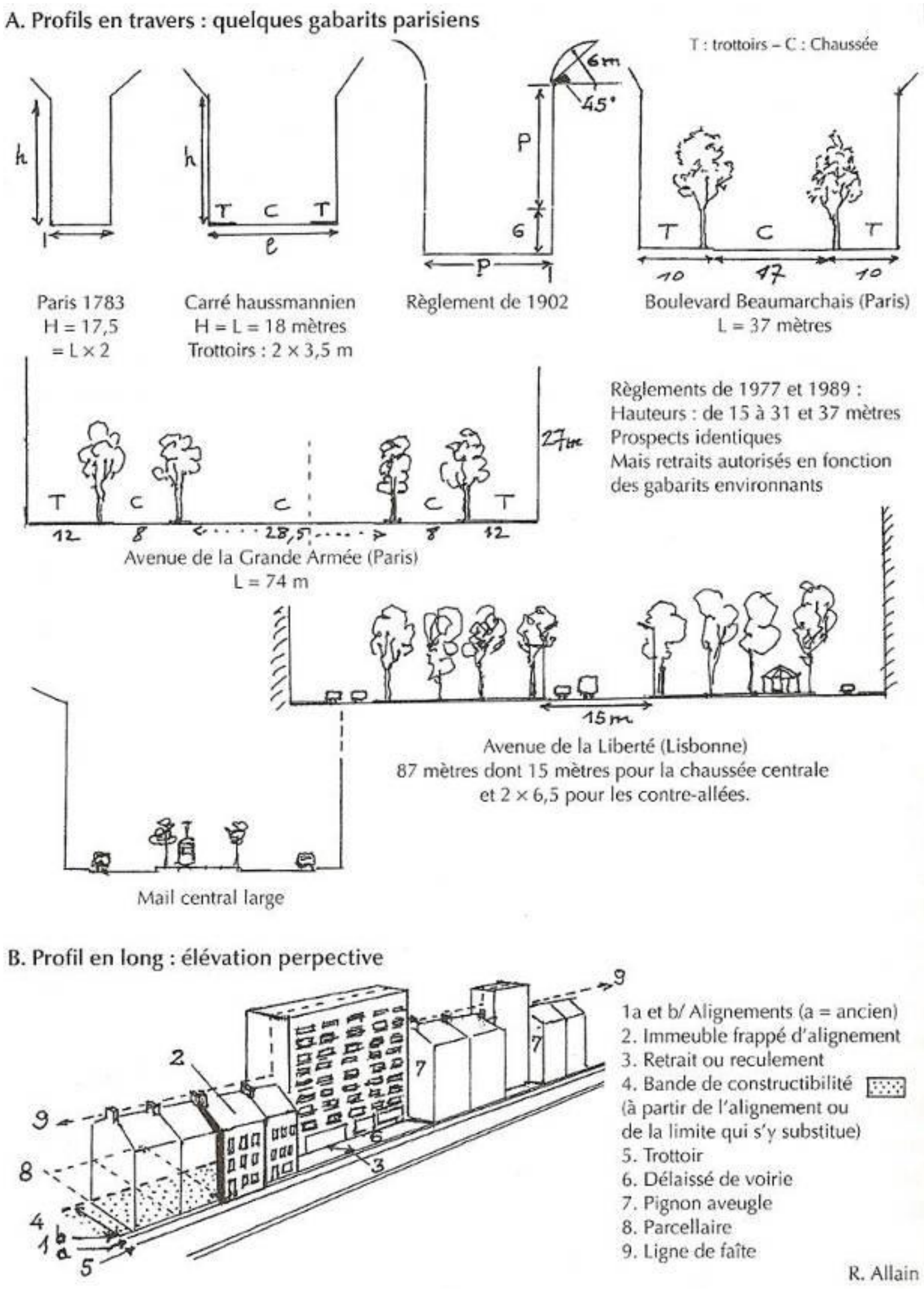


Figure 20: Streets profiles: A. Cross sections of some Parisian building outlines, B. Profiles along a perspective elevation.

Source : Allain, R. (2004). *La morphologie urbaine*. Paris, Armand Colin/SEJER.

2.4.1 Simplified building outlines

A large number of solar recommendations related to the ratio of building heights to the street widths was established. The building outline is the virtual volume that buildings must not exceed. Defined by the vertical height (starting from the wall plate) to the crown (attic volume), it is commonly expressed by the number of floors (*e.g.* ground floor+1, ground floor+4+attic). The rooftop can either be flat or variable-sloped. Height and building outline are most often determined by prospect rules[18] (*e.g.* Building height= Street width) and by the distance at the parcel boundaries (*e.g.* Street width = Building Height /2 ≥ 3m), except for common houses. Regulation can however be much more specific (see Figure 20).

The unhealthiness of the poorer districts increased dramatically. Many theories were suggested in order to improve their conditions together with concerted calls from the *hygienists* to increase the width of streets and to reduce the height of the façades. The first authors to become interested in the establishment of this ratio highlighted the need to link street widths to façade heights. They subsequently contented themselves with reporting the new regulations that had been enacted, which were rather a novelty at that time and which were certainly not sufficiently enforced and applied. A second step called for research into the refinement of this ratio and to the establishment of new regulations. These different theories of building outlines and streets have been summarized in Figure 21 and Table 6.

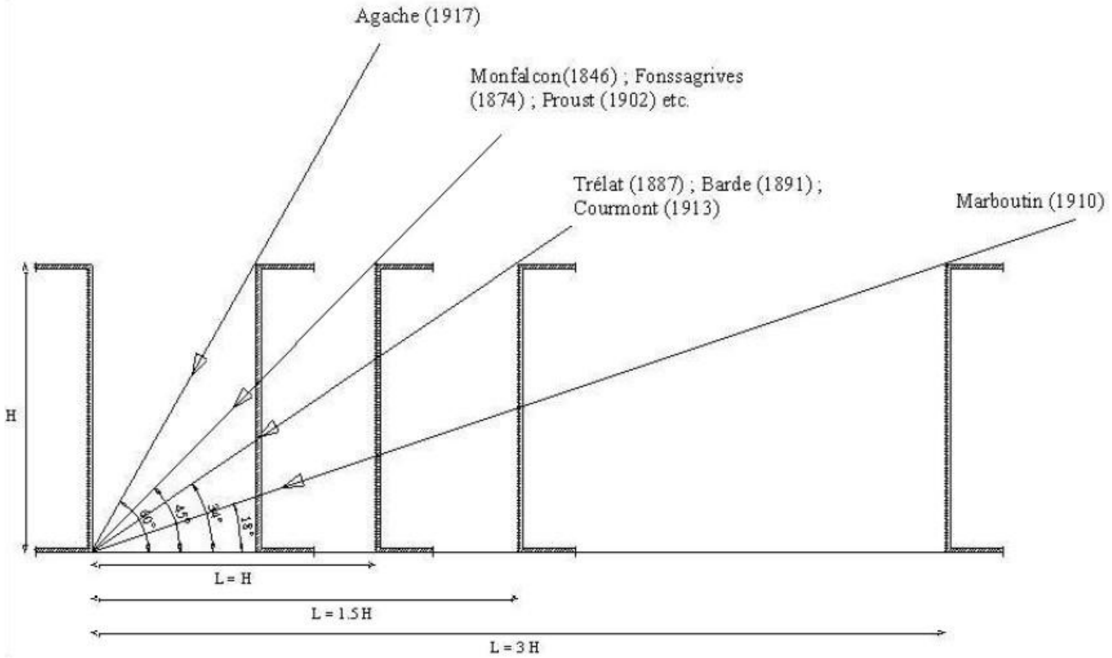


Figure 21: Juxtaposition of proposed building outlines and streets.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

Arguments put forward by authors recommending an aspect ratio equal to one (street width = façade height) systematically called for a proper airing and a proper insolation. Proust finds a social interest in maintaining this ratio, whereas Hénard proposes that the angle of the solar beams hitting the façade should exceed or equal 45°. Cloquet & Cobbaert assert that with a cast shadow arriving at a 45° angle one building does not shade another one. Juillerat’s objective is to bathe façades in sunshine from top to bottom for at least several hours a day. Gide suggests that this ratio varies as a function of latitude and solar elevation angle. Rey agrees with Gide and proposes a resizing of the streets according to this angle, which is considered as being the most active at 45° (see Figure 22 and Figure 23).

[18] Minimal distance between buildings authorised by street regulation, calculated by a satisfactory daylighting.

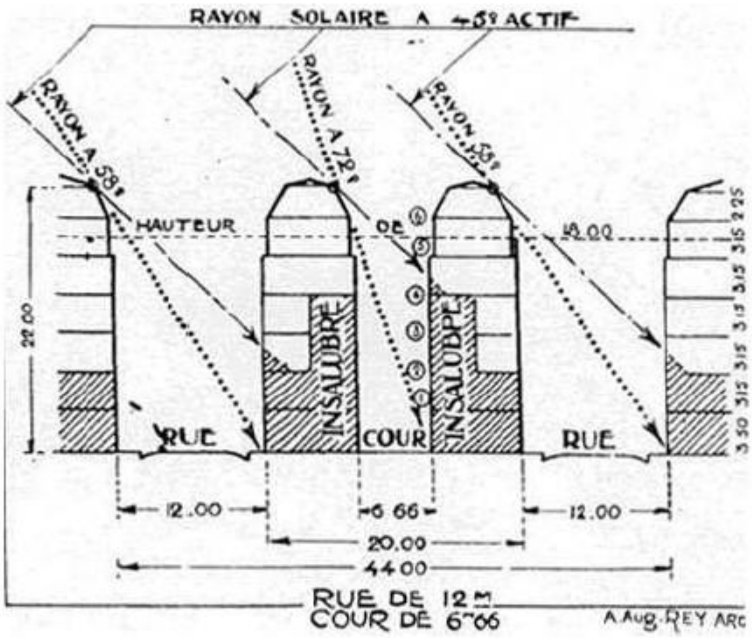


Figure 22: Augustin Rey. Figure showing the building parts not reached by 45° sunbeams, deemed therefore as unhealthy.

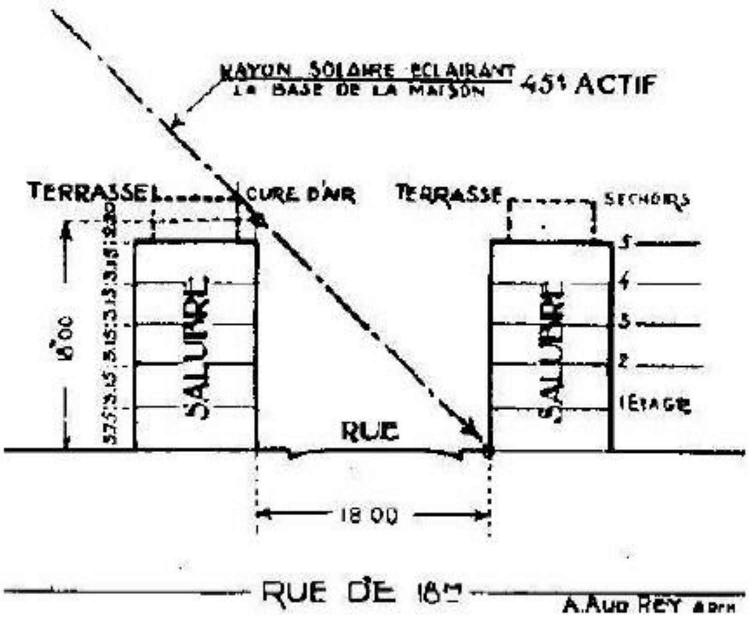


Figure 23: Augustin Rey sizes the streets so that 45° sunbeams hit the building bottoms, guaranteeing, if the street is correctly oriented, the housings' healthiness.

Source Figure 22 and Figure 23: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. Ecole *Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

Table 6: Street outlines theories

Building Height Vo Street Width Ratio			
Theories	**Years**		**Authors**
Street width = Building Height	1846	–	Jean-Baptiste Monfalcon &
	1846	–	Isidore-Augustin-Pierre de Polinière
	1874	–	Jean-Baptiste Fonssagrives
	1881/1902	–	Achille-Adrien Proust
	1903	–	Eugène Hénard
	1906	–	Joseph Stübben
	1913	–	Cloquet & Cobbaert
	1905/1921	–	Paul Juillerat
	1925	–	Charles Gide
	1930	–	Jean Raymond & W. Kharachnick
	1946	–	Albert Besson
	1946	–	Augustin Rey
Street width = Building Height Objectors	1885	–	Félix and Emmanuel Putzeys
	1887	–	Etienne Clément
	1910	–	Félix Marboutin
	1917	–	Donat-Alfred Agache
	1920	–	Léon Jaussely
	1945	–	Gaston Bardet
Street width = 1.5 Building Height	1887/1901/1905	–	Emile Trélat
	1891	–	Charles Barde
	1913	–	Jules Courmont
	1928	–	Augustin Rey
Street width = 3 Building Height	1910	–	Félix Marboutin
According to the latitude: **Street width / Building Height ratio** **Latitude 40° : Street width = 0.8 Building Height** **Latitude 60° : Street width = 2 Building Height**	1948	–	Robert Leroux
Mathematical formulations	1829	–	Anton Von Camerloher
	1885	–	Adolphe Vogt
	1887	–	Etienne Clément
	1902	–	Henri Bertin-Sans
	1908/1928	–	Augustin Rey
	1910	–	Félix Marboutin
	1913	–	Jules Courmont
	1948	–	Robert Leroux
Streets width according to the building heights and the orientation	1885	–	Adolphe Vogt
	1887	–	Emile Trélat
	1887	–	Etienne Clément
	1891	–	Charles Barde
	1908	–	Augustin Rey
	1930	–	Edmond Marcotte
Several indicative methods	1909	–	William Atkinson

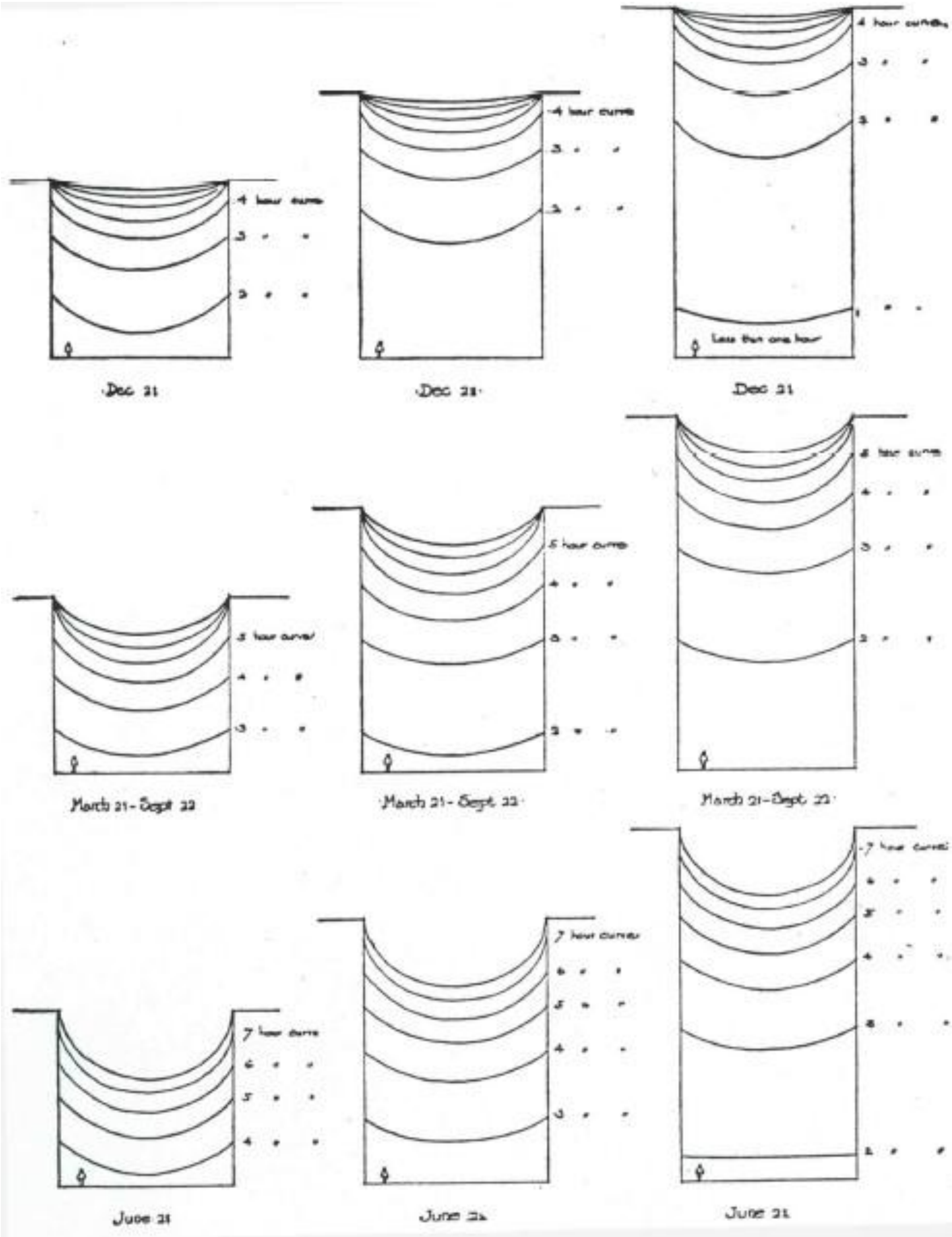


Figure 24: William Atkinson. Sunshine durations in north-south orientated street profiles. From left to right: aspect ratios (façade heights to street widths) equal 1, 1.5 and 2 respectively.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

This ratio provoked several protests. Jaussely strongly opposed this standardizing and non-founded scientifically prescription. He claims that it is invalid because it does not take into consideration latitude and street orientation. Bardet writes that this building outline determination as a function of the 45°-angled sunbeams is erroneous because it ignores the sun's own movement. Furthermore, the building outline including these particular sunbeams only guarantees the complete insolation of the façades for two hours from April 20th to August 10th.

Harzallah (Harzallah 2007) agrees with the opponents of the "L=H" outline: calculating an aspect ratio on the basis of the 45° or 60° sunbeams inclination prevents all of the wintertime sunrays from reaching façades, which would exclude valuable microbicidal sunshine. Moreover, these authors do not take into account the seasonal variations of modulable solar insolation.

As regards the 1.5 aspect ratio, Trélat is inspired by Vogt's procedure, mentioned in Point 2.4.2, to create a maximal daylighting as deep as the room interior. In order to achieve that, he advises that, for any street width, the construction heights should not exceed the incline line of 30°. Trélat describes another indirect daylighting source: the reflection of the opposite walls, constituting a backup of lower magnitude than direct daylight. These reflections would be degraded by material darkened by time or dirtiness. Harzallah (Harzallah 2007) writes that even if Trélat follows a seemingly scientific and rational procedure by setting the road outline as a function of solar elevation angles, he still does not take into consideration the fact that this angle varies in the course of time and seasons.

For some authors, one of whom is Barde, this proposal should go hand in hand with the façade height variation and with the façade orientations. In addition, he advises against constructing very high buildings and streets that are too wide, as follows:
- If Height = 7 → 8 metres, Street width = 8 → 10 metres;
- If Height = 16 metres, Street width = 20 metres.

Finally, Atkinson gives a correct relationship between street orientations and outlines. He supplies ways to accurately measure the sun-related consequences of a given outline with a given orientation (see Figure 24).

More recently, Goulding (Goulding, Lewis et al. 1986) explains that one has to identify the correct slopes and the effects of solar gains in accordance with the opposite buildings that provide a proper solar access during the heating season. Sloped south-directed terrains are likely to be made denser than flat ones. In southern Europe, sloped west-directed terrains are less adequate as far as energy efficiency is concerned (see Figure 25).

While for Ganz (Ganz, Muller et al. 1990) the inter-building distance must be adapted to the street orientation. Figure 26 shows the influence of this distance on useful solar gains during the heating season. The enforcement of proper distances also has a positive effect on the daylighting of rooms.

Using numerical techniques, Klemm (Klemm and Heim 2009) analysed the wind flow pattern and the sun distribution on an east façade located in a narrow passage in Lodz (Poland) shown on Figure 27. If one assumes that the height of the buildings and the width between them are identical (street width=height), then the solar penetration will decrease as the width between the buildings is reduced (about 25% for ½h and 50% for ¼h). The results for the heating season (September through April in this study) showed that there was relatively superior insulation in Case C, where the existing building was more exposed on the east side. Conversely, in Cases B and D the east façade received only half as much sunlight. From May until August, there was little difference in the amount of direct solar energy received by the four cases. In each case (A, B, C and D) there was a noticeable shading effect throughout the year. Once again, Case C received higher sun penetration from the south-east during the Winter months.

In conclusion, except for the Summer months where there is little difference in all four cases, Case C is far more conducive than the other three to solar penetration for the remainder of the year.

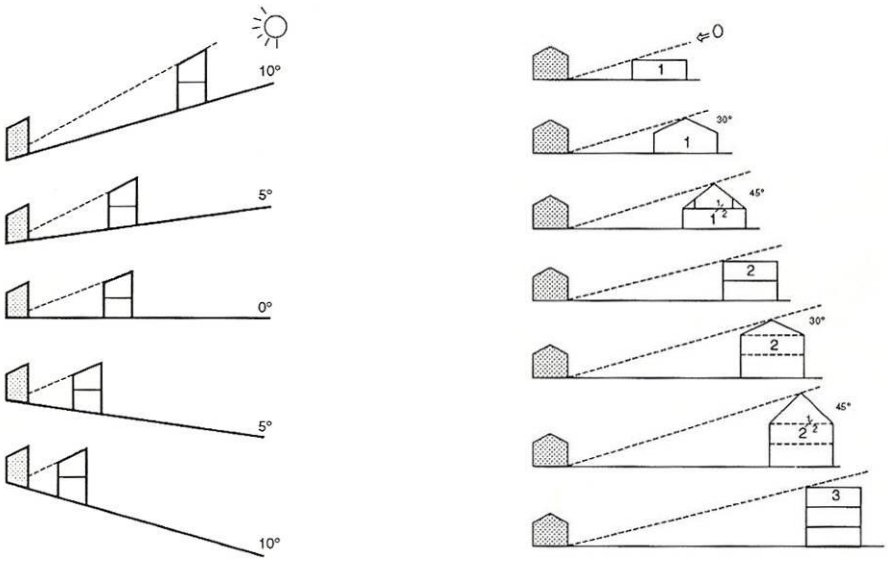


Figure 25: Solar access for different slopes and development densities (left) and the effect of neighbouring building on solar access (right).

Source: Goulding, John R., Lewis, J. Owen, Steemers, T. C. (1986). *Energy in architecture: the European passive solar handbook*. London, Batsford for the Commission of the European Communities.

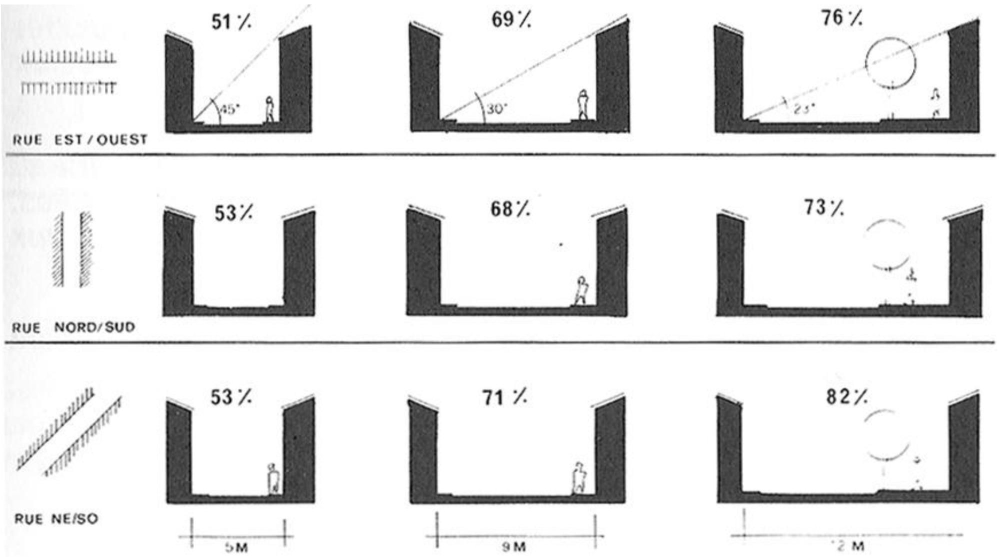


Figure 26: Useful solar incomes during the heating season of an accommodation as a function of the proximity of the opposite building. Basis : 100% for a two-level building without any opposite building (6.8 m² on main façade, 3 m² on other façade).

Source : Ganz, C., Muller, A., Gay, J.-B., Kohler, N., Roulet, C.-A., Scartezzini, J.-L. (1990). *Le Soleil, Chaleur et lumière dans le bâtiment*. Zürich, SIA.

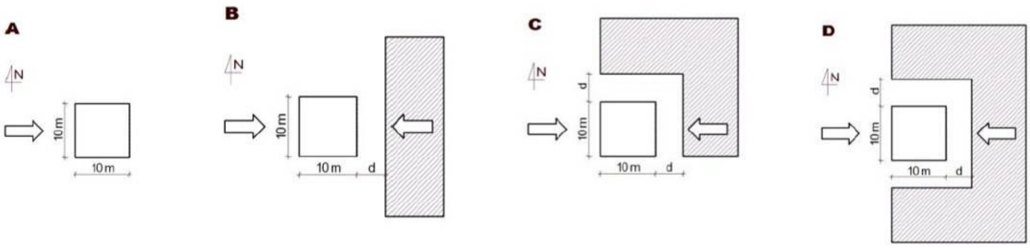


Figure 27: Analysed cases of main building and its surroundings.

Source: Klemm, K., Heim, D. (2009). Wind flow and sun accessibility in narrow spaces between buildings. In *Proceedings CISBAT 2009*, 2-3 September 2009, Lausanne.

2.4.2 Mathematical formulations

The mathematical formulations of the problem reflected a more scientific approach to the question. Some authors devised mathematical formulae that mainly correspond to the proposals of Von Camerloher (1829), Vogt (1885), Dr Clément (1887), Bertin-Sans (1902), Rey (1908/1928), Courmont (1913), Marboutin (1910) and Leroux (1948). Coumont's and Bertin-Sans' proposals correlate the street orientation and the incidence angle of sun beams, whereas Marboutin sought to avoid the orientation factor. Most authors were inspired by a theory put forward by Dr Adolphe Vogt from Berne (Switzerland). Harzallah (Harzallah 2007) writes that Dr Vogt was the first to have expounded and definitively resolved the solar radiation problem for houses. Vogt puts forward a well-developed formula which integrates several variables in order to assess for any given location the street width suitable for the house insolation. He makes this value dependent on the latitude and orientation. In short, Vogt emphasizes the sunbeams' incidence angle in the place of interest and street direction. Table 7 summarizes the values assessed for east-west and north-south streets. Vogt applies his theory to suggest layouts of north-south-oriented street blocks cut through by infrequent and wide equatorial crossroads and narrow meridians.

Table 7: Synthesis of Adolphe Vogt's recommendations

Rules	**Latitudes**	**East-West Streets**	**North-South Streets**
Street width / Building Height = sin (30° + δ) cotg α	Under 40°	H : L = 1 : 1,3263	H : L = 1 : 2,2971
	Under 45°	H : L = 1 : 1,7121	H : L = 1 : 2,9654
L : Street width	In Berne	H : L = 1 : 1,9243	H : L = 1 : 3,3333
H : Height of the neighbouring houses	Under 50°	H : L = 1 : 2,3778	H : L = 1 : 4,1184
δ : Direction of the street from North	Under 55°	H : L = 1 : 3,8238	H : L = 1 : 6,6230
α : Incidence angle of the sun rays	Under 60	H : L = 1 : 9,5027	H : L = 1 : 16,4591

Von Camerloher (1829) also resorts to mathematical methods to calculate the façade height in relation to the street width, and uses the sun elevation angle to assess this aspect ratio. Harzallah (Harzallah 2007) agrees that von Camerloher follows a logical and consistent procedure, but that he was wrong about the maximal elevation angle of sunbeams at Equinoxes for Munich's latitude (48°9' instead of 41°51').

Clément (1887) refers to Vogt, but does not mention the formula relating street length and building heights. He puts forward his own rule and comes to similar conclusions, as far as latitudes exceeding 40° are concerned: he suggested the relation described in Table 8 and Figure 28. To this, he added a supplementary element that is not in Vogt's formula. Moreover, he proposes 27-metre-long streets for 20-metre-high buildings to allow the penetration of sunbeams inside spaces up to a height exceeding that of a human.

Table 8: Synthesis of Clément's recommendations

Latitudes	**Rules**	**Inspirations**
No indication	Street width = Building Height × tang Z × sin (ϴ + y) L : Street width H : House height Z : Solar zenith angle (90° – solar altitude angle) ϴ: Gives a measure of time (arc which the Sun will have to scan before crossing meridian) y : Direction of the street from North	
> 40°	Multiply North-South streets (more than East-West streets) that will be much broader than façades will be high	Adolphe Vogt
Between 0° et 30°	Streets tilted from 15° to 20° on the meridian, deeper than broad (sufficient insolation in winter, not excessive in summer)	

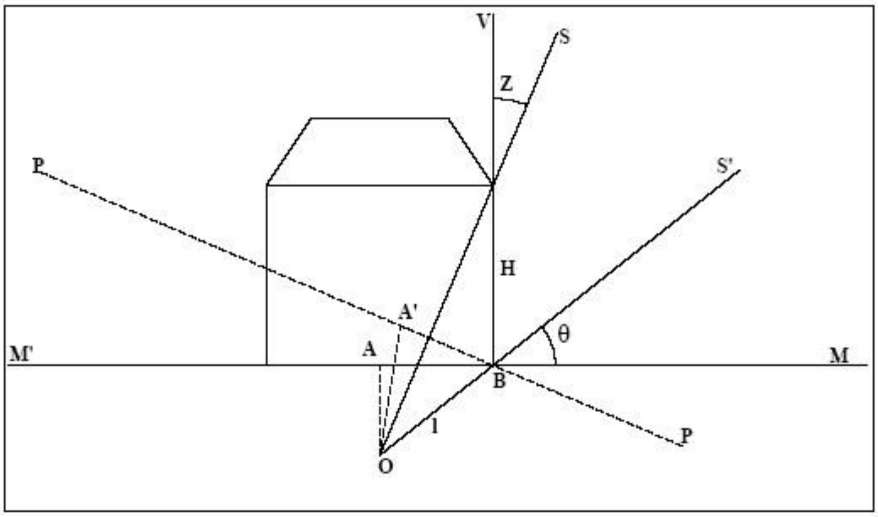


Figure 28: Amina Harzallah. Diagram based on Clément’s formula.

Source Tables 7, 8 and Figure 28: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

LATITUDE	ORIENTATION PRÉFÉRENTIELLE DES FAÇADES PRINCIPALES	DÉGAGEMENT DES FAÇADES ET OBSERVATIONS .	COEFFICIENT DE DÉGAGEMENT
ZONE POLAIRE BORÉALE au-dessus de 66°N	Indifférente (dépend de la provenance du vent régnant)	Pour l'hiver, la demeure doit être enterrée.	⩾ 3.0
de 66°N à 50°N	Au Sud ou au S.-E., ou S.-O. (locaux de travail au Nord)	Les bâtiments ne doivent pas se porter ombre mutuellement.	2,0
de 50°N à 42°N	Indifférente (dépend du vent régnant, du site, de la pluie, etc. Locaux de travail au Nord)	Aux équinoxes et en été, les bâtiments ne doivent pas se porter ombre mutuellement.	1,5
de 42°N à 23°N	Au Nord ou N.-O., ou N.-E. (habitations comme locaux de travail)	Les bâtiments doivent se porter ombre mutuellement.	⩽ 1,0
de 23°N à 23°S	Façades principales au Nord ou au Sud (habitations comme locaux de travail)	Climats constants, humides, pluvieux, impliquant la maison éolienne.	3,0 à 4,0
		Climats intermédiaires assez inconstants, n'impliquant pas la maison éolienne.	1,0
		Climats très secs, très inconstants des régions sahariennes : maison enterrée.	< 0,5
En dessous de 23°S	Au Sud ou S.-E., ou S.-O. (habitations comme locaux de travail)	Les bâtiments doivent se porter ombre mutuellement.	⩽ 1,0

Figure 29: Robert Leroux (1951). Table setting out clearance coefficient according to latitudes and orientations.

Source : Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

To Rey (1908), façade heights, street widths and orientations are mutually dependent factors. By taking street orientations into consideration and using his own method, he agrees with Dr Vogt. Harzallah (Harzallah 2007) noting that Rey, through his procedure, addresses sunshine durations of the street, rather than those of the façades. Furthermore, the aspect ratio (Street width = Building height) is approximately identical for buildings with varying heights and orientations. In 1928, Rey sets this aspect ratio to 1.5 and varies it as a function of the location. Deschamps in particular (1930) questions the rule by which a façade should receive sunrays in winter for at least one hour per day, which to him, is irrelevant.

The engineer Leroux (1948) differed from other authors by assessing the façades' clearances[19] in a way to guarantee three factors: the solar, daylighting and natural ventilation potentials. He recommended that façade clearances be 1½ higher for latitudes between 42° and 50°. Switzerland fits into this range. This ratio varies according to latitudes. Orientation factor are not considered in the ratio between street lengths and façade heights (see Figure 29).

In 1952, Leroux puts side by side two approaches that had a significant impact: namely Rey's (gnomon-like solar diagram) and Marboutin's theories (Street width = Height× cotg(h) × (sin (α – t))). Leroux reports that Rey searched for the highest sunshine hours without considering its quality or the thermal aftermath of his device.

More recently, the pioneering study of Nunez (Nunez and Oke 1976) shows, through measurements of long-wave radiative flux divergence on calm, cloudless days, the importance of reflections occurring in the urban canyon due to the its three-dimensional arrangement (see Figure 30).

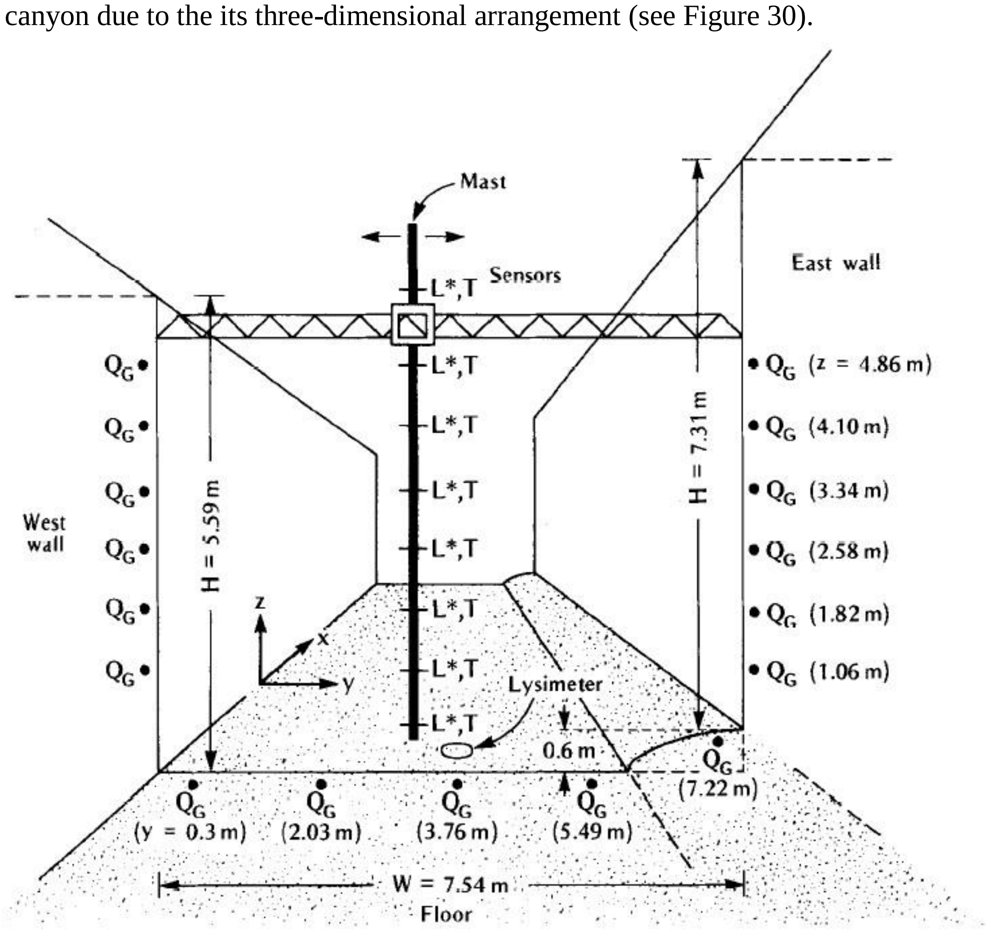


Figure 30: Experiment lay-out, dimensions and coordinate system at the canyon cross-section.

Source: Nunez, M., Oke, T. R. (1976). Long-wave radiative flux divergence and nocturnal cooling of the urban atmosphere. *Boundary-Layer Meteorology*, 10 (2): pp. 121-135.

[19] Distance between façades.

Aida (Aida and Gotoh 1982) applies a Monte-Carlo method to determine the effective albedo[20] emerging from a north-south street canyon located on the Equator (Marunouchi area in Tokyo). He then recommends to control the urban albedo through a canyon width which should be about twice the block width (W1/W2 = 1/2), if the aim is to design a city absorbing as much solar radiation as possible (see Figure 31). In this case it may be more desirable to introduce a seasonal change in surface reflectivity in some climates. This model may be applied to an urban model situated at higher latitudes assuming that the canyons simply become deeper when the sun is lower.

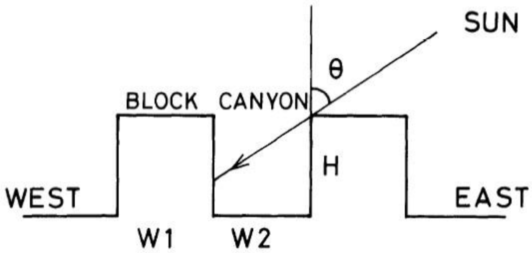


Figure 31: Urban block-canyon model and an illustration of incident radiation.

Source: Aida, M., Gotoh, K., (1982). Urban albedo as a function of the urban structure — A two-dimensional numerical simulation, Part II. *Boundary-Layer Meteorology*, 23(4): pp. 415-424.

Sailor (Sailor and Fan 2002) shows that for four distinct urban land use categories (see Figure 32) the nadir-view albedo (NVA) typically underestimates daily solar radiative loads by 11–22%, depending upon the land use (Monte Carlo style simulations). The mean albedo for these categories was found to range from 0.13 to 0.17. He then suggests, depending upon the level of desired accuracy, that a suitable estimate for albedo of all urban categories is 0.15 ± 0.02. There has been a slight decrease in albedo with the road ratios (1% variation for a variation of H / W between 1 and 3). On the other hand, the sensitivity in albedo for roofs is more important: 7% change in the effective albedo of an urban landscape for a variation in albedo roofs of 10%. Finally, the heterogeneity of the building heights tends to increase the albedo. Models that represent regular and uniform buildings overestimate the impact of geometry in urban areas that are very heterogeneous.

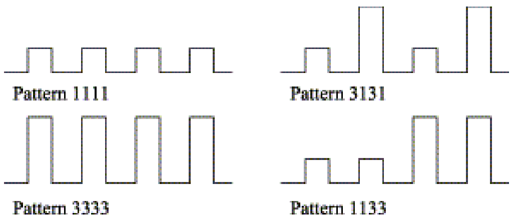


Figure 32: Pattern scenarios for one- and three-story buildings used in this study. Patterns for one- and two-storey configurations are analogous.

Source: Sailor, D., Fan, H. (2002). Modeling the diurnal variability of effective albedo for cities. *Atmospheric Environment*, 36(4): pp. 713-725.

Ng (Ng 2004) found that an irregular (instead of a uniform) skyline could enhance the daylight of buildings by 20-30% in high density and high rise sites (Ng 2004). His results were achieved by means of CFD and computer lighting simulations. In fact, he would use these findings to design a graphical tool, UVA (Unobstructed Vision Area), which can roughly determine the vertical daylight factor on buildings. UVA relates the height of the building with the gaps between them.

As mentioned in Section 2.3, street canyon orientation (not only the H/W ratio) is frequently a crucial factor in the solar aspect of urban design. In Figure 33, Bourbia (Bourbia and Awbi 2004) demonstrates

[20] The albedo of an object is the extent to which it diffusely reflects light from the Sun. It is therefore a more specific form of the term reflectivity. Albedo is defined as the ratio of diffusely reflected to incident electromagnetic radiation. It is a unitless measure indicative of a surface's or body's diffuse reflectivity.

by computer simulations of direct solar radiation within street canyons not only the effects of the H/W ratio but also those of the orientation at latitude 33°N.

The findings from this study may be summarised as follows:
- in Summer and Winter at all orientations the shading fractions increase with increasing H/W ratio;
- in Summer higher floor shading fraction is obtained in north-south streets than in east-west streets - and vice versa in Winter;
- the performances of diagonal streets (i.e. northeast-southwest and northwest-southeast) always fall between the performances of the opposite cardinal streets.

The results of wall shading fraction is similar to that of floor shading. The exception to this rule is that in Winter, the diagonal streets have lower shading than all the others. According to Bourbia, this is due to the coincidences of diagonal orientations with sunrise and sunset azimuth angles.

Bourbia concludes that the most favourable urban canyons, in terms of solar conditions, are north-south canyons with low H/W ratio (between 1 and 2); east-west orientations should be avoided as it permits high solar penetration in Summer and blocks solar access in Winter.

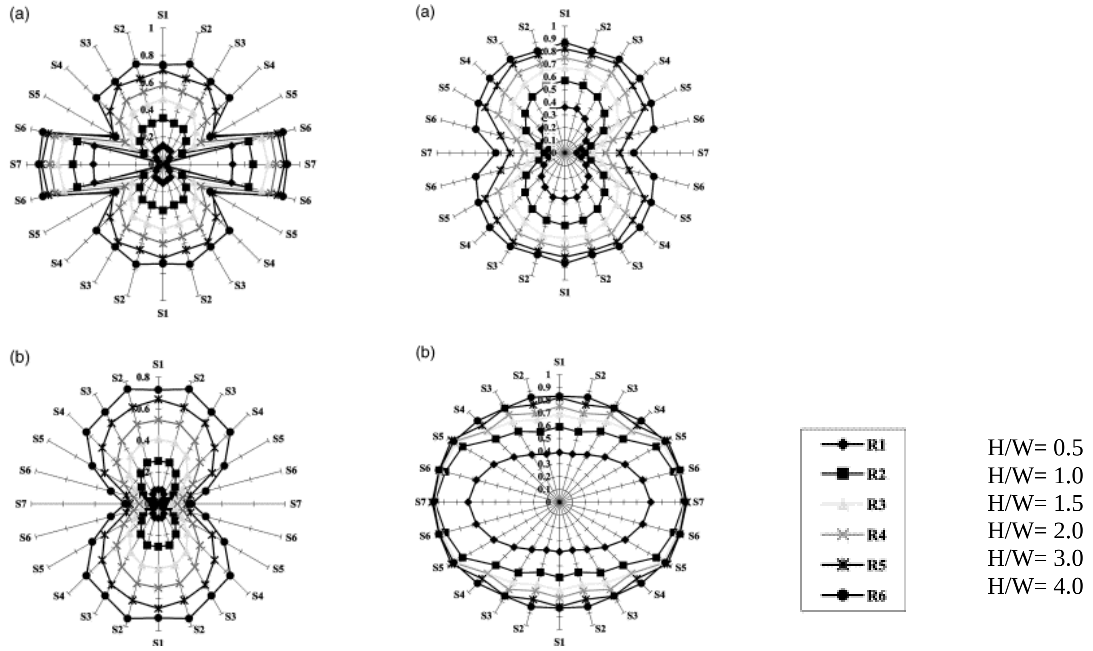


Figure 33 : Average monthly walls shading fraction for street orientation of 15° steps from the north (S1) to the east and west (S7) (left) and average monthly floor shading fraction for street orientation in steps of 15° from the north (S1) to the east and west (S7) (right).

Source: Bourbia, F., Awbi, H.B. (2004). Building cluster and shading in urban canyon for hot dry climate, Part2: Shading simulation. *Renewable Energy*, 29: pp. 291–301.

Cárdenas-Jirón (Cárdenas-Jirón 2009) has studied energy performance in urban planning using a wide range of methodology. Her use of Townscope, described in Section 2.7, focussed on the Winter months in the district of La Florida in Santiago City. With an orientation of 33°S – 70°W there are two distinctive urban fabrics:
- Block city model tends to have aspect ratios lower than 1;
- Garden city model tends to have aspect ratios larger than 1.

Once again, orientation proves to be a key factor. In fact, she concludes that the energy performance of the urban fabric depends largely on orientation, H/W ratio and irradiance.

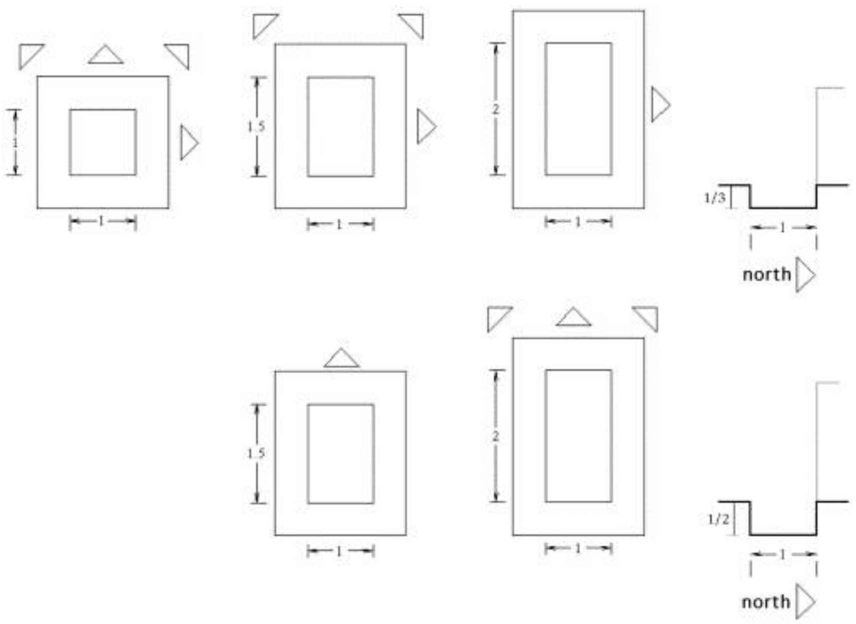


Figure 34: Recommended profile for different urban squares according to their proportion and orientation (32°North Latitude).

Source: Yezioro, A., Capeluto, Isaac G., Shaviv, E. (2006). Design guidelines for appropriate insolation of urban squares. *Renewable Energy*, 31(7): pp. 1011-1023.

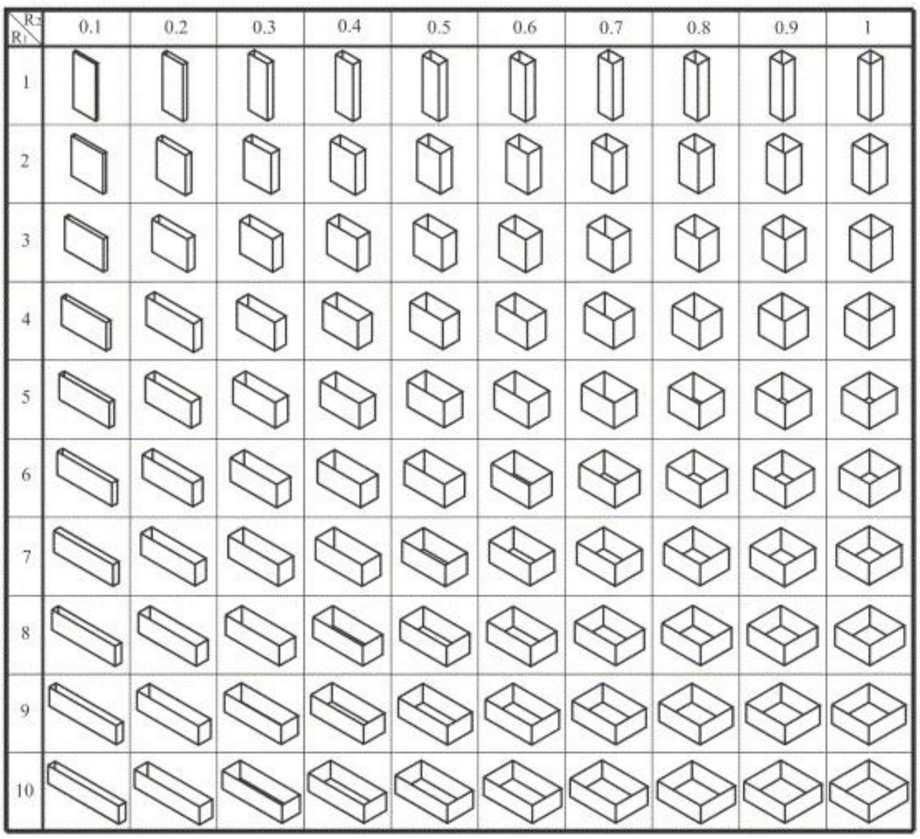


Figure 35: Investigated rectangular courtyard forms: R1= courtyard forms, R2 = elongation values.

Source: Muhaisen, A.S. (2006). Shading simulation of the courtyard form in different climatic regions. *Building and Environment*, 41(12): pp. 1731-1741.

2.5 Recommendations for courtyards

The characteristics of courtyards that were considered as unhealthy aroused the interest of many other *hygienists*. Their notes and recommendations dealt basically with the proportions of these yards and with providing healthier solutions; they are summarized in Table 9 and Table 10. The lack of regulation setting minimal courtyard dimensions within parcels was reflected by the excessive density of the urban fabric. In Paris, only in 1872 was the first legal order enacted, which aimed at establishing a precise ratio between building heights, street widths and courtyard areas. This regulation was considered to be insufficient for the hygienists who advocated the suppression of courtyards and proposed alternative solutions. One must refer to Cristiana Mazzoni (Mazzoni 2000) for a history of the origin and of the establishment of these alternatives: from the closed, to the open yard, and then to the open block in the projects of housing districts, considered during the inter-war years in Paris and its suburbs.

Table 9: Closed Courtyards recommendations and objectors.

Theories	Years		Authors
Yard = 3-4 m² minimum	1891	–	Charles Barde (ground floor+2)
Various closed courtyard studies	1905	–	Émile Trélat
Courtyard Width > Street Width	1920	–	Léon Jaussely
Courtyard Width = Street Width Courtyard Width ≥ Height surrounding buildings	1921	–	Paul Juillerat
Closed courtyard objectors	1915	–	Agache, Aburtin & Redont
	1928	–	Augustin Rey
	1930	–	Edmond Marcotte
	1934	–	Jean Raymond

Table 10: Opened courtyards and building “set back” (redans & redents) instigators.

Theories	Years		Authors
Opened courtyards	1908	–	Henri Provensal
	1921	–	Paul Juillerat
Opened Courtyards Width = 24m (variable in relation to the storeys)	1946	–	Augustin Rey (ground floor+5 +2 attics)
Building “set back” (*Redans & redents*)	1903	–	Eugène Hénard
	1908	–	Henri Provensal
	1904	–	Léon Jaussely
	1920/1921/1925/1935	–	Le Corbusier
	1925	–	Tony Garnier
	1928	–	Augustin Rey

Barde (1891) sizes the courtyard area in proportion to its wall heights and recommends covering it with glazing because of humidity. Jaussely (1920) advises assigning higher proportions to yards than to streets. For Juillerat (1921), courtyards and streets provide the same function of air and light distribution: in this, they should abide by the same sizing and proportion rules. Finally, a whole range of authors –Agache (1915), Aburtin & Redont (1915), Rey (1928), Marcotte (1930) and Raymond (1934)– would have liked to suppress the courtyard completely.

Even though the state of courtyards was considered as catastrophic in the nineteenth century, it was only in the early twentieth century that the open courtyard alternative was proposed by several authors. Provensal (1908), like Rey (1928), recommends removing closed courtyards to make way for a direct circulation with the street. Juillerat (1921) calls for a removal of the courtyard within the street block, by transforming it into an internal street. On the other hand, the remaining authors proposed a “set back" (*redans*) system derived from the open courtyard. "set back" buildings move the internal courtyard towards the street thereby breaking up the line of the façade.

More recently, courtyard recommendations were extended by Mohsen (Mohsen 1979), Yezioro (Yezioro, Capeluto et al. 2006) and Muhaisen (Muhaisen 2006; Muhaisen and Gadi 2006). Specified for latitudes between 26° and 34°, Yezioro suggests design guidelines that should be applied in the early design stages to provide proper insolation of different urban squares and any other open spaces (e.g. Courtyards). Results show that the best solution is the long, rectangular courtyard along the north–south orientation (see Figure 34). Elongated rectangular courtyards along northwest-southeast and northeast-southwest axis also achieve good results. In these cases, the buildings around the courtyard can be as high as one half the width of the courtyard. Otherwise, buildings around the courtyard should be only one third of the courtyard's length. The most undesirable orientation for a rectangular yard is east–west. Yezorio specifies that his recommendations would be equally valid for other latitudes.

Muhaisen mainly focussed on a modelling study carried out to understand the effect of rectangular courtyard proportions on the shading and sun exposure conditions on the internal envelope form in four different countries (see Figure 35). These locations, Kuala Lumpur, Cairo, Rome and Stockholm, were chosen to represent the climatic regions of hot humid, hot dry, temperate and cold climates, respectively. Results showed that the optimal proportions are those which capture the highest quantity of sunlight in Winter and the lowest in Summer. For hot and humid climates, Muhaisen recommended courtyards with courtyards forms (R1 values) between 3 and 7 and any stretch (R2 value). In hot dry climates, in which buildings tend to be a little deeper, the proper R1 proportions vary between 4 and 8 with various stretch values. Generally, the trend is towards shallow shapes in moderate and cold climates because of the solar altitude angle.

With a view to obtaining a reasonable efficiency, Muhaisen recommended that in a hot humid climate the long axis of the courtyard should be directed along the northeast–southwest whereas in temperate cold climates, the courtyard should lie somewhere along the north–south axis. In a hot dry climate, shapes with an orientation between the northeast–southwest axis and the north–south axis guarantee efficient functioning in both seasons (see Figure 36).

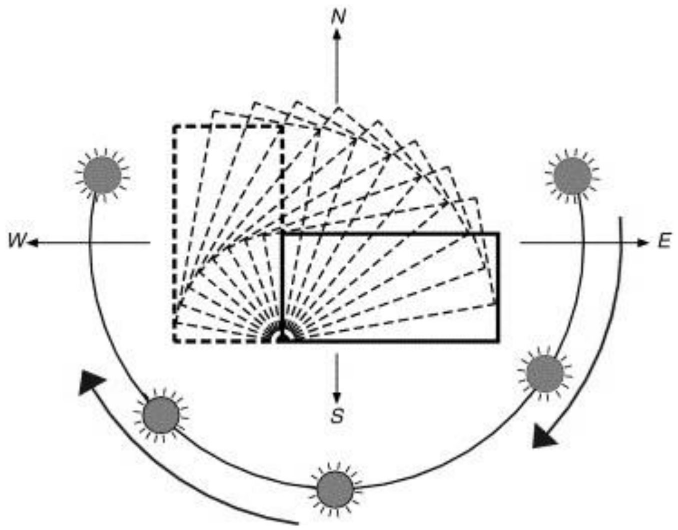


Figure 36: Changing the orientation of the courtyard form from 0° to 90° in 10° steps.

Source: Muhaisen, A.S. (2006). Shading simulation of the courtyard form in different climatic regions. *Building and Environment*, 41(12): pp. 1731-1741.

The optimal building height to obtain reasonable wintertime and summertime efficiencies is three storeys in hot humid climates, two storeys in hot dry climates and temperate climates, and one storey in cold climates. In Summer, to maximize the shaded zone both in Cairo and in Rome, three-storey buildings are recommended - given that the reduction of the lit zone in Winter is minimal.

2.6 Buildings: establishment and density questions

In the middle of the twentieth century, the deletion of the courtyard in green spaces gave way to a space-consuming building layout in parallel blocks development layout. This transformation was theoretically based on the Modern Movement[21]. The old type of town was condemned. Some authors, such as Le Corbusier (1931), Roger Ginsburger (1931), Luwig Hilberseimer (1936) and Walter Gropius (~1930), sought to prescribe, and even impose universal layout rules by claiming to take into consideration daylighting-related criteria. These prescriptions mirrored a systematic approach and a simplistic mechanism (Harzallah 2007). The *Congrès International d'Architecture Moderne* (CIAM)[22], particularly the one in 1933, provided a theoretical basis formalized and popularized by Le Corbusier (Allain 2004) (see Figure 37).

Figure 37: The Modern City by Le Corbusier (1931).

Source: Le Corbusier (1935). *La Ville radieuse*. Boulogne, Editions de l'Architecture d'Aujourd'hui.

In his writings of the 1930's, Walter Gropius (1883-1969), the German architect and urban planner, also looked into the question of a rational building layout that guaranteed daylighting and ventilation. He argues that high-rise buildings, 10-12 storeys, are better than 3-, 4-, or 5-storey buildings: better in terms of a higher population density which can be achieved at less cost while preserving light, air and elbow-room. In particular, he agrees that the amount of open space for each inhabitant (the open-space ratio) be increased as the height of the blocks increases (Gropius 1935). Garry Stevens[23] (1990) reported some principles of it and has verified the mathematical validity of these rules.

[21] The Modern Movement, also known as Modern Architecture, is a current of architecture that appeared in the first half of the twentieth century with the Bauhaus Movement, characterized by a return to minimal decoration, with geometrical and functional lines and the downgrading of the shapes to new techniques. The Modern Movement developed through architects Walter Gropius, Adolf Loos, Auguste Perret, Ludwig Mies van der Rohe, Oscar Niemeyer and Le Corbusier.
[22] CIAM or International Congress of Modern Architecture, founded in 1928 and disbanded in 1959, was a series of international conferences of modern architects.
[23] Garry Stevens (1990). *The reasoning architect: Mathematics and Science in Design*. McGraw-Hill International Editions, New-York.

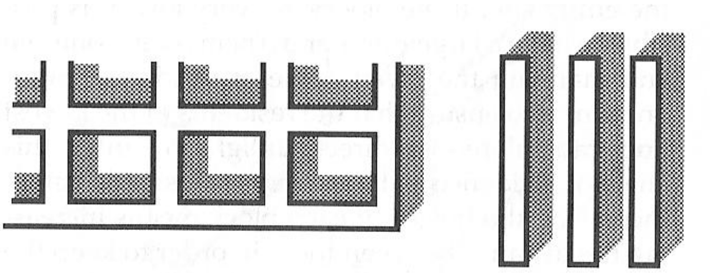


Figure 38: Garry Stevens. City-block development layout (left) and parallel block development layout (right).

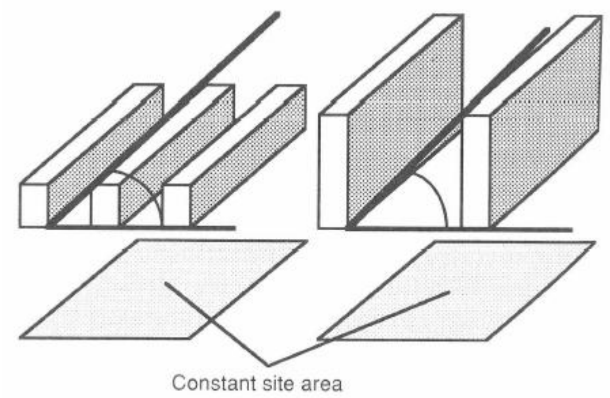


Figure 39: Garry Stevens. Given a certain site area and sunlight incidence, the number of people housed increases with the number of storeys.

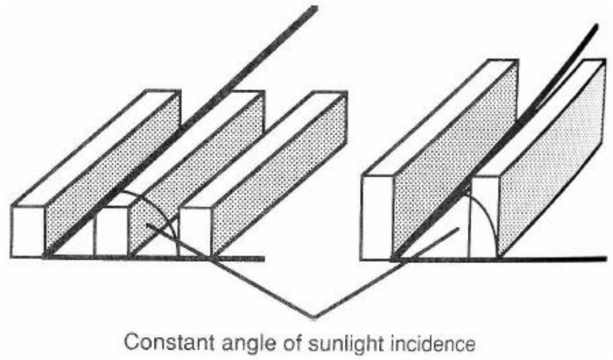


Figure 40: Garry Stevens. Given a certain sunlight incidence and a number of people to house, the size of the required site decreases with the increased number of storeys.

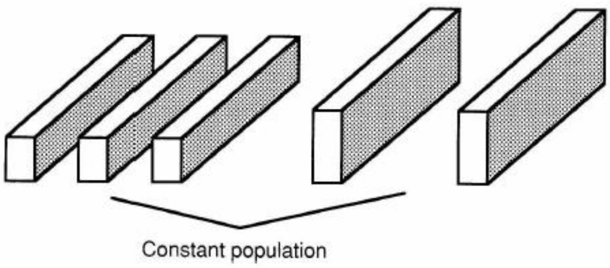


Figure 41: Garry Stevens. For a given ground occupation area and a given population density, the incidence angle of sunrays decreases if the number of storeys for each block increases.

Source Figure 38 to Figure 41: Garry Stevens (1990). *The reasoning architect: Mathematics and Science in Design*. McGraw-Hill International Editions, New-York.

Gropius preached for a building settlement likely to favour a healthy amount of sunshine and ventilation for housing . He deplored a city-block development layout (see Figure 38) with edifices that surrounded closed yards (unfavourable arrangement as far as air and natural light access is concerned). He recommended instead a parallel block development layout. To him, such a configuration would have contributed to housing exposed to favourable orientations that would ensure a balanced exposure to the sun (avoiding the exposure to the north). The ventilation of flats would also be facilitated by this configuration, in the absence of hobbling perpendicular buildings. Gropius also recommended the construction of high buildings, augmenting, in a cost-effective way, the population density, while preserving acceptable ventilation and daylighting. He added that the open-air area from which each occupant would benefit would increase with the height of the building. He laid out three rules for parallel block development layout, around four different variables: the number of storeys, the population density for each block, the site area and also the incidence angle of sunlight at the bottom of the buildings in Winter (Harzallah 2007).

The first Gropius rule stated that for a given site area and sunlight incidence, the number of people housed increases with the number of storeys (see Figure 39).

The second rule stated that for a given sunlight incidence and a given number of inhabitants, the size of the required site decreases with the increasing number of storeys (see Figure 40).

The last of Gropius' rules stated that for a given site area and a given number of inhabitants, the sunlight incidence decreases with the increasing number of storeys (see Figure 41).

With these three rules Gropius finds that the optimum building height of the parallel block development layout is 10 to 12 floors. Moreover, he claimed that, in terms of quantity of space, highrise built form uses land more efficiently than its lower rise counterpart; however, in reality, the quality of space is as important as its quantity. For instance, it might be that the smaller areas between the low rise blocks which offer diverse facilities and conditions for the residential community are more adequate than a large open space (see Figure 42) (Harzallah 2007).

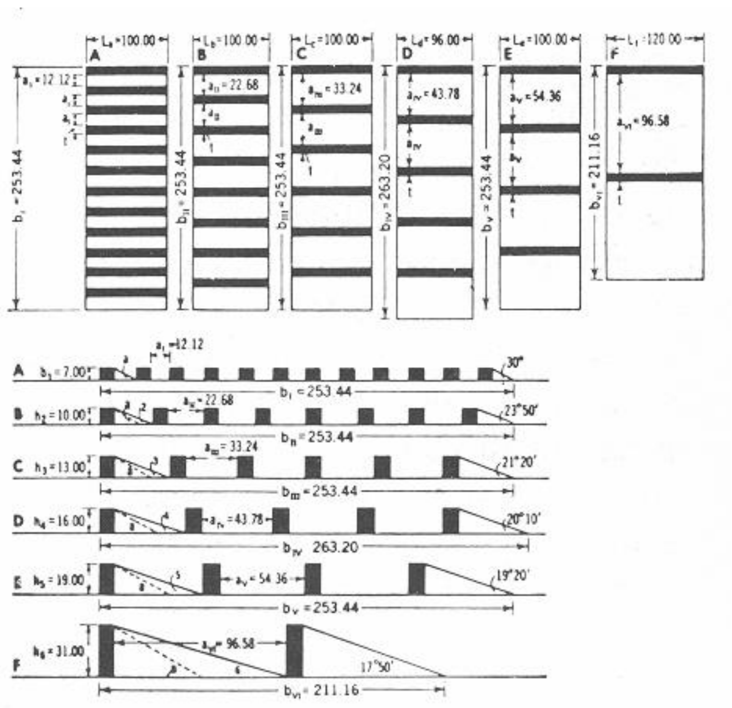


Figure 42: Walter Gropius. Rational building settlement that guaranteed a healthy amount of sunshine.

Source: Ruano, M. (1999). *EcoUrbanism.Sustainable Human Settlements: 60 cases studies*. Editorial Gustavo Gili SA, Barcelona.

In 1939, the architect Roger Ginsburger published an article in the journal *L'Architecture*, entitled "Why can't healthy housing districts be built in Paris?" He presented four maps (see Figure 43) showing the progressive transformation of the building establishment on a block to improve the airing and then the daylighting of buildings. Ginsburger showed that the first plan (see Figure 43, top left), in compliance with that time's regulations, presented 45% of flats lit up and ventilated solely through courtyards (whose area made up 25% of the total area). The second plan (see Figure 43, top right) presented an open-yarded settlement, improving flats' ventilation and augmenting the quantity of received light. However, this layout produced, according to the author, north-exposed flats and other ones that were shaded by another building volume. The third map (see Figure 43, bottom left) presented a parallel block development layout with "yards in lengths opened on both sides". According to the author, even though the quantity of direct daylight entering the flats would have been smaller than in the second project, this configuration allowed the entire set of façades to be exposed to sunlight, "at least in their upper part". The third plan (see Figure 43, bottom right) was considered as the "ideal project" according to Ginsbuger insofar as it offered a "perfect ventilation and a very strong daylighting", though the population density turned out to be reduced (Harzallah 2007).

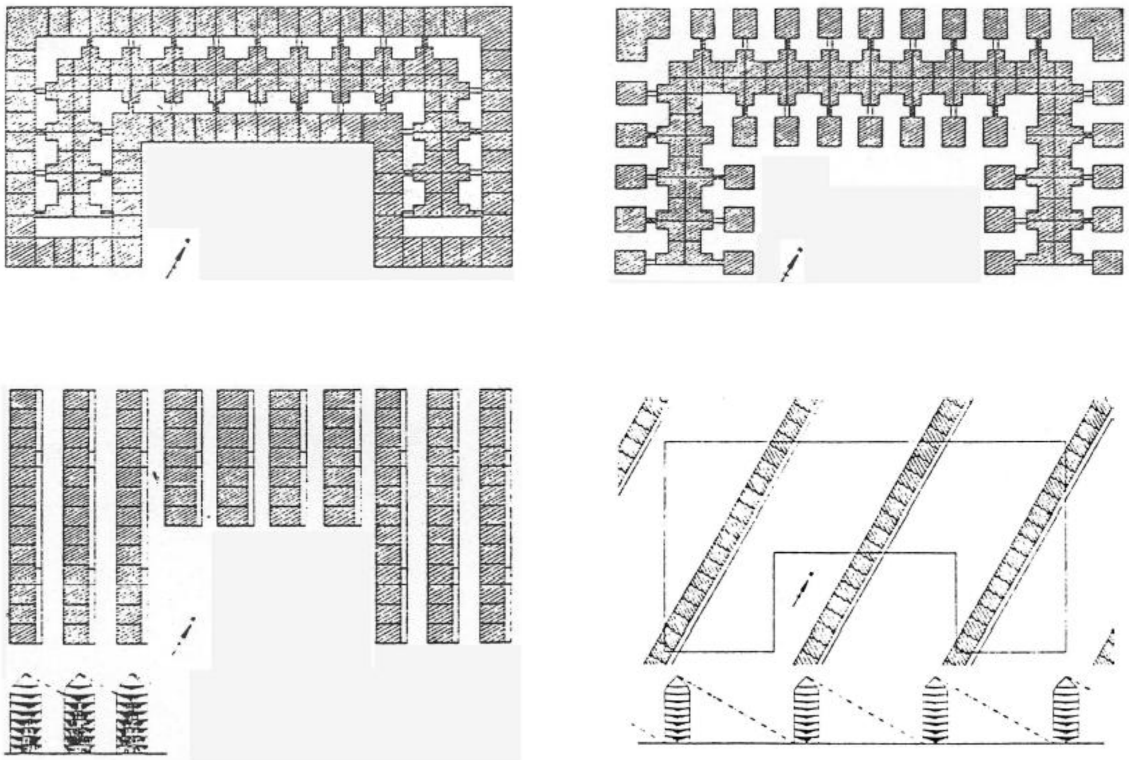


Figure 43: Ginsburger. Progressive transformation of the building establishment on a block to improve the airing and then the natural lighting of these buildings.

Source : Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

In 1936[24], the German architect and urban planner Ludwig Hilberseimer (1885-1967), published an article in the German journal *Moderne Bauformen* addressing the relations between sunshine and density issues. He presented the principles and precepts that J.-P. Péneau likened to those of rationalistic and systematic orientation provided by H. Meyer, one of whose disciples was indeed Hilberseimer.

24 Ludwig Hilberseimer (1936). Raumdurchsonnung und Siedlungsdichtigkeit. *Moderne Bauformen*, Suttgart, Julius Hoffmann, February, **35**: 69-76.

Hilberseimer submitted various diagrams showing the influence of the latitude and of the building height on this urban density (see Figure 44, Figure 45 and Figure 46). He proved that with buildings of the same height, of the same number of storeys, one would get half of Moscow's population density compared to that of Paris if the same solar radiation received by each house were imposed. This density varied also as a function of orientations: arranging all of the homes openings toward the north would cause a low urban density. He noted the drawbacks of constructions with several storeys, if one wished to adhere to other accepted daylighting conditions (Harzallah 2007).

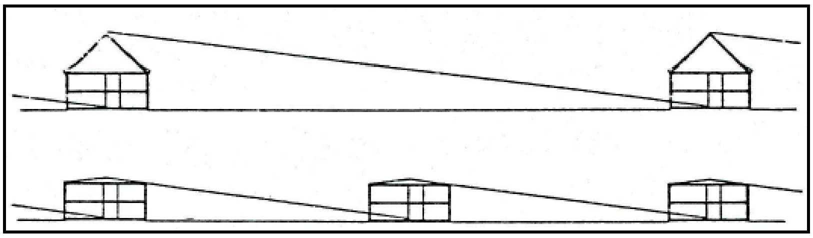


Figure 44: Ludwig Hilberseimer. Diagram showing the influence of the building roofs on urban density, in order to receive 4 hours of sunshine on 21st December.

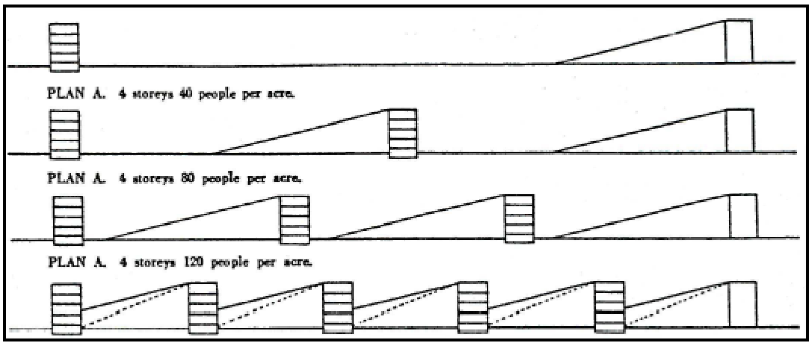


Figure 45: Ludwig Hilberseimer. Building arrangements with various urban densities, Continuous line: latitude 51°30, dotted line: latitude 42°.

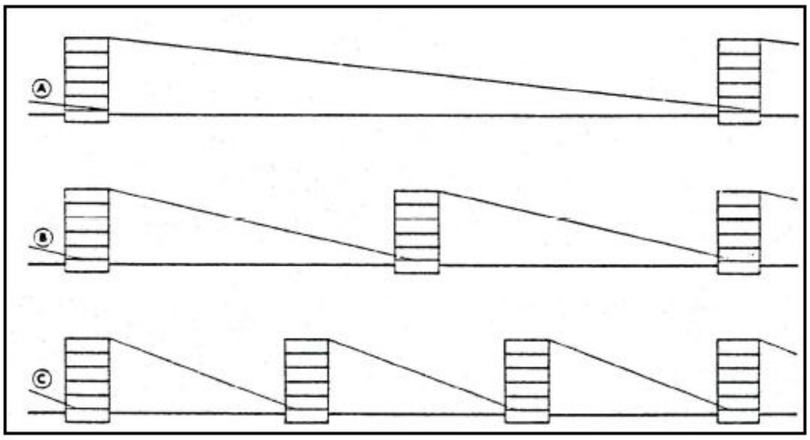


Figure 46: Ludwig Hilberseimer. Diagram showing the relation between the latitude and the population density, A: latitude 55° Moscow, B: latitude 48° Paris and C: latitude 42° Chicago.

Source : Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. Thèse de doctorat. *Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

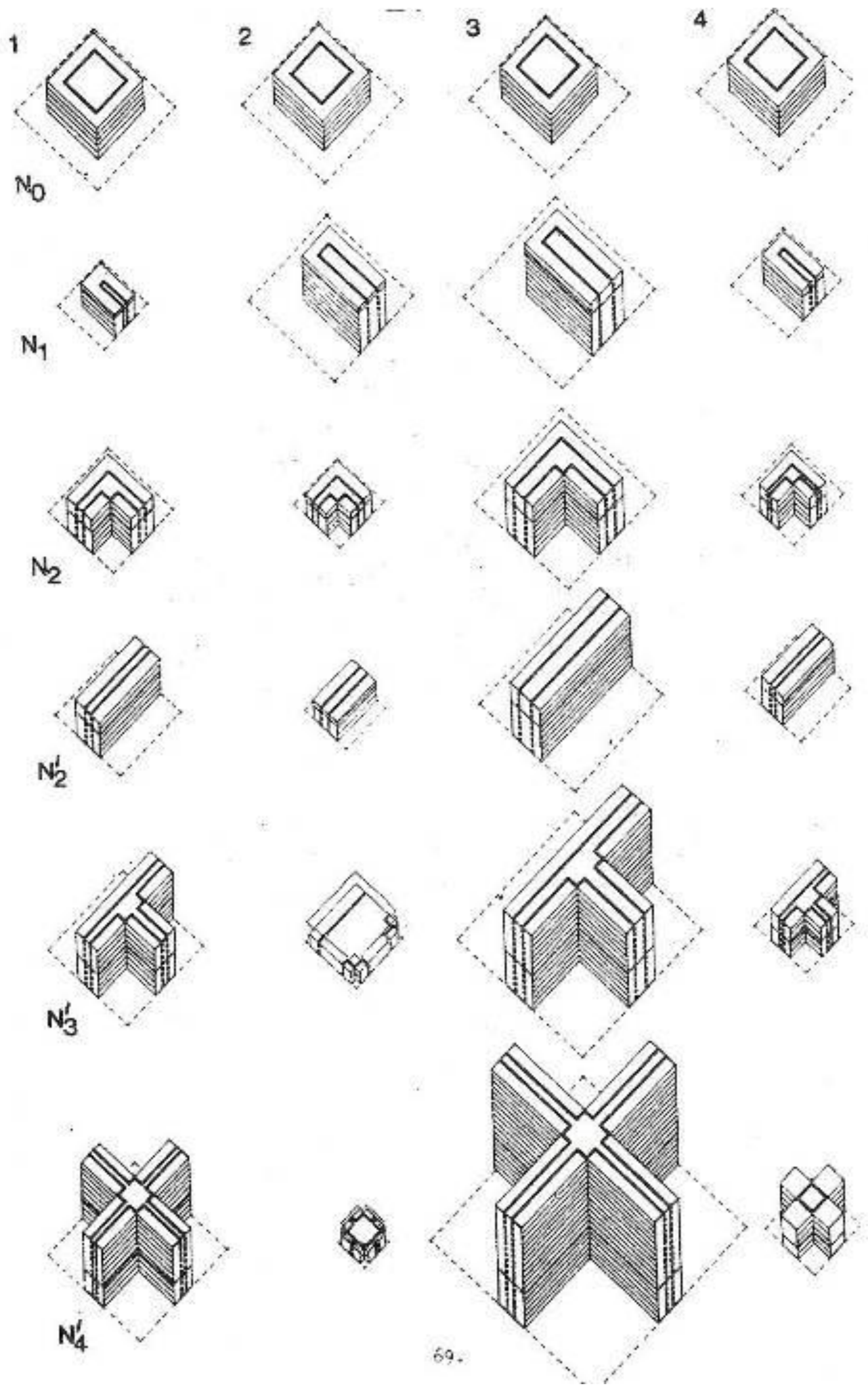


Figure 47: Selected array of built forms' showing courtyard housing as the most efficient way of covering the ground.

Source: Lionel March and Michael Trace (1962). The land use performances of selected arrays of built forms, Working Paper N°2. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

On the other hand, Lionel March of Cambridge University has reported that given a fixed obstruction angle, the floor area ratio of an array of continuous courtyards is always greater than that of an array of pavilions for any given number of storey (March 1972). For instance, Geoffrey Broadbent wrote that: "*It is no coincidence that in the design of Pollard's Hill McCormack had drawn on the work of researchers in Land Use and Built Form Studies (now The Martin Centre for Architectural and Urban Studies) at Cambridge University. For McCormack had been a student at Cambridge University where various permutations of Martin, March and Trace had been researching into the nature of efficient land use. In 1968, for instance, March and Trace had published The Land Use Performance of Selected Arrays of Built Forms. They started form Le Corbusier's basic premises: that dwellings should be so planned that, even on the worst day of the year, the Winter Solstice, sunlight – in the absence of clouds – should penetrate for a minimum of two hours into each living room.*

Le Corbusier, Gropius and others had used this to argue that, given the same sun-angle the slab-blocks of the Modern Movement, wide spaced in park land were more efficient users of the land than two-storey, three-storey, or other terrace-forms might be.

Given access to computers which the pioneers had never had, March and Trace were able to test a wide range of building forms against the criterion of sun-penetration: terrace housing at various heights, blocks, slabs, T-shaped and other kinds of tower, concluding that of all possible built forms, the most efficient of all in terms of land-use would be four storey courtyards (see Figure 47).

It is hardly surprising that, working in Cambridge as they were at the time, March and Trace should be aware of the court – or the Oxford quad – in terms of its social advantages, but their analysis of sun-penetration was thoroughly objective and remains one of the most significant pieces of research ever to have been undertaken on urban built form. What is extraordinary is that, with the honourable exception of McCormack, until recently so few architects should have seized the opportunities which March and Trace had provided for building such urban forms.

Especially since the founding father himself, Le Corbusier, had, quite intuitively, come to similar conclusions concerning land use, which he demonstrated in the Maison Jaoul of 1955?

He built these two houses in an L-shape – obviously the corner of a courtyard – on a concrete platform raised half a storey out of the ground. There was parking underneath and the houses themselves were built in that assemblage of masonry – in these cases brick – with shallow vaults in concrete of the kind which, mistakenly, Le Corbusier though to be Catalan. The houses themselves represent a thorough recantation by the Master himself of the position he had taken up in the 1920's. Their thick wall, thick vault, small window construction, with its excellent thermal capacity, avoidance of solar heat gain, admission of daylight to give sparkle where required, sound insulation properties, and so on, was a direct, highly, personal refutation of his Five Points for a New Architecture of 1927.

Those are architectural matters but in the Jaoul Houses also, Le Corbusier attempted, very clearly, to refute his planning ideals of the 1920's. Here the towers and slabs have been abandoned; so have the motorways: Instead we have a human-scale environment; the houses themselves are nowhere more than three storeys high, on their half-storey plinth. What is more the car is stored where it should be, underneath, thus allowing human scale to prevail at ground level" (Broadbent 1990).

March and Trace have mathematically addressed the question of which building forms make an optimal land use. Their studies led to several postulates of which the most important is: "*It is impossible in any arrangement of built forms to provide unobstructed floor space exceeding four times the land area*" (March and Trace 1962).

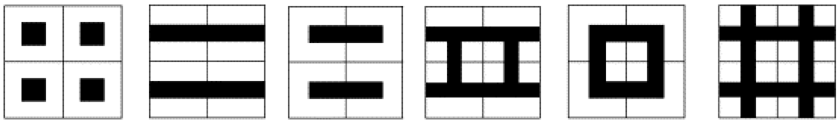


Figure 48: Generic urban forms, based on Martin and March (Martin and March 1972) and environmentally reviewed by Steemers et al. (Steemers, Baker et al. 1997). From left to right: pavilions, slabs, terraces, terrace-courts, pavilion-courts and courts.

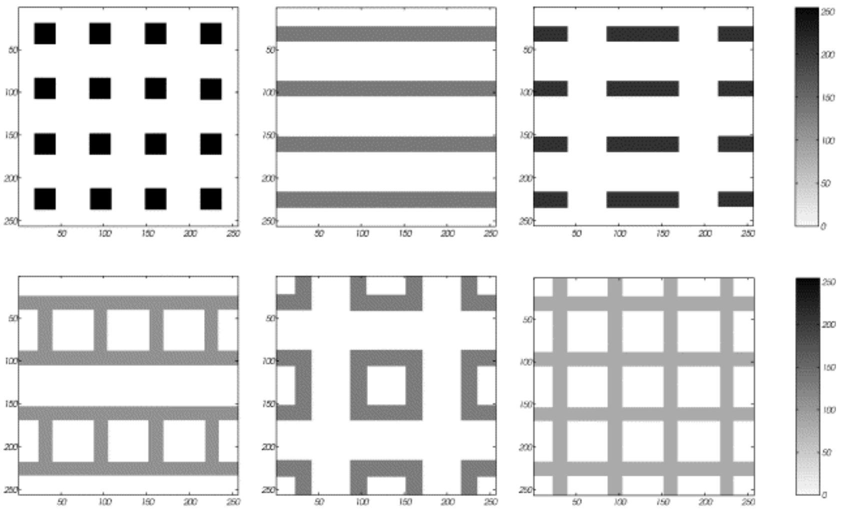


Figure 49: DEMs of the generic urban forms.

Source Figures 48 and 49: Ratti C., Raydan D., Steemers K. (2003). Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and Buildings*, 35 (1): pp. 49-59.

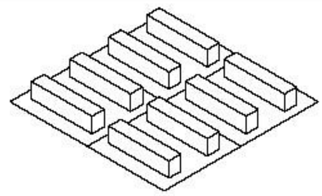
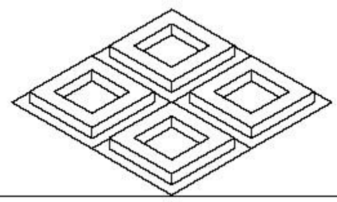
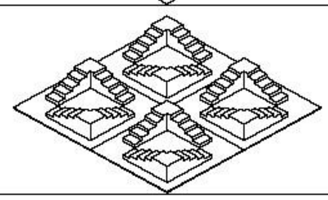
Module Parameters		Layout (2 x 2 modules)
Urban Form: Linear		
Module Length: 76.8 m x 76.8 m Building Length: 60 m Building Height: 15 m Street Width: 26.4 m, 16.8 m Foot Print/Module: 1440 m^2 Surface Area/Volume: 0.28	Total Area: 5898 m^2 Building Width: 12 m Court: 60m x 26.4 m Orientation: 0 °, 45 °, 90 ° Floor Area Ratio: 1.2	
Urban Form: Block		
Module Length: 76.8 m x 76.8 m Building Length: 60 m Building Height: 9 m Street Width: 16.8 m Foot Print/Module: 2304 m^2 Surface Area/Volume: 0.2	Total Area: 5898 m^2 Building Width: 12 m Court: 36 m x 36 m Orientation: 0°, 45° Floor Area Ratio: 1.17	
Urban Form: RSB		
Module Length: 76.8 m x 76.8 m Building Length: 60 m Building Height: 3-15 m Street Width: 16.8 m Foot Print/Module: 1840 m^2 Surface Area/Volume: 0.31	Total Area: 5898 m^2 Building Width: 12 m Court: 36 m x 36 m Orientation: 45° Floor Area Ratio: 1.1	

Figure 50: Main parameters of urban forms studied for incident solar radiation.

Source: Okeil, A. (2004). In Search for Energy Efficient Urban Forms: The Residential Solar Block. In *Proceedings of the Fifth International Conference on Indoor Air Quality*, Ventilation and Energy Conservation in Buildings, May 2004, Toronto.

Furthermore, March set forth a theorem linking the geometrical characteristics and physicothermical characteristics (transmittance[25]) to the envelope of a building. The conclusion is that the ideal shape of a building is the rectangular parallelepiped for which the three dimensions are a function of the transmittance values of the building envelope. Indeed, the small Georgian square came close to their optimum; four-storey housing around such squares have rather special properties.

March, Trace and Martin's studies (March and Trace 1962; Martin and March 1972) have also influenced a number of researchers. Those mentioned below are some of the most important; the list is not comprehensive and contains only a few examples of concrete urban forms. Vinod Gupta (Gupta 1984; Gupta 1987) has assessed and compared as a function of their thermal behaviour three building archetypes during their construction, termed the pavilion, street, and courtyard, as non-air-conditioned buildings in arid climatic zone.

Steemers (Steemers, Baker et al. 1997) has explored the relationship between urban form and its surroundings. He linked up the various urban textures and their impact on the availability of (direct and diffuse) solar radiation, the effects on the air and its pollutants and the consequences for energy use. Carlo Ratti (Ratti, Raydan et al. 2003) extended the analysis of March, Trace and Martin by using innovative techniques for the analysis of the urban environment, based on image processing (DEM - Digital Elevation Model). This approach shows the complexity of the environmental behaviour in urban context. This analysis is complemented by a case study in hot urban context (see Figure 48 and Figure 49). Under the same plot ratio, he suggested six archetypal forms linked with several basic indicators; especially the ratio of passive to non-passive floor area ratio that indicated the impact on building energy consumption. Ratti came up with the conclusions that efficiency results of urban forms hung on the climate area in which they lay. The case study showed that the courtyard layout responded better to calculated environmental variables (surface to volume ratio, shadow density, daylight distribution, sky view factor) than pavilion-shaped types in a hot climatic area. He thereupon deduced that the courtyard type would not be an appropriate solution in a hot humid climate (tropical).

Okeil (Okeil 2004) developed the Residential Solar Block (RSB) and proved that it can maximise solar energy on façades and minimize solar energy on the roofs and on the ground surrounding buildings in an urban area in winter at latitude 48° (see Figure 50). He then compared the direct solar radiation distribution on urban surfaces, slab and pavilion-court. The results show that the RSB combines the functional, spatial, social and visual advantages of the conventional residential block with the energy efficiency advantage of the linear urban form. The results also show that the RSB supports strategies for mitigating the urban heat island by increasing airflow and by promoting marketable green roofs.

Cheng (Cheng, Steemers et al. 2006) has recently conducted a parametric study on built forms to address the best urban configuration from a solar point of view (see Figure 51).

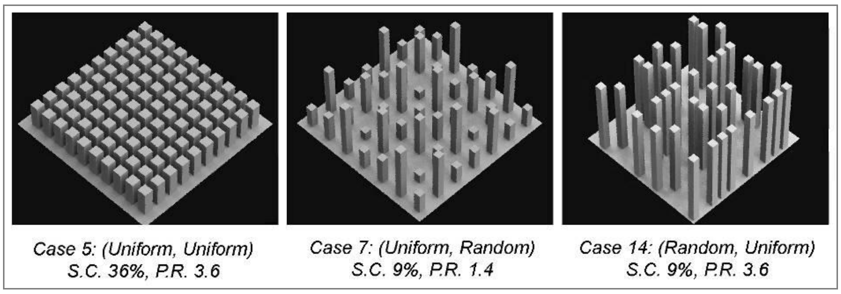


Figure 51: Illustration of a sample of generic models used for simulation.

Source: Cheng,V., Steemers, K., Montavon, M., Compagnon R. (2006). Urban Form, Density and Solar Potential. In *Proceedings PLEA 2006, 23rd International Conference on Passive and Low Energy Architecture*, 6-8 September.

[25] Transmittance is defined as the ratio between the light flux transmitted by a transparent body and the flux of incident light which it receives.

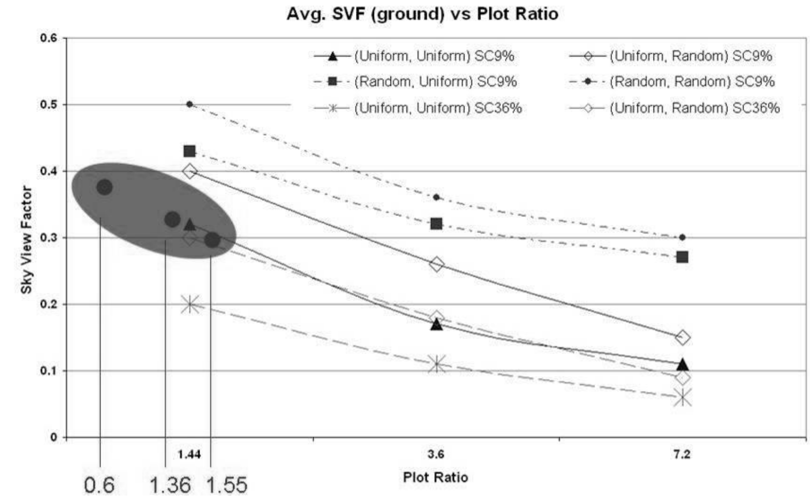


Figure 52: Comparison of proposed sample areas (in red) with generic data, suggesting that higher SVF's can be achieved by increasing the randomness of heights and spacing within each area.

Source: Steemers, K., Montavon, M. et al. (2007). Testing the master plan. An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge: 35.

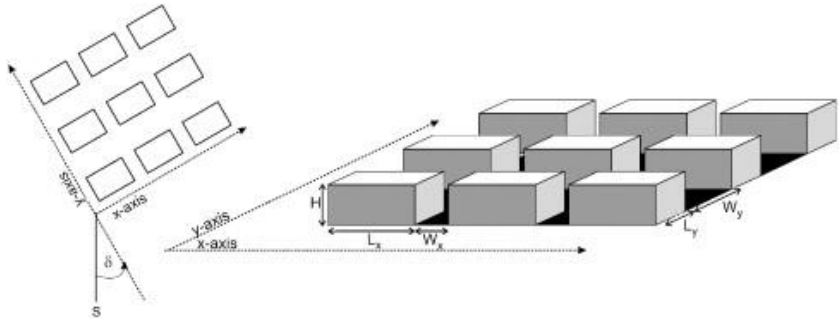


Figure 53: Definition of urban form parameters: grid azimuth (anti-clockwise angle from South, δ); building height (H), width (Lx) and depth (Ly); building spacing in x-direction (Wx) and y-direction (Wy).

Source: Panão Oliveira, M. J. N., Gonçalves, H. J. P., Ferrão, P. M. C. (2008). Optimization of the urban building efficiency potential for mid-latitude climates using a genetic algorithm approach. *Renewable Energy*, 33 (5): pp. 887-896.

Table 11: Optimal urban forms' characteristics for each latitude assuming a floor space index of 1.0 and building surfaces absorptivity of 0.5

Latitude	Urban forms	Grid azimuth (deg)	No. of floors	N–S aspect ratio	W–E aspect ratio
35	Pavilions Slabs terraces	0 (all), ±15 (pavilions)	2 (terraces) 3 (slabs) 3–6 (pavilions)	0.6 (slabs and terraces) 0.7 (pavilions)	1.7–2.8
40	Pavilions Slabs terraces	0	3 (slabs and terraces) 4 (pavilions)	0.5 (slabs and terraces) 0.7 (pavilions)	1.5–2.7
45	terraces	0, ±15	3–4	0.4–0.5	1.3–1.9
50	pavilions	0, ±15, ±30, ±45	4–9	0.7	2.7–2.9

Source: Panão Oliveira, M. J. N., Gonçalves, H. J. P., Ferrão, P. M. C. (2008). Optimization of the urban building efficiency potential for mid-latitude climates using a genetic algorithm approach. *Renewable Energy*, 33(5): pp. 887-896.

As illustrated in Figure 52, both irregular building disposition (horizontal irregularity) and height variations (vertical irregularity) are expected to result in a higher SVF_g as compared to a uniform urban form with the same building shape, density and average height.

Oliveira Panão (Panão, Gonçalves et al. 2008) determined (see Figure 53 and Table 11) that for all latitudes the base length should be decreased to an acceptable minimum taking into account constructive and design restrictions. Furthermore, it is concluded that for latitudes between 35° and 45°, the grid azimuth angle should stay between −15° and +15° and the spacing between blocks in the north–south direction should be maximized. For a latitude of 50°, grid azimuth can range from −45° to +45°.

Oliveira concluded that pavilions are urban forms suited to low latitudes (35°), because they reduce the solar incidence on roofs in summer season, as well as for higher latitudes (50°), because they increase the vertical solar incidence in winter season. The main aspect ratio (N-S, NE–SW or NW–SE) for pavilions being equal to 0.7 for any latitude, building mutual shading is always achieved during the winter season. Pavilion-like shapes also raise diffuse irradiation owing to inter-reflections between buildings.

Kämpf (Kaempf, Montavon et al. 2007; Kaempf, Montavon et al. 2009) proposed a methodology that involves a multi-objective evolutionary algorithm: he introduced a second objective linked to the minimisation of the buildings volume that leads to a Pareto front. This enables the identification of cases which minimise the energy consumption for a given volume. As an application of this methodology, he parameterised three urban forms: the Terraces Flat Roofs, the Slabs Sloped Roofs and the Terrace Courts (see Figure 54).

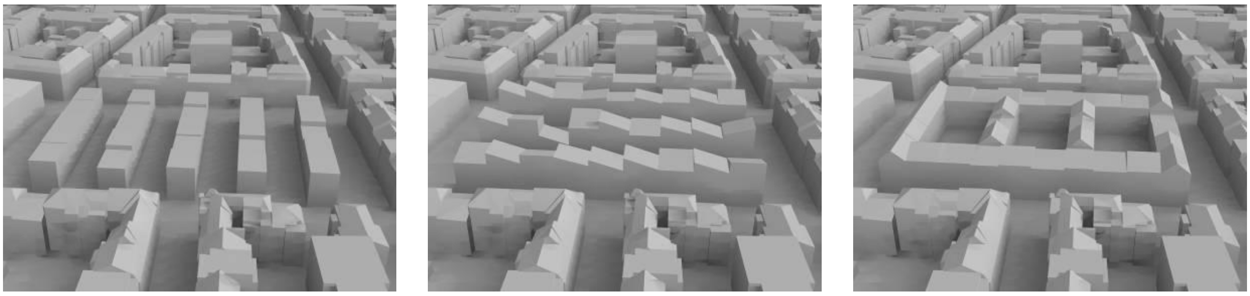


Figure 54: Jérôme Kaempf. Shape resulting of the optimisation of Terraces Flat Roofs, Slabs Sloped Roofs, and Terrace Courts.

Source: Kämpf, J. H., Montavon, M., Bunyesc, J., Bolliger, R., Robinson, D. (2007). Optimisation of Buildings Daylight Availability. In *Proceedings CISBAT 2007*, 4-5 September 2007, Lausanne.

For each of these cases clear trends in the optimal sizing and form of buildings are discernible for different target built volumes. The Terraces Flat Roofs show a lower performance: it can be demonstrated that all buildings need to have some height producing shadowing on each other in order to reach a given volume. This is not the case for the Terrace Courts configuration, which always shows a better performance compared to the other cases (see Figure 55).

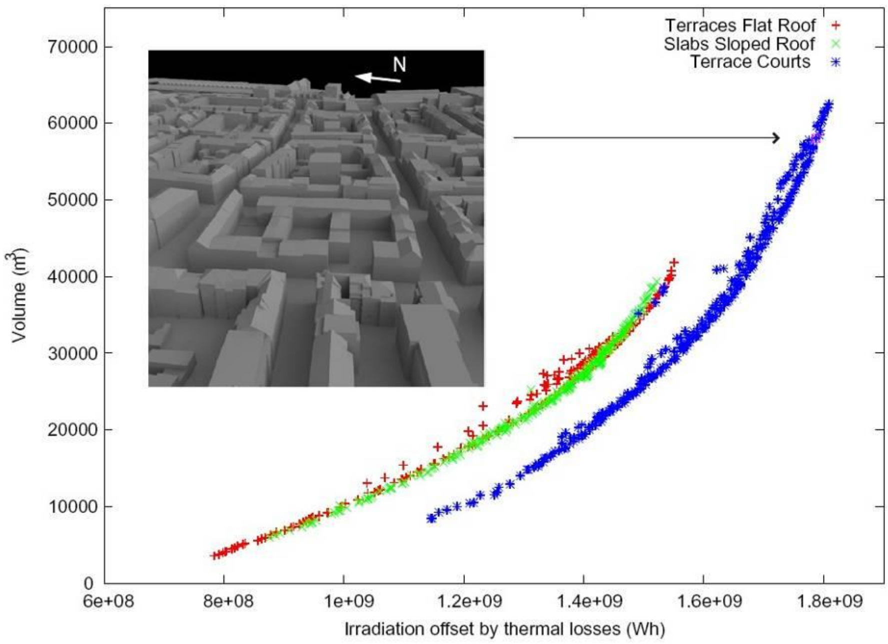


Figure 55: Jérôme Kämpf. Superposition of the Pareto fronts obtained for Terraces Flat Roof, Slabs Sloped Roof and Terrace Courts. On the left, a synthetic image rendered using RADIANCE showing Terrace Courts at 80% of the maximal allowed volume and their surroundings.

Source: Kämpf, J. H., Montavon, M., Bunyesc, J., Bolliger, R., Robinson, D. (2009). Optimisation of buildings' solar irradiation availability. Solar Energy, 84(4): pp.596-603.

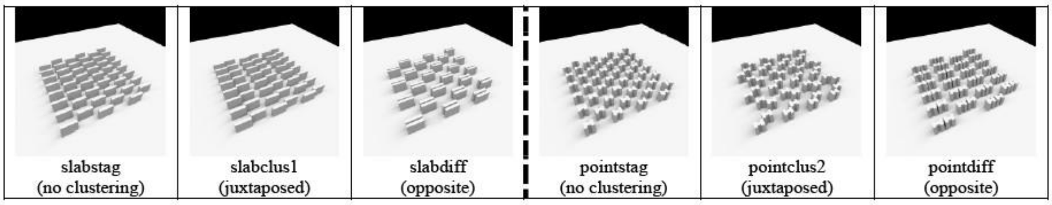
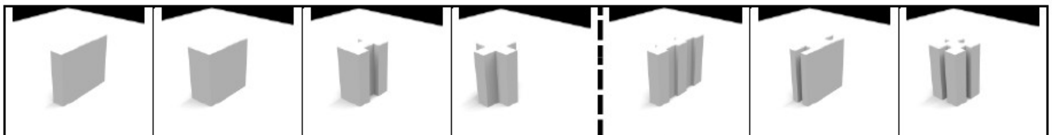


Figure 56: Kam Shing Leung. Generic forms representing two approaches of building clustering.



slabreg (I-shape)	lcourt (L-shape)	pointreg (H-shape)	pointconv1 (+ shape)	slabconv1	slabconv2	pointconv2
Building depth (volume-to-façade area ratio, in m)						
5				4.3	4	
Area of south/north-facing façade as a percentage of the total façade area						
80%	67%	50%	50%	71%	80%	53%
Convolution Index						
0%	8%	20%	24%	16%	36%	50%

Figure 57: Kam Shing Leung. Generic forms with different levels of directionality and façade convolution.

Source Figure 56 and Figure 57: Leung, K. S., Steemers, K. (2009). Exploring solar-responsive morphology for high-density housing in the tropics. In *Proceedings CISBAT 2009*, 2-3 September 2009, Lausanne.

More recently, Leung (Leung and Steemers 2009) used RADIANCE to assess the amount of solar radiation falling onto building façades in high-density collective housing. The results from Singapore (hot-humid climate) and Abu Dhabi (hot-arid climate) are presented on Figure 56.

Leung observed that morphological design reducing solar irradiation on building façade by orienting the building to the south in the tropical region is effective only when the site coverage is increased significantly. Preliminary results suggest that, for the purpose of reducing solar heat gain, façade convolution and building clustering create a more “egalitarian” radiant environment across the height of a building than high site coverage (see Figure 57).

2.7 Backward solar radiation and visibility

Early investigation in passive and active solar design resulted in site layout criteria for solar access (HMSO 1971a) and manual design tools, such as sunlight and daylight indicators (HMSO 1971b) – based on manual projection of obstruction skylines onto sunpath / solar availability charts and the complementary “sky maps” for diffuse radiation (ETSU 1987). On a related note, Everett (Everett 1980) has used “shadow footprints” to assist with site layout: isocontours corresponding to direct solar energy transmission loss through vertical façades are drawn around different block shapes and sizes.

Many of the software developments in subsequent years were based on computerisations of similar concepts.

The principles of projection have been employed in the development of the Solar Envelope concept (Knowles 2003), originally developed in the 1980’s. Given some solar access criteria (e.g. number of hours of sun visibility in Summer / Winter) solar access volumes are projected from façades. These volumes correspond to zones in which construction may take place. Consequently, they may be used to identify conflicts a priori (e.g. a proposed design might not sufficiently respect the solar access needs of existing buildings and thus has to be revised or vice versa) (see Figure 58). Since then, Morello (Morello and Ratti 2009) simplified solar envelope calculations in order to be able to launch simulations on wider urban sectors. He also put forward the concept of iso-solar surfaces, that extend the concept of solar envelope through energy considerations. Proposed routines refined the definition of solar envelopes to better reflect the monitored city irradiance and to obtain a result directly applicable in urban planning. His technique relied on urban digital elevation models processing (DEMs).

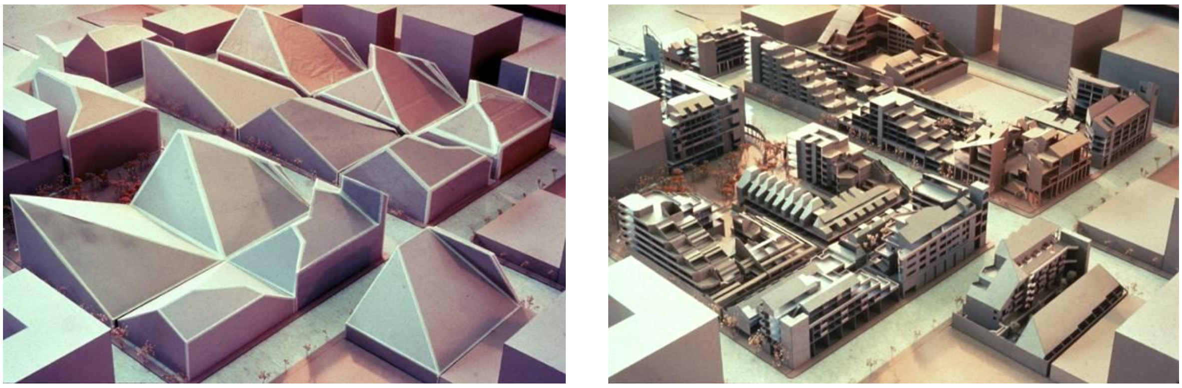


Figure 58: Typical housing project: viewed from the east, this test project illustrates multiple land parcels with housing over street-front shops; solar envelopes provide 6 h of solar access above a 20 ft shadow fence at neighbouring properties (left) and all designs under the solar envelope provide at least 4h of solar access and cross-ventilation for each dwelling unit (right).

Sources : Knowles, R.L (2003). The solar envelope: its meaning for energy and buildings. *Energy and Buildings*, 35 (2003): pp. 15–25.

Instruments such as the *Vidélios*, the *Horizontoscope* or the *Globoscope* make it possible to take readings of sunshine or shading hours and to define precise azimuths and openings' elevation angles or solar masks. Thereby, it becomes practical to achieve a punctual constraint for the very point were the instrument is used (see Figure 59). The feedback to a solar or visual intention is extremely fast with this kind of tool. For instance, *Vidélios* with the exposure from a Polaroid camera, enable the architect to decide very quickly if a project will fulfil the solar or visual intention (according to the existing masks projected on the solar availability chart). Needless to say, if the point of interest (the position of the instrument centre) is inaccessible (storey of a future building, virtual site, etc.), it is impossible to accomplish a simulation with *Horizontoscope* type tools. In that event, the modelling or the drawing of the site and its environment is mandatory for the achievement of the simulation. Moreover, this kind of instrument does not enable the visualization of the masks in three dimensions. It seems therefore less effective, in backward simulation, than the three-dimensional simulation tools mentioned in the current state of the art (Houpert 2006).

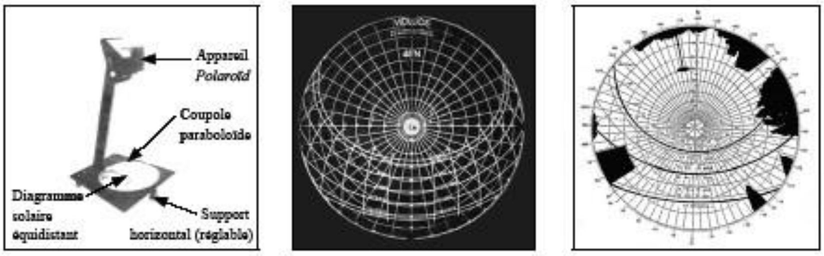


Figure 59: The Vidélios enables the immediate identification of a site's solar periods (left), Equidistant horizontal Sunpath graph used with Vidélios (middle) and Example of solar masks released by the Vidélios on the site of Euralille (right).

Source : Houpert S. (2006). Approche inverse pour la résolution de contraintes solaires et visuelles dans le projet architectural et urbain, Développement et application du logiciel SVR. Thèse de doctorat. Ecole *Nationale Supérieure d'Architecture de Nantes*. Université de Nantes.

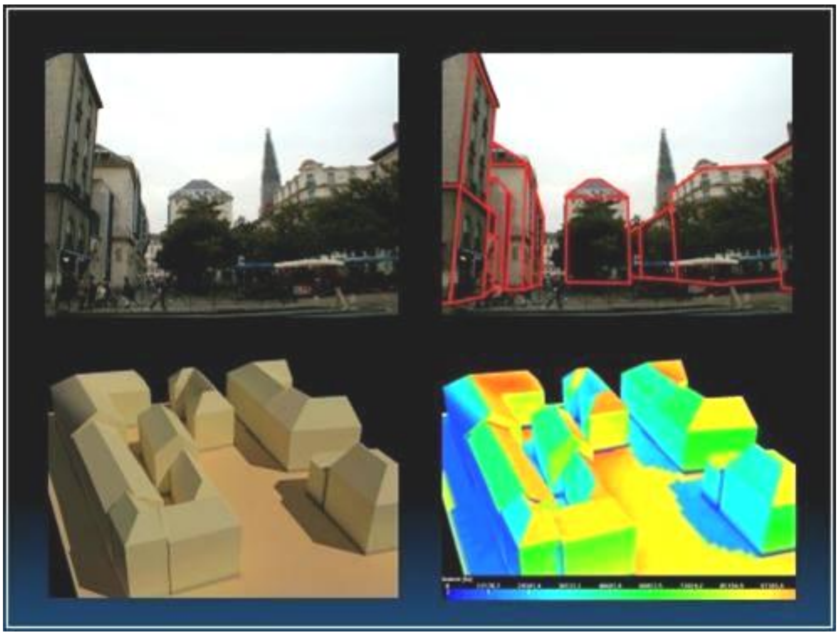


Figure 60: Solar radiation simulation software Townscope II. Simulation steps: a) top left: consider a complex urban space; b) top right: simplify it by removing everything the calculations do not take into consideration; c) bottom left: cut out the modelling space into faces; d) bottom right: obtain false-coloured images through application of algorithms.

Developed primarily for solar access evaluations, the 3D scene Townscope (Teller and Azar 2001) produces a series of images using different types of geometric projection (see Figure 60). Sunpath curves are overlaid on stereographic projections of the urban scene to judge solar access from a given view point. Isoaire projection (projection which respects the solid angle) of the scene is used to indicate sky access, with the proportion of white space (sky) being equivalent to the sky factor[26]. Assuming hourly sun positions for each mid-month day isotropic sky conditions and a single diffuse reflection, the software also predicts global irradiation on the built surfaces; based on methods of surface projection and masking. Finally, the sky component of the daylight factor is also predicted for each surface as an indicator of daylight access. A. J. Marsh (Marsh 2004) has recently employed a similar technique in his software Ecotect – using an isotropic sky but with real sun positions to predict direct and diffuse, (though not reflected) annual irradiation.

In a similar vein to the shadow footprints of Everett, the software “shadow” automatically calculates ground contours, expressed as percentages relative to unobstructed values (Kristl and Krainer 2001). Taking this principle a step further, “shadowpack” produces ground irradiance isopleths based on point calculations of direct irradiance in urban settings (Peckham 1985), “shading” calculates façade shading fractions (Yezioro and Shaviv 1994). This idea has since been extended by Quaschning and Hanitsch (Quaschning and Hanitsch 1998) by also accounting for diffuse shading of an isotropic sky using projected shading factors due to obstructing polygons, in calculating direct and diffuse (though not reflected) surface irradiance.

An alternative technique for solar access studies involves the use of image processing techniques to manipulate digital elevation models, in which a pixel location has (x, y) coordinates and z is represented by a 256 digits greyscale (Richens 1997). In the present context, the central feature of this technique is a shadow-casting algorithm. Pixels are shifted into neighbouring locations along the opposite vector of the sun and values are diminished according to the displacement in z. A union of these images is built until pixels have shifted off the image or reached the ground (z=0). A corollary of this involves repeated shadow casting from a random choice of sky point vectors. The negative of the union of images, with appropriate cosine weighting, is then proportional to sky view factor.

It is interesting to note that existing site layout and planning guidelines relating to the utilisation of daylight and solar radiation (e.g. (Littlefair 1991) and (Littlefair, Santamouris et al. 2000)) seem to be derived exclusively from the Solar Access method discussed above and do not reflect later developments in accounting either for non-isotropic skies or reflected energy.

In a departure from these projection-based methods, a more accurate approach to the analysis of daylight and solar radiation potential in urban settings involves the use of numerical simulation methods. In this way, a realistic sky brightness distribution can be considered together with the sun, as can multiple reflections (both diffuse and specular) from urban obstructions of arbitrary complexity. There are two approaches to numerical simulation of radiation exchange: radiosity and ray tracing. The former essentially involves discretising the surfaces within the computational domain and solving for exchanges between light source(s) and illuminated patches and then for successive exchanges between the patches, assuming diffuse reflection characteristics (see (Cohen and Wallace 1993) for a detailed explanation). The latter may be either forwards or backwards; for the latter case, rays are spawned from surfaces within an observer’s visual field (the image to be rendered) initially towards light sources and subsequently within the ambient environment, using a Monte Carlo technique. This is a recursive process, so that once a reflecting surface is encountered, this too spawns rays. The process continues according to pre-defined image quality settings (such as minimum distance between sample points – affecting interpolation – and number of ambient bounces) until a satisfactory result has been achieved (see (Ward Larson and Shakespeare 2003 [1998]) for a detailed explanation).

[26] This is used in resolving “rights to light” cases in the UK.

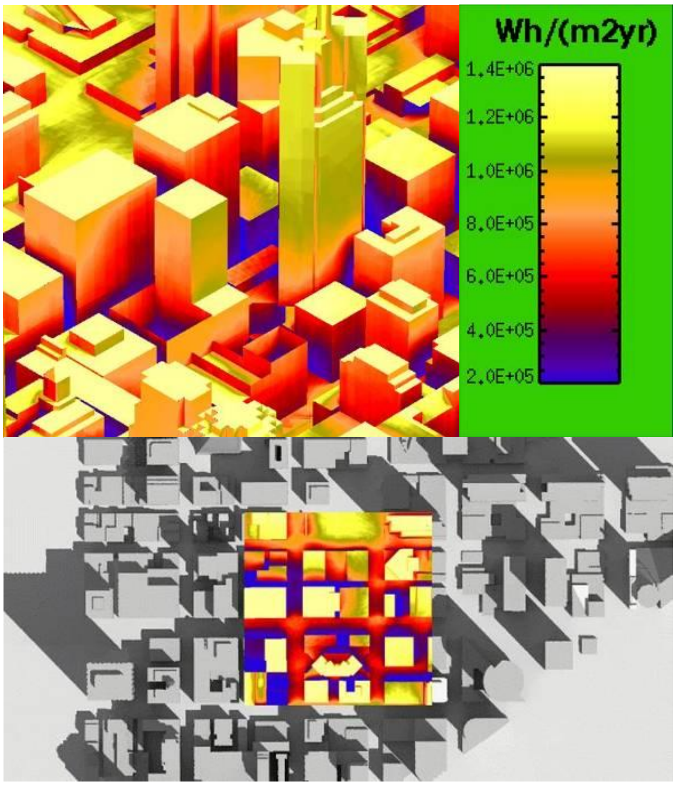


Figure 61: Total annual irradiation map for San Francisco (based on VRML model): a) top left: From North-West view; b) top right: irradiation scale; c) bottom: zenith view.

Source: EPSRC Project. Irradiation mapping of San Francisco Financial District. [online] URL: http://www.iesd.dmu.ac.uk/~jm/icue/ (Consulted on June 19nd, 2002).

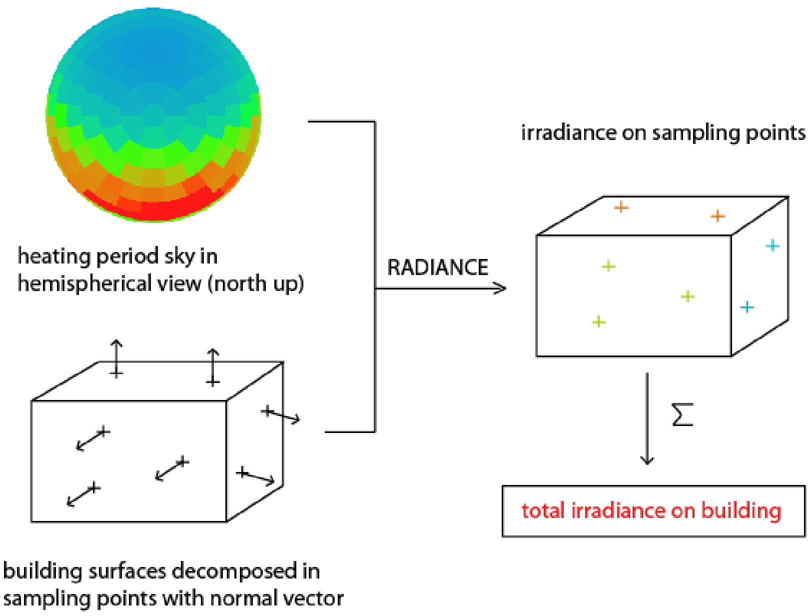


Figure 62: Jérôme Kämpf. Solar potential determination using the RADIANCE software.

Source: Kämpf, J. H., Montavon, M., Bunyesc, J., Bolliger, R., Robinson, D. (2009). Optimisation of buildings' solar irradiation availability. Solar Energy, 84(4): pp.596-603.

Numerous software tools have evolved which utilise radiosity and ray-tracing algorithms (or hybrids). Several studies have compared the methods on the basis of accuracy (Mardaljevic 1995) and usability (Ashmore and Richens 2001). The freeware ray tracing program RADIANCE (Ward Larson and Shakespeare 2003 [1998]) and related interfaces consistently outperform competing tools and RADIANCE being commonly used to produce high quality renderings (and associated quantitative results) for snapshots in time.

The power of numerical simulation has recently been exploited to excellent effect in the current context in the form of predicting solar irradiation. In one early study this was based on performing hourly simulations (Kovach and Schmid 1996), but subsequent work focussed on ways of reducing the computational expense of this form of analysis. Mardaljevic (Mardaljevic and Rylatt 2000) (Mardaljevic and Rylatt 2003) used image processing techniques to construct long time series (e.g. annual) results from a statistical subset of hourly simulations. Resultant false-coloured images then help with visual diagnosis, such as identifying potential for the use of solar energy conversion technologies (see Figure 61). An alternative method, introduced by Compagnon (Compagnon and Raydan 2000) (Compagnon 2004), involves the significantly quicker statistical pre-processing of the sky radiance distribution, as opposed to the post-processing of simulation results. The resultant synthetic sky can be used to produce the false-coloured images of Mardaljevic; the main aim is to produce results for a set of grid points, slightly offset from the normal of the set of built surfaces in an urban scene. Although this involves a large number of hourly simulations (potentially more than the technique suggested by Mardaljevic, depending on the size and complexity of the urban scene), the results from this set of "virtual pyranometers" can be processed, for example to produce solar and daylighting histograms. These solar-morphology fingerprints provide a priori information regarding the relative effectiveness of alternative designs. Furthermore, they may be combined with energy thresholds to quantify the proportions of built surface that could exhibit potential for passive and active solar or daylight utilisation. Furthermore, false-coloured images can be thresholded to outline the solar potential (Compagnon 2004) (Robinson and Stone 2004)[27]. Compagnon's method adopted for this research is described in details in Chapter 3.

More recently Kämpf (Kaempf, Montavon et al. 2009) has coupled a multi-objective optimisation algorithm with the backwards ray tracing program RADIANCE; the latter uses a cumulative sky model for the computation of incident irradiation (Wh/m2) in a single simulation in order to improve the sustainability of new and existing urban settlements.

RADIANCE is used to place virtual radiometers on building faces and roofs. The sampling points are separated by a maximal distance of 1m in order to capture the main features of the irradiance map on the surfaces. A cumulative sky (Robinson and Stone 2004) for the period of interest (heating period) is available for Basel from SOLURBAN project (Scartezzini, Montavon et al. 2002; Montavon, Scartezzini et al. 2004; Montavon, Scartezzini et al. 2004; Robinson, Scartezzini et al. 2005; Robinson 2006). Figure 62 represents the whole process of solar potential determination. Detailed features of the buildings (windows and differently painted walls) are not represented. A global approach is used considering a 20% Lambertian (diffuse) reflectance on all surfaces (walls and roofs).

2.8 Conclusion

The current chapter has presented the various works and sun-related recommendations that have appeared mainly since the end of the nineteenth century, together with the various scientific models and software tools pertaining to this topic. Many theories, tools and methods have been proposed by physicians, engineers and physicists, as well as by the architects themselves. Solar radiation problems arising in this period and the solutions suggested by architects and urban planners have left written and built traces and sometimes open questions. The logical relationship of these theories, their various

[27] This is also based on cumulative sky modelling for which the methodology is described in some detail – the implementation details of this approach differ, but the principles are similar.

probable applications, their careful comparison with earlier or contemporary foreign theories will be studied more effectively with an enlargement of geographical and temporal sectors.

Many lessons can be learnt from the past. In the first place, choosing between various proper solar orientations alternatives has been a persistent problem from the 19^{th} century until the beginning of the 20^{th}. Even today, in spite of the scientific knowledge and various conceivable parameters, this choice is frequently problematic and restrictive. At the present time, it is still impossible to respond spontaneously to the questions at the beginning of Chapter 2 “Which urban form is the healthiest and which offers the best all-season access to the sun?”

There are too many factors to consider. Certainly, urban solar conditions depend very much on the position of the sun and on the shape of the urban space. However the sky clearness is another crucial factor. Other factors such as albedo or the reflectivity of surrounding surfaces affect solar irradiation; however their effects are much less important than geometry. Suffice it to say that, under clear sky conditions where direct solar radiation is dominant, the H/W ratio and sky view factor are vital in determining urban solar environment.

Secondly, it can be seen that the sunlight problems architects have to solve are changing from era to era. The hygienist movement called for a constant solar ideal with the goal of fighting the existing putrid smells. On the other hand, today’s designers have to cope with the issue of summertime comfort behind glazed areas. Ironically, they are now frequently seeking to provide protection against excessive solar gains.

Finally, numerous theories, simulation tools and methods have been proposed to such an extent that today, even for a professional, it is difficult to make a choice. In actuality, sunshine-related issues encountered by designers are complex. It is a matter of reconciling financial aspects and environmental care, energy efficiency of buildings, summertime and wintertime comfort, expected ambience quality that often call for transparency and clearness, protection and freshness as well as view and privacy.

Nowadays, construction techniques, materials, digital modelling and rendering tools enable all kinds of complex shapes to such an extent that energy efficiency of the architectural or urban form often plays a second role. Priorities should be redefined and one should determine, prior to construction, which architectural or urban form would make the most out of these new building techniques. This is certainly a more logical and simpler procedure than trying to correct design errors months or years after construction.

Chapter 3: Research methodology

3.1 Introduction

As shown in the previous chapter, several famous architects and urban planners designed their buildings by tracing sunrays on the basis of the daily sun course. However, these first solar-oriented works on urban planning were carried out manually without the benefit of modern instruments. Nowadays, computers have replaced these traditional methods offering more efficient and more accurate approaches. The advent of numerical methods is linked to the development of computer technology whose speed has continually increased over the years. The use of information technology goes beyond the simple visual presentation of architectural projects, as is often the case in architecture. Computer tools have gradually influenced architects to rethink their design methodology during the elaboration of architectural projects. Formerly, architects or urban planners had designed by formulating conceptual ideas to define the main axes of development and objectives of their architectural project. This first step typically took the form a paper sketch. Working out an architectural or urban project is however a complex process, dealing simultaneously with rational and intuitive thoughts. This search for architectural solutions and tradeoffs requires rigorous tools, which can provide convincing scientific arguments to justify the crucial decisions an architect must take.

The current chapter gives an overview of the procedures and methods frequently used in the field of computer graphics, particularly in numerical simulation as well as the different methods used to create a 3D virtual city. The actual urban models that were used within this research work are presented in Chapter 4, as well as their digitalization process: the purpose of this chapter is to introduce important notions encountered therein.

Two illumination models are used to produce realistic synthesis images, namely ray tracing and radiosity. Although they differ in their approach, they both give realistic renderings via the modelling of phenomena linked with global illumination. Therefore, the combined exploitation of these techniques enhances the realism of the results.

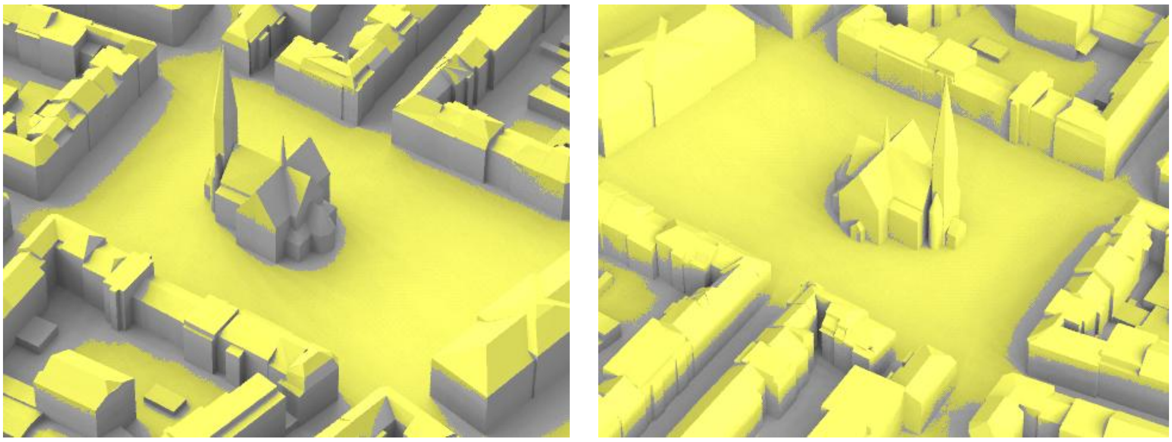


Figure 63: Thresholded image relating to passive solar gain (165 kWh/m2.year) in Matthaeus district (Basel). Appropriate glazing choices vary greatly, depending on the location of the solar gain on roofs, walls, and the building interior through window in Winter (where passive solar heating is desired).

To understand the notion of realism, it is crucial to find a powerful tool that will supply accurate information on the various factors influencing this realism. Several methods currently use this principle, one of which is PPF/Radiance, a method applied and discussed in detail in this work. PPF/Radiance is an architecture design aid, which makes it possible —through the accuracy of its results —to assess the solar and daylighting potentials in an urban context. In particular, it is able to predict the most appropriate location on buildings for the various solar technologies (passive and active solar heating, daylighting, photovoltaic electricity) (see Figure 63). It generates, by way of wintertime and annual statistics and through false-coloured images, all the architect's options, predicting in this way the urban forms which will be the most suitable for the chosen location.

The method generally adopted for the entire set of simulations was to create—via a computer-aided drawing piece of software, namely AutoCAD— the digital model of each building prior to exporting it to the PPF software package. PPF simulation package was originally developed by Professor Raphaël Compagnon at the University of Applied Sciences of Western Switzerland (HES-SO). This technique was previously applied within an international project (Sustainable Urban Spaces), in two European projects (PRECis and RUROS), in the Swiss-funded (OFEN) project SOLURBAN, as well as in several studies pertaining to the urban form and renewable energies. The selected urban districts studies were partly carried out within national and international research projects (Compagnon 2000; Steemers, Raydan et al. 2000; Compagnon 2004; Montavon, Scartezzini et al. 2004; Montavon, Scartezzini et al. 2004; Nikolopoulou 2004; Robinson, Scartezzini et al. 2005; Cheng, Steemers et al. 2006; Cheng, Steemers et al. 2006; Montavon, Steemers et al. 2006; Kaempf, Montavon et al. 2007; Steemers, Montavon et al. 2007; Marchand, Montavon et al. 2008; Kaempf, Montavon et al. 2009).

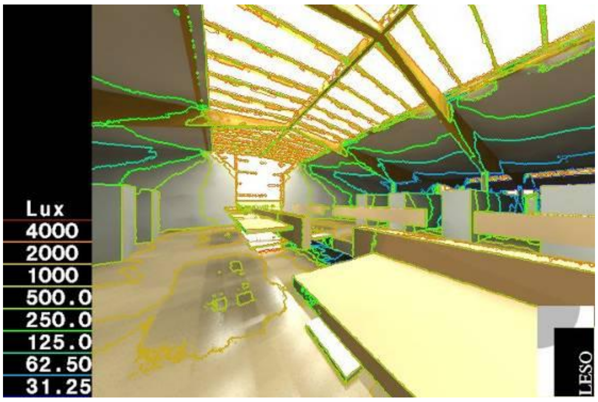


Figure 64: Virtual model of a factory hall with illuminance contours © 1994 by J-L Scartezzini, R. Compagnon.

Source: [online] URL: http://radsite.lbl.gov/radiance/frameg.html (Consulted on February 25[nd], 2008).

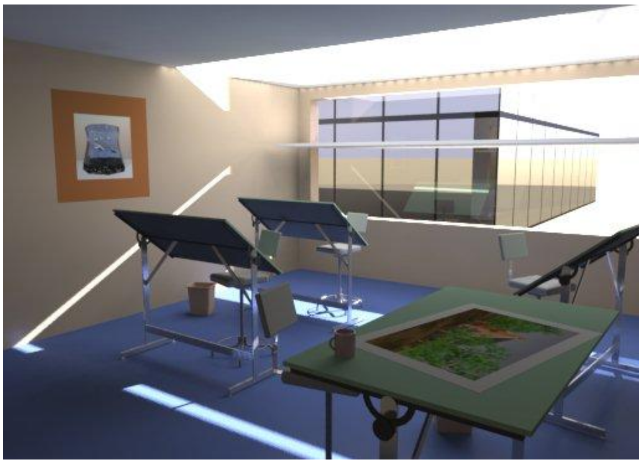


Figure 65 on right: Light Shelf Office. Furnished interior view, lower noise and specularity, © 1994 by Greg Ward

Figure 66 on left: Still Life picture with vases, oranges, lemons, bowl, textures, etc. © 1994 by Martin Moeck, Siemens Lighting.

Source Figure 65 and Figure 66: [online] URL: http://radsite.lbl.gov/radiance/frameg.html (Consulted on February 25[nd], 2008).

3.2 Assessment methodology

The realism of synthetic images, which the designer uses for the development of his architectural project, is a by-product of a broader activity: computer graphics. The latter is located at the meeting point of computer science and graphics. The software that is currently available in this domain has led to spectacular breakthroughs; so too have other building engineering programmes available for acoustics space design, lighting simulation, building energy analysis and solar performance assessment. Nevertheless, the basics of the underlying computer simulation methods are only suitable for single buildings and not for the miscellaneous variations of urban conditions (shadowing effect, inter-reflections within urban canyons, etc.). The current research work oriented toward the physical modelling of urban districts aims to extend building performance calculations by accounting for the variations and complexities of the built-up urban environment.

These programmes make it possible to explore and optimize, in a realistic way, the solar performance of the considered group of buildings. Today, 3D numerical models of buildings are used in almost every architecture and urban planning project. Compagnon (Compagnon 2002), a promoter of these novel urban modelling software reveals the benefits of these computer tools by emphasizing that it is "*needless today, when designing a project, to invest time and money into material prototypes*". Computer programmes, such as Radiance for instance (Ward Larson and Shakespeare 2003 [1998]) enable the planning and appraisal of indoor and outdoor lighting environment, increasing in this way our judgment capability of architectural and urban projects (see Figure 64). These numerical simulation programs provide a basis for representing a realistic sky luminance distribution, as well as the sun and the effects of multiple reflections (both diffuse and specular) from urban obstructions of arbitrary complexity (Robinson, Scartezzini et al. 2005).

Two approaches are available for numerical simulation of short and/or long waves radiation exchange: (1) the ray tracing technique expresses itself in terms of luminance by dealing with specular reflections, (2) whilst the technique of radiosity involves the calculation of radiative flux exchanges (short or long waves), before it supplies luminances values by assuming that all objects are perfectly diffusing (Djafi 2005). These two computer simulation approaches will be briefly presented in the following paragraphs.

3.2.1 Ray tracing technique

From an historical perspective, the *ray tracing technique* was put forward even before algorithms using the local lighting principle. The latter takes into account only the direct illumination of the surface of objects of a given scene, namely only the luminous interactions between the objects and the light source, which is supposed as punctual and isotropic (i.e. of a body that, in respect of one or more characteristics, possesses the same properties in all directions). Both the Gouraud (1971) and Phong (1975) models are two main references to it. In architecture and in other domains, realism remains a relative notion. For this reason, and for their rapidity of execution, techniques of local illumination are still widespread. On the contrary, ray tracing and radiosity are techniques of global illumination which are used when realism is sought in synthetic imaging. Appel (1968) introduced this term first. He supplied a powerful calculation technique for luminous reflection and transmission situations, thereby providing an almost photography-like aspect to rendered scenes. At that time, in spite of the quality of the produced synthetic images, this model was unsuitable for computers, which lacked sufficient calculation power. This technique was then set aside until Whitted (1980) published an article, which started from Appel's principle, and then described a simpler and more efficient computer method for the generation of realistic synthetic images: the latter include shadows, transparency and multiple lighting effects. The method was capable of reproducing specular reflection and refraction of light rays, particularly important for the rendering of an object reflecting on another one (Djafi 2005).

Ray tracing is a synthetic image computing method which can take into account most optical phenomena, such as self-shadings, cast shadings, specular reflections, regular transmission, as well as refraction through materials such as glass and crystal. The images obtained are frequently referred to as *photo-realistic* images due to the fact they mimic reality in a very accurate way (see Figure 65 and

Figure 66). However, the mere implementation of ray tracing cannot account for other optical phenomena, such as caustics (the envelope of rays emanating from a point and reflected or refracted by a curved surface) and light diffusion (the radiosity method tackles this difficulty).

The basic principle of the (backward) ray-tracing technique is inspired by a reverse vision process and uses a simple rule: it follows the light rays' path inside an imaginary three-dimensional scene (3D scene) starting from the observer's eye. As the follow-up of the light rays is performed backwards from the eye to the scene - the designation "backward ray tracing" is generally employed. This technique functions in a reverse way to nature, which casts rays from light sources toward the eye or a camera. It turns out that this procedure is far more efficient than the one used in "forward ray-tracing". The algorithm acts by casting a light ray (primary ray) for each single pixel of the screen: a straight line actually, connecting the observer's eye to the pixel of interest, cutting across the first object found in the scene, identifying thus an intersection point of this ray with the closest scene's object. The colour of the object is then deduced. From that point, other rays (secondary rays) can be, according to each object's property, generated toward other objects and/or a light source. The propagation of a ray comes to an end when all of the rays recursively reach the light source or the scene boundaries.

The procedure of this technique, illustrated by Figure 67, can be summarized as follows (Roudaut and Vidal 2008):

1. For each screen's pixel, calculate a straight line connecting the observer's eye to the considered pixel ;
2. When the first intersection of this ray with an object of the scene is found, define it as the closest object. Deduce the colour of this object at that point ;
3. Calculate a ray from the intersection point of the ray with the object and the light source. Find the first intersection of that ray with an object of the scene. If this intersection exists, and if the cut across object is opaque, then the considered point is on shade. If no intersection is found toward the light source, then the object is lit up. Carry out the illuminance computation;
4. Should the surface of the object be reflective, calculate a new reflected ray from the intersection point. Recursively call the same procedure for this new ray;
5. Should the surface of the object be transparent, calculate a new ray from the intersection point. Recursively call the same procedure for this new ray;
6. Add up the colour found for the reflected ray and the one found for the transmitted ray to the previously calculated pixel colour;
7. Proceed likewise for the subsequent pixels.

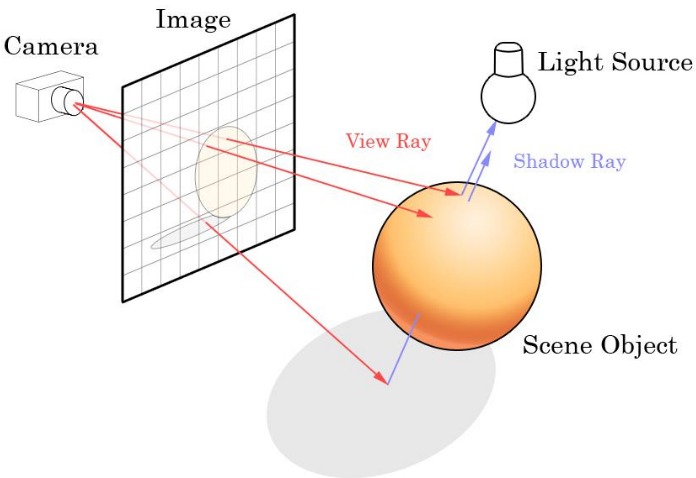


Figure 67: Diagram illustrating the backward ray tracing algorithm for rendering an image.

Source: [online] URL: http://www.http://en.wikipedia.org/wiki/Ray_tracing_(graphics) (Consulted on February 25nd, 2008).

Until 2001, due to the limited power of computers, this technique enabling the generation of very realistic images could be extremely time-consuming according to the complexity of the 3D scene. On the other hand, unlike other synthetic image algorithms, it does enable the mathematical definition of the objects to be rendered and not only by means of defining that object's surfaces. Since then, under specific conditions, numerous optimization processes of the algorithm can provide a real-time rendering (few images per second) and even a fluid one (more than 25 images per second).

Other computer techniques are likely to speed up this time-consuming process. When it comes to polygonal objects (e.g. objects made up of triangles), drawing the object in a classical way (*e.g.* via a raster) makes it possible to determine accurately which pixels are visible and to cast rays only for a limited set of pixels. In addition, the different techniques of identification of hidden surfaces allow the number of cast rays to be limited.

In conclusion, the benefits of the ray tracing technique come from the spectacularly realistic rendering of images: effects such as specular reflection on surfaces, light transmission by refraction and cast shadows are inherently reproduced. Moreover, smooth objects are rendered with fidelity and are not "pixelized" into elementary facets or patches. One of the main drawbacks of this technique is the recursion of rays, which can cause very large calculation time (several hours for a complex scene). This is due to the fact that, for each intersection of an object with a light ray, two additional rays must be potentially traced: one ray for light transmission through the object and another for specular reflection. However, this technique does offer the possibility of achieving a very faithful realism when the recursion level is carried on for a certain amount time. Another shortcoming is linked to the problems of illuminance calculations: ray tracing cannot reproduce an effect such as light propagation through a magnifying lens (light concentration or attenuation in certain areas), because it models only imperfectly energy transfers and light diffusion through materials (particularly air) (Janey 2007).

Despite some drawbacks, several studies have compared the lighting calculation methods on the basis of accuracy (Mardaljevic 1995) and usability (Ashmore and Richens 2001). These studies revealed that the freeware ray tracing program RADIANCE (Ward Larson and Shakespeare 2003 [1998]) consistently outperforms other computer tools and is consequently used most frequently to produce high quality image renderings (and associated quantitative results). For more details, the reader should refer to the book by Greg Ward Larson and Rob Shakespeare, *Rendering with Radiance* (2003 [1998]) (Robinson, Scartezzini et al. 2005).

3.2.2 Radiosity method

The *Radiosity method* is a lighting calculation technique used for rendering of 3D computer graphics, which does not allow for the direct calculation of a synthetic image. It was first developed around 1950 in the domain of heat transfer. The method was later refined specifically for application to the problem of image rendering in computer graphics in 1984 at Cornell University (Goral, Torrance et al. 1984). It is a global illuminance calculation technique, in the same way as Phong's[28] or Gouraud's[29] algorithm, are local illuminance calculation techniques. For that reason, radiosity is frequently associated with ray tracing (or Z-buffer[30]), which allows image rendering on the basis of its results (see Figure 68).

[28] The term *Phong shading* is used for the Phong illumination model and the Phong interpolation, two algorithms of 3D computer graphics.

[29] *Gouraud shading* is a technique of 3D rendering suggested by Henri Gouraud. Once limited to the context of synthetic imaging, it is nowadays used by all of the 3D graphic cards on the market.

[30] In computer graphics, *Z-buffering*, also known as *depth buffering*, is the management of image depth coordinates in three-dimensional graphics, usually made within hardware, sometimes in software. Z-buffering, which deals with the visibility problem by determining which of the scene items must be rendered, which ones are hidden by others and in what order the display of the primitives must occur.

The radiosity method is quite distinct from ray tracing, which addresses specular reflection. Radiosity is a global illuminance (or radiance) calculation method which determines the distribution of radiative fluxes (short or long wave) in an environment supposed to be perfectly diffusing. As a consequence, the illuminance on each elementary facet of the considered scene cannot be calculated separately, the entire set of radiative transfers being globally solved. The radiosity method takes only diffuse reflections into account and assumes that every surface of the considered scene is opaque and split up into a finite number of small patches (e.g. a facet) on which the radiosity (i.e. the luminous energy emitted by a unique patch) is regarded as constant (Djafi 2005) (see Figure 69).

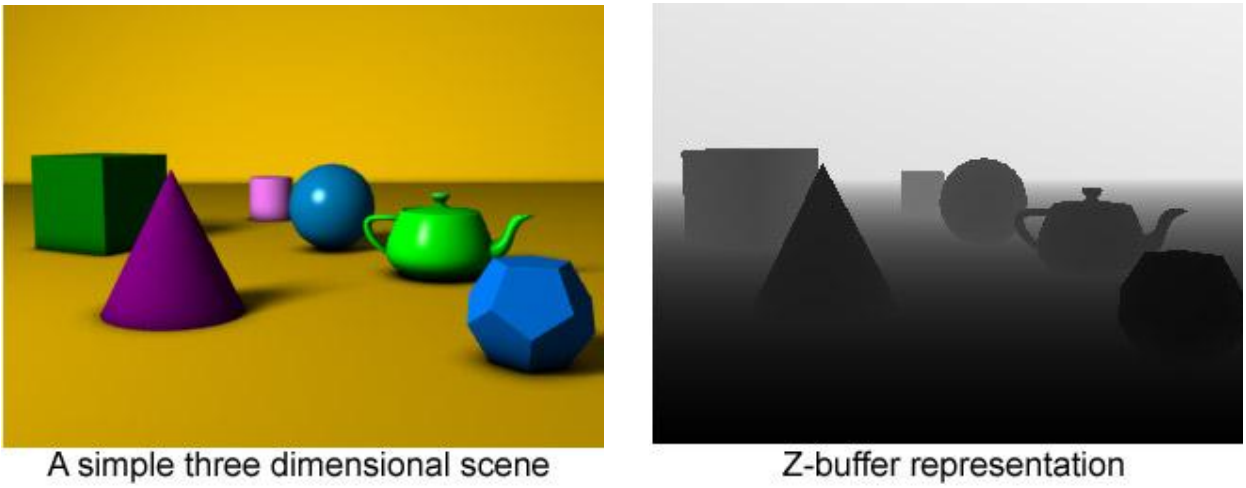


Figure 68: Images illustrating the Z-buffer data of a three dimensional scene.

Source: [online] URL: http://fr.wikipedia.org/wiki/Z-buffer (Consulted on February 25nd, 2008).

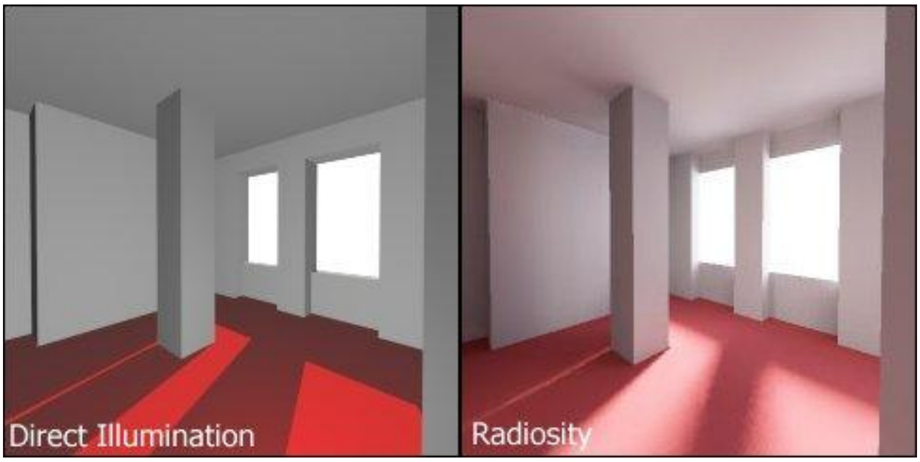


Figure 69: Comparison of direct illumination calculation with radiosity method (Models created by Hugo Elias).

Source: [online] URL: http://freespace.virgin.net/hugo.elias/radiosity/radiosity.htm (Consulted on February 25nd, 2008).

The determination of the radiative fluxes generated by all these patches within the scene, starting from one or several primary light sources, – is the core of the radiosity method. For this purpose, the scene is supposed to be closed, objects being located in the void and all inter-reflections between patches being accounted for. Every patch receiving luminous energy sends it back to the other patches of the rendered scene. A solution is attained as soon as a state of energy balance (*i.e.* a patch no longer gains energy) is encountered for each patch (Djafi 2005).

One of radiosity's advantages is that a very good estimate of light (or energy) fluxes within a scene is achieved, giving rise to very realistic images (if solving of local illuminance calculation is obtained by the ray tracing technique) (Janey 2007). Fast computing time is another advantage: once the energy balance is calculated, the display of a rendered scene is very fast (speed of the Z-Buffer or of ray tracing). Unlike the ray tracing technique, the energy balance must not be recalculated if a shift of the observer within the scene is operated, thereby enabling the generation of several perspectives by the way of the same calculation. As long as the scene is not modified, computer animations can be achieved in almost no time at all.

One of the shortcomings is that the radiosity algorithm only takes into consideration diffusive objects. It cannot account for specular reflections and regular transmission of light. The spatial discretization of the rendered scene and view factor calculations via the hemisphere (or hemicube method) cause certain aliasing problems to occur, such as problems related to shadows (too fuzzy and/or aliased edges, absent shadows for thin objects) or related to lighting (poor lighting of some areas, lack of precision on objects located close to the observer). Another drawback is linked to the computing time, the two phases of view factors calculation and linear equation system solving requiring numerous calculation operations. The view factors calculation phase is the most time consuming. More accurate result is achieved with a higher degree of discretization requesting a more extensive calculation time (Janey 2007).

Well-known commercial radiosity and currently available programmes are Lightscape (now incorporated into the Autodesk 3D Studio Max), Radiozity by Auto*Des*Sys and EIAS (Electric Image Animation System).

3.2.3 PPF simulation package (PRECis project file handler)

The PPF simulation package, originally developed by Professor Raphaël Compagnon at the University of Applied Sciences of Western Switzerland (HES-SO) (Compagnon 2000; Compagnon and Raydan 2000; Compagnon 2004), uses a sophisticated computer simulation method in order to determine the radiative exchanges between the sky vault and the urban context. All of the evaluation procedure resorts to a (a) detailed numerical model of the considered urban district, (b) a statistical database of solar irradiation and illumination generated by the Meteonorm programme (statistical annual and winter skies) and (c) a ray tracing program (Radiance). This procedure was implemented through an interface software package namely PPF. It makes it possible to link the whole set of required computer operations on a Linux/PC platform. Data are displayed numerically, graphically (as histograms) and visually (as renderings and false-coloured images) enabling the analysis and direct comparisons of varying complex urban configurations. (d) The use of Winter and annual energy thresholds (*e.g.* determining the pertinence of passive and active solar collectors, photovoltaic panels and daylight technology) allows an appraisal of the quantity and appropriate location of any given solar energy technology to be exploited. In addition, important modifications were made to the software package during this thesis, compared to a first application centred more on computer graphics. The objective was to enable an appropriate combination of digital building data with those of the geographical topography of the site in order to be able to use the ray tracing technique to assess the solar potential of buildings at an urban scale.

The relationship between the three steps (a, b and c) presented above can be expressed as a symbolic equation where the ↳ symbol denotes an operation performed by a computer simulation tool (Compagnon 2000) (see Source Figure 70).

[Final Energy]

=

[Urban Solar and Daylight Availability]

⇘

[Utilisation Factors]

with:

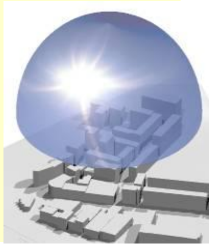
[Urban Solar and Daylight Availability]

=

[Sky Model]

⇘

[Urban form]



Source Figure 70: Compagnon, R. (2000). PRECis: Assessing the Potential for Renewable Energy in Cities, Annex 3: Solar and daylight availability in urban areas. Fribourg, University of Applied Sciences of Western Switzerland (HES-SO).

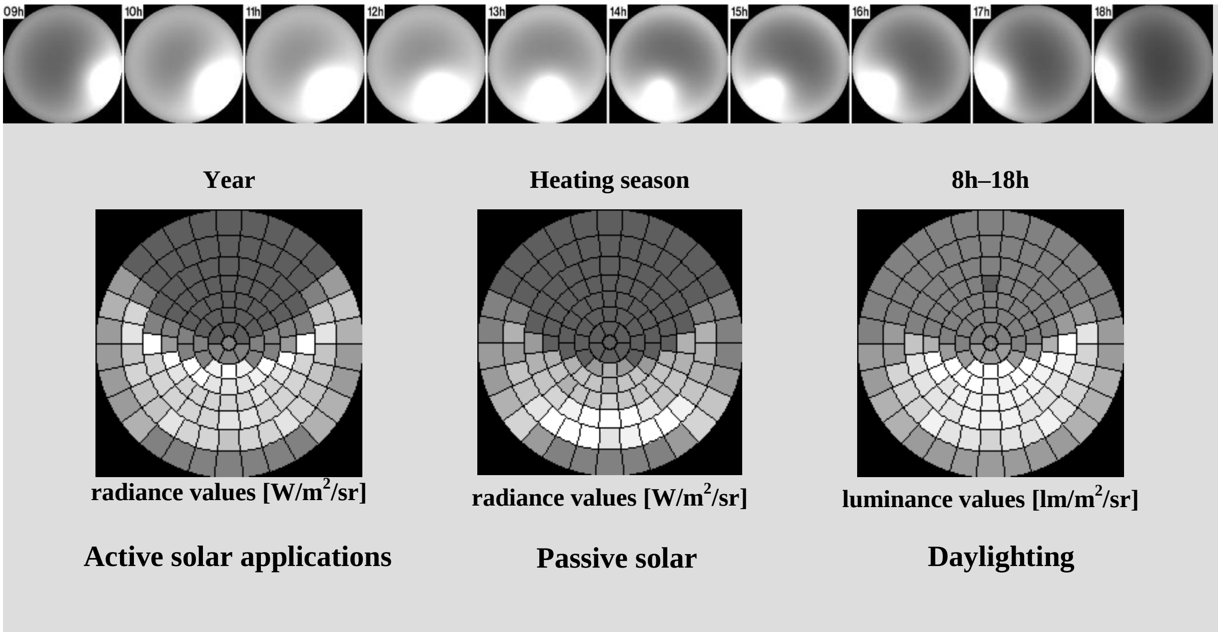


Figure 71: Stereographic representation of radiance levels for the Fribourg radiometric average sky. Radiance levels are averaged over 4330 diurnal hours for a whole year.

Source: Compagnon, R. (2000). PRECis: Assessing the Potential for Renewable Energy in Cities, Annexe3: Solar and daylight availability in urban areas. Fribourg, University of Applied Sciences of Western Switzerland (HES-SO).

Essential elements[31]

The 3D geometry of a given neighbourhood, once defined using a 3D modelling tool such as AutoCAD, is imported into PPF in DXF format and translated into its native ASCII format. Some basic computations are carried out in this format, for example to deduce total built floor area (using specified or deduced numbers of storeys). A further translation is then performed to produce a model in the format required by the extensively validated, ray tracing program RADIANCE (Mardaljevic 1995; Ward Larson and Shakespeare 2003 [1998]) to which the sky model is also parsed. A set of performance-related quantities is calculated by PPF[32] in order to determine the potential of urban sites to utilise different radiation-based technologies (passive and active solar and daylighting), for which different sky types are required.

Firstly, to assist with the interpretation of results and potentially to inform judgements regarding long wave radiation exchange potential (e.g. for radiant cooling of buildings) a uniform overcast sky is described. By integrating the energy received per unit sky over the hemisphere we have an irradiance I ($W.m^{-2}$) of πR, for radiance R ($W.m^{-2}.Sr^{-1}$). For a unit radiance sky we can therefore calculate a sky view factor as I/π. In contrast to this continuous treatment of sky brightness, to determine annual solar irradiation the sky is represented as a set of 145 sky zones, each represented as a discrete but relatively large light source (i.e. of solid angle not much less than $2\pi/145$). The radiance of each sky zone is the cumulative radiance over the period of interest, so that the units are $Wh.m^{-2}.Sr^{-1}$. When calculated over the duration of the heating season we describe the sky required to calculate the heating season solar irradiation. Furthermore, by multiplying the former values by a relevant luminous efficacy and by dividing the corresponding results by the number of daylight hours, we have the sky required to calculate annual mean illuminance (see Figure 71)

The PPF software package involves a quicker statistical pre-processing of the sky radiance distribution, as opposed to the post-processing of simulation results used by Mardaljevic. The resulting synthetic sky can also be used to produce false-coloured images, the principal aim being to calculate irradiance and illuminance on a set of grid points, slightly offset from the normal of the set of built surfaces in an urban scene. Actually, this means that measuring points (virtual radiometers) are located in the scene. Due to Radiance's accuracy, they cannot be attached to façades: they have to be moved slightly. PPF includes a parameter enabling the placement of these measuring points 5 cm away from the façade.

When used in conjunction with various thresholds, results from calculations performed using these skies contain all of the information required by the present project. For example, results can be processed to determine the area and proportion of built surface for which solar photovoltaic panels, solar thermal collectors, passive solar systems and daylight responsive electric lighting will be viable (the basis upon which these judgements is made is discussed in Section 3.3.

However, several modifications needed to be made to PPF to handle the large scale of the urban districts under examination within this project (up to almost 1,000 ha or more – 2471 acres) as well as different 3D model formats and combinations of building and site topography models. Furthermore, a separate easily programmable post-processor has been developed at EPFL to provide greater flexibility for

[31] For the main points of this paragraph (subsections 1, 2, 4 and 5) I am indebted to Robinson, D., Scartezzini, J.-L., Montavon, M., Compagnon, R. (2005). SOLURBAN: Solar Utilisation Potential of Urban Sites, Swiss Federal Office for Energy (OFEN). Lausanne (Switzerland), Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL).

[32] Checking surface areas with the PPF tool was carried out during this study. A difference of 0% was recorded between the three-dimensional models of simple geometrical shapes with AutoCAD and the surfaces produced by PPF. Whenever the virtual model would take on serious complications, this margin of error would climb to 0.68% for the façades and to 2.5% for the sloping roofs. In this case, the difference was minimal, thereby confirming the validity of the PPF and the results that were presented.

results analysis, rather than relying upon continuous modification and re-compilation of PPF. The final technical report about PPF is available in (Compagnon 2000).

Irradiation and illuminance on sampling points

For all the simulations the sampling points of urban models were placed at 1 m. Nevertheless, a battery of variations to the veritable limits of the possible was imposed in order to test the accuracy of this decision. Once again, it has to be pointed out that the calculation time depends on the distance between the sampling points and smaller this distance is, longer the time of calculation will be. Table 10 shows the points calculated for the generic model “Slabs East-West”. The simulation has been carried out using the typical winter sky conditions of London (Compagnon 2004).

Table 12: Irradiation on sampling points for “Slabs East-West” with the Winter sky of London

	Slabs EW		Solar thermal viability	E/A kWh/m².year			Variations	
Samples (m)	**Façades (annual)**	**Roofs (annual)**	**Envelope (annual)**	**Façades (annual)**	**Roofs (annual)**	**Envelope (annual)**	**RP – Samples**	**%**
10.00	53.5%	100%	65.1%	429.4	896.5	546.2	-4.7	-0.85%
5.00	67.4%	100%	75.5%	436.9	899.1	552.5	+1.6	+0.29%
2.00	63.0%	100%	72.3%	434.4	899.9	550.8	-0.1	-0.01%
1.00 (RP)	**63.4%**	**100%**	**72.6%**	**434.4**	**900.4**	**550.9**	**0.0**	**0.00%**
0.80	63.4%	100%	72.6%	434.3	900.3	550.8	-0.1	-0.01%
0.70	63.1%	100%	72.3%	434.4	899.2	550.6	-0.3	-0.05%
0.60	63.7%	100%	72.8%	434.8	900.5	551.3	+0.4	+0.07%
0.50	63.3%	100%	72.5%	434.5	899.6	550.8	-0.1	-0.01%
0.40	63.5%	100%	72.6%	434.5	899.1	550.7	-0.2	-0.03%
0.30	63.4%	100%	72.5%	434.4	899.3	550.6	-0.3	-0.05%
0.20	63.3%	100%	72.5%	434.2	899.2	550.4	-0.5	-0.09%
0.10	63.2%	100%	72.4%	433.7	897.8	549.7	-1.2	-0.21%
0.05	63.0%	100%	72.2%	433.0	895.5	548.6	-2.3	-0.41%

At first sight, the results reveal a negligible difference of 2.3 kWh/m^2.year by placing the points at 5 cm instead of at 1 m and a difference of 4.7 kWh/m^2.year as a result of placing the points at 10 m. In a second analysis, one can see for example that the results of the solar thermal viability are much more dramatic. They indicate that 63.4% of the façade area is usable for solar thermal in the façade at a distance of 1 m, 63% at 0.05 cm and 53.5% at 10 m. To have used a distance of 10 m would have skewed the results. Conversely, a considerable amount of time would have been gained by placing sampling points at 2 m instead of at 1 m. At less than 1 m, the results do not greatly change. Placing the irradiation and illuminance on sampling points at 5 cm would not have been viable because of the long calculation times which would have ensued because of this decision. Certainly, this solution would have been closer to reality but on the other hand it is completely unrealistic.

There are two important reservations that should be noted before leaving the topic of PPF. Firstly, the distance of the sampling points has to be decided according to the object to be simulated. Secondly, for an optimal result, one has to differentiate between a detached house, a city block or a district for the correct alignment of the points.

3.2.4 Description of 3D Digital models of urban sites

The third dimension is a long-known theme in measuring techniques, in particular for all-purpose construction projects in the form of contour lines for the whole land, in country-wide maps and in the site plan of official measuring as stated in (Wirth 2005). Due to constraints related to utilization possibilities, the contour lines and profiles were the most widespread forms of representation. The advent of computer-aided design (CAD) made the resort to the third dimension in engineering and architecture more common. The development of powerful computers enabled the processing and elaboration of three-dimensional (3D) digital models that were closer to reality.

Rebuilding a 3D virtual city from cadastral maps, architecture plans, airborne or ground-shot photographs of buildings is a complex issue requiring vast efforts. In frequent cases, most of the tools for city representation are still incomplete, bi-dimensional (2D) documents that give a restricted view of the proposed building project. However, the city is a volume made up of increasingly more complex constructions and non-built areas. The main reason for working with urban space representation is that is enables the designers, urban planners and researchers to understand the consequences of strategy-linked choices without discarding the architectural details. 3D digital models are currently used in the following fields (Wirth 2005):
- Environmental engineering (noise, radiation, climate, fate and transport of pollutants, etc.);
- Protection of the cultural property and monuments;
- Urban planning and architectural projects;
- Management of urban infrastructures and networks;
- Aviation-applied electronic techniques;
- Establishment of hazard maps (avalanches, stones falls, floods, slide zones, etc.).

During the last fifteen years, various approaches were developed to capture the geometry of buildings and city sets, as well as surface topography. Some studies relied on photogrammetry or computer-assisted vision; others addressed the development of tools for laser acquisitions of 3D cluster points in order to generate a Digital Terrain Model (DTM-AV).

The DTM-AV represents the earth surface topography without vegetation and buildings with a height accuracy of ± 0.5 m. This conventional method interpolates the digital model from a set of known and outspread points, measured beforehand. Nowadays, new sensing techniques exist: X-Band Radar, satellite and aerial imaging systems, light intensity detection and ranging. The airborne laser enabling the acquisition of altimetry data is a competitive solution for the generation of DTM-AV and especially for Digital Height Model (DHM). A DHM models reproduce the shape of the earth's surface including all permanent and visible landscape elements such as the vegetation, forests, buildings and other civil engineering structures (height accuracy of ± 0.5 m in open zones and ± 1.5 m in dense-vegetation zones).

Thanks to the LIDAR technique (LIght Detection And Ranging), every point of the considered model is directly measured at the time of the flight over of the zone. The second advantage is that the laser is capable of measuring several heights (elevations) in the same scan: in this manner the top and base of a building can be identified. The representation of a city's buildings or a forest is made possible by way of specific data post-processing; the same data acquisition can be used for several kinds of applications (DTM-AV, DHM, vegetation analysis, urban measurements, etc.). 3D digital models of urban sites are generated in the form of regular DHM grids, regular built-Digital Elevation Model (DEM) and possibly vegetation-DEM, as well as in the form of wireframe models.

A presentation of the various ways of acquiring topography data from aerial photographs is given by J.-B. Henry. Figure 72 makes it possible to classify the solution resorting to a drone[33] among the main solution using airborne carriers. The metrical to centimetrical accuracy improvement announced in terms of geometrical rendering for X, Y and Z coordinates seems very promising (Raclot, Puech et al. 2005).

Some researchers have devoted their studies to the development of specialized CAD software for 3D modelling (Allplan, ArchiCAD, AutoCAD, 3ds MAX, Arc+, etc.). Google Earth (developed by

[33] An unmanned aircraft or ship guided by remote control used for various tasks (high-altitude reconnaissance, battle field surveillance and digital war).

Keynole Inc. and bought by Google) enables the user to fly over the Earth's surface and to zoom on selected locations: depending on the geographical region, three-dimensional information is available. The 3D modelling of buildings and infrastructures is even available now through the help of an architecture-oriented software (SketchUp). Google 3D Warehouse, referred to in French as *Banque d'images* is a service offered by Google SketchUp (the latter was bought by Google) to store 3D models created by users. It makes it possible to download other users' models, to store them and to share them with the rest of the world. These new tools will certainly be very helpful in the near future for the generation of 3D digital models of cities.

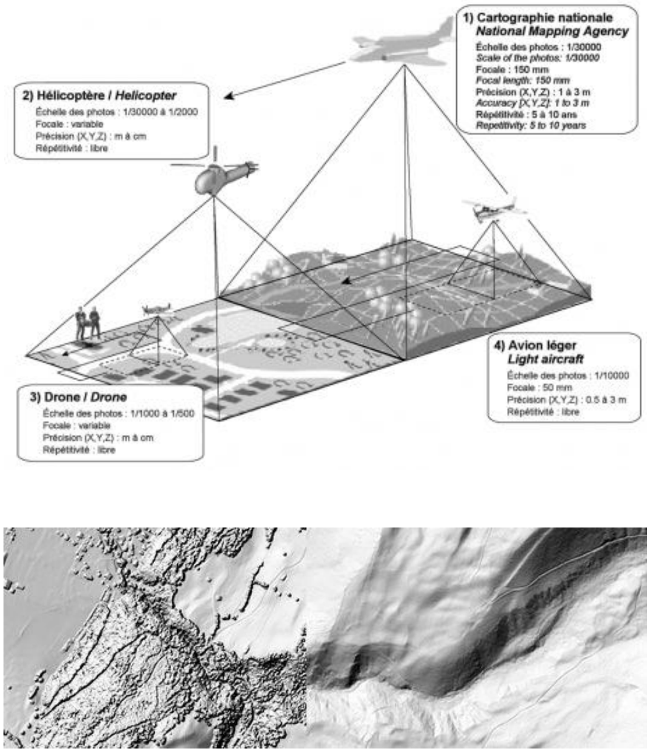


Figure 72: Different modes of photo acquisition and final accuracy of the processed DEM (top) and DOM or DHM /DTM – AV samples (bottom).

Source Figure on top and on bottom: [online] URL: http://geomorphologie.revues.org/document209.html and URL: http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/downloads/height/dom_dtm-av.html (Consulted on March 3nd, 2008).

Other researchers addressed the automatic or semi-automatic generation of 3D digital models of urban sites relying on the use of an architectural knowledge data base. "*Assuming that one has a DTM model and the land register of a scene at one's disposal, it becomes possible to generate a first 3D model in which buildings heights have a default value*" as stated in (Beaudry 2005). The model can be displayed on a VDT screen under any angle; the user can edit the height of the buildings according to the available information. Photographs can also be shot from the ground or the roof of edifices thereby offering a more authentic view. They can be superimposed on the initially created 3D digital model. By matching the virtual model and a photograph, the position of the camera that captured the image can be deduced. With a sufficient number of points, the camera orientation can also be determined. By displaying the model on top of the background photograph, the user can retrieve the building heights (Beaudry 2005).

The *Centre de Recherche en Architecture et Ingénierie de Nancy* created a method in 1998 which in most cases makes it possible to solve and generate plausible urban volume data. The 3D digital models obtained, in spite of their geometric simplicity, are sufficient for urban planning purposes for which high precision is not required. The method has been included in the MEDINA system; several experiments were carried out with a satisfactory success rate (Perrin, Allani-Bouhoula et al. 1998). Since then, (Chevrier and Perrin 2001) have developed an interactive tool in the Maya environment (ALIAS Wavefront) which can achieve an approximate 3D virtual reconstruction of buildings.

Most of these methods necessitate either frequent intervention from the users, important financial or time-consuming resources or complicated data reconstruction processes. Methods are also contingent on the required accuracy level. A coarse reconstruction is sometimes satisfactory, whereas, in other cases, a smaller area must be more faithfully reproduced. In most cases the main principles consist in splitting up the reconstruction process into the following steps:

- obtain the most relevant documents (2D cadastral plans and architecture plans);
- outline the contour lines and elevation numbers of terrain (e.g. DTM-AV, DHM);
- take photography of the considered district’s buildings (if needed);
- locate buildings on the 2D cadastral or architectural plans;
- assess the buildings’ heights (in particular the facades);
- assess the buildings’ shapes (in particular the roofs);
- improve realism and buildings details (dormer windows, balconies, cornices, etc.);
- calculate the relief of the terrain.

One of the difficulties of this work was to retrieve topographical maps of the considered districts and to achieve a simplified virtual reconstruction of the built environment by matching the buildings with the terrain data. The principal objective of this work being the assessment of the solar utilization potential of the site (by the way of PPF software), this difficulty had to be overcome in order to be able to use this software. Unfortunately, in most cases, three-dimensional data of the buildings and/or the terrain were lacking: as a consequence, the first step consisted in setting up a 3D model of the area using the available bi-dimensional data (e.g. digitized cadastral plans and/or conceptual architecture plans).

For a better understanding, the next chapter presents in detail the 3D digital models of the different urban sites that were considered in the framework of comparative studies and the associated modelling results. Most of them were built up using AutoCAD (3D Face command), which reproduce most of the 3D morphological objects by the way of 3 or 4 edges elementary facets. As the positions of the apices of these facets are not forced, the 3D object can be non-planar. However, points must be entered in the correct order to form an outline. The corresponding AutoCAD command offers the possibility of building a series of contiguous, but independent, 3D facets making up a row (see Figure 73).

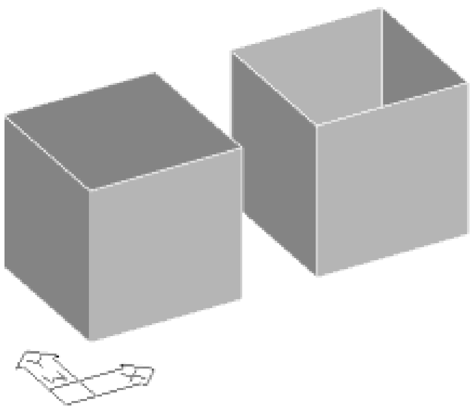


Figure 73: Examples of simple volumes generated via the 3D FACE command.

It must be outlined that the modelling task did not rely on the use of self-generation algorithms for 3D morphological objects. However, scripts were used to build up the façades of several 3D digital models, such as those of the districts of Bellevaux in Lausanne, Luz & Barra Funda in São Paulo, Pâquis in Geneva and The Contemporary City from Le Corbusier.

3.3 3D Digital model set

3.3.1 Scope and limitation of assessment method

Computer simulation is an efficient analysis and design tool for urban planners, which allows a better understanding of the physical phenomena involved within urban sites (such as solar energy collection on the building roofs for instance). It has progressively gained more importance within the urban and solar energy research community. In spite of some intrinsic limitations of numerical modelling, which formally requires validation by the way of experimental data, the asset of computer simulation lies in our case in the possibility of comparing different urban planning projects: it enables us to grasp the performances of existing urban sites versus new urban planning projects.

3D building models are three-dimensional representations of existing or conceptual urban objects, which can be very detailed. The urban morphological elements, used in this study in order to describe these objects, are peripheral wall heights and building roofs geometry. In order to reduce the computation time, buildings were in some cases described as simple prismatic volumes: this is the case for the Meyrin district for instance. The Eastern Quarry's district was analysed using assumptions on the buildings' shapes, data related to roof heights and shapes being unavailable. Likewise, for this last example, the topography of the urban site was modelled using a limited amount of available input data: only contour lines and elevation figures were used in this case (see Sections 4.4.2 and 4.7.2 for a better understanding of this important argument).

The urban models used in this study can be ranked according to the accuracy and completeness of the corresponding digital data, leading to the following decreasing order:
- Tower Works, urban district in Leeds (England);
- Bellevaux district in Lausanne (Switzerland);
- Les Pâquis 1+2 districts in Geneva (Switzerland);
- Matthaeus district in Basel (Switzerland);
- The Contemporary City in Paris (France) suggested by Le Corbusier;
- Luz and Barra Funda urban districts in São Paulo (Brazil);
- Eastern Quarry in London (England);
- and Meyrin site in Geneva (Switzerland).

The urban district of Leeds is in consequence the most accurate and the one of Meyrin the least realistic. Indeed, the final 3D digital model of Leeds is very precise (with 1 cm accuracy). All flat or sloped roofs were properly modelled, including the overhang parts (e.g. the presence of openings, supporting pillars, balconies, etc.). Unfortunately, in the case of Meyrin, the model remains somewhat crude, sloped surfaces of buildings being undefined. An average height is suggested and therefore leads to roofs with a flat shape. All buildings having a height lower than 1 meter have been deleted.

For most cases, the following building elements were not included in the 3D digital models:
- eaves;
- overhang parts (overhang slabs, canopies, outdoor staircases and outdoor landings);
- superstructures (chimneys, balconies, canopies, cornices, dormer windows, skylights, elevator shafts, blower rooms, ducts, etc.);
- open building parts (sheltered terraces, verandas, etc.).

All these elements are responsible for certain shading effects: the latter were considered as negligible in the course of the overall evaluation of urban performance carried out in this study.

The photometric characteristics of the building surfaces, as well as those of the ground (*e.g.* the surface reflectance[34]) are considered to be homogenous over the building envelope and equal for all buildings (ρ=20%) : the on-site monitoring of each building would have required a tremendous effort. This rather low reflectance value was obtained by averaging the albedo of the corresponding façades (that can be as high as 80% for light-coloured buildings) and the window openings that appear as a dark area from outside. A precise positioning of the windows on the external building envelopes would have been of high interest; nevertheless, this was set aside because of time-related constraints (Compagnon 2004).

Other limitations in the modelling arise from the possible direct shading effects of the trees on the buildings, as well as their indirect impacts (evapo-transpiration exchanges, cooling and wind obstacles) related to rain water drainage or carbon capture.

Meteorological data were used to build-up several statistical skies which are used to assess the solar radiation and daylighting conditions of urban areas, as well as the solar energy supply from active and passive solar systems. This method does not take into account the heat flux transmissions within buildings, that is to say thermal energy losses and solar gains of buildings. Neither was the effect of human behaviour on building performance nor the local thermal urban situation (heat highlanding) taken into account. Nor were decentralised energy supply systems considered (such as district co-generation for instance).

Finally, the different studies do not include a financial evaluation of various energy conservation strategies (such as thermal insulation of the building envelopes for instance); solar radiation thresholds were used however for the different solar technologies in order to account for their financial profitability and feasibility (Steemers, Montavon et al. 2007).

Table 13: Threshold values proposed to compute the potentials for the corresponding solar techniques

Solar techniques	Threshold for systems mounted on façades	Threshold for systems mounted on roofs
Photovoltaic systems	800 [kWh/m^2.year] annual solar irradiation	1000 [kWh/m^2.year] annual solar irradiation
Solar thermal collectors	400 [kWh/m^2.year] annual solar irradiation	600 [kWh/m^2.year] annual solar irradiation
Daylighting systems	10 [kLux] mean daylighting during office hours (8:00-18:00)	
Passive thermal heating	Varies according to climates: is defined as the amount of solar irradiation required to fully compensate the heat-loss through a standard double-glazed window during the heating season for Basel (Switzerland) Degree-days = 2,808 DD, HT = 167 [kWh/m^2.year]	

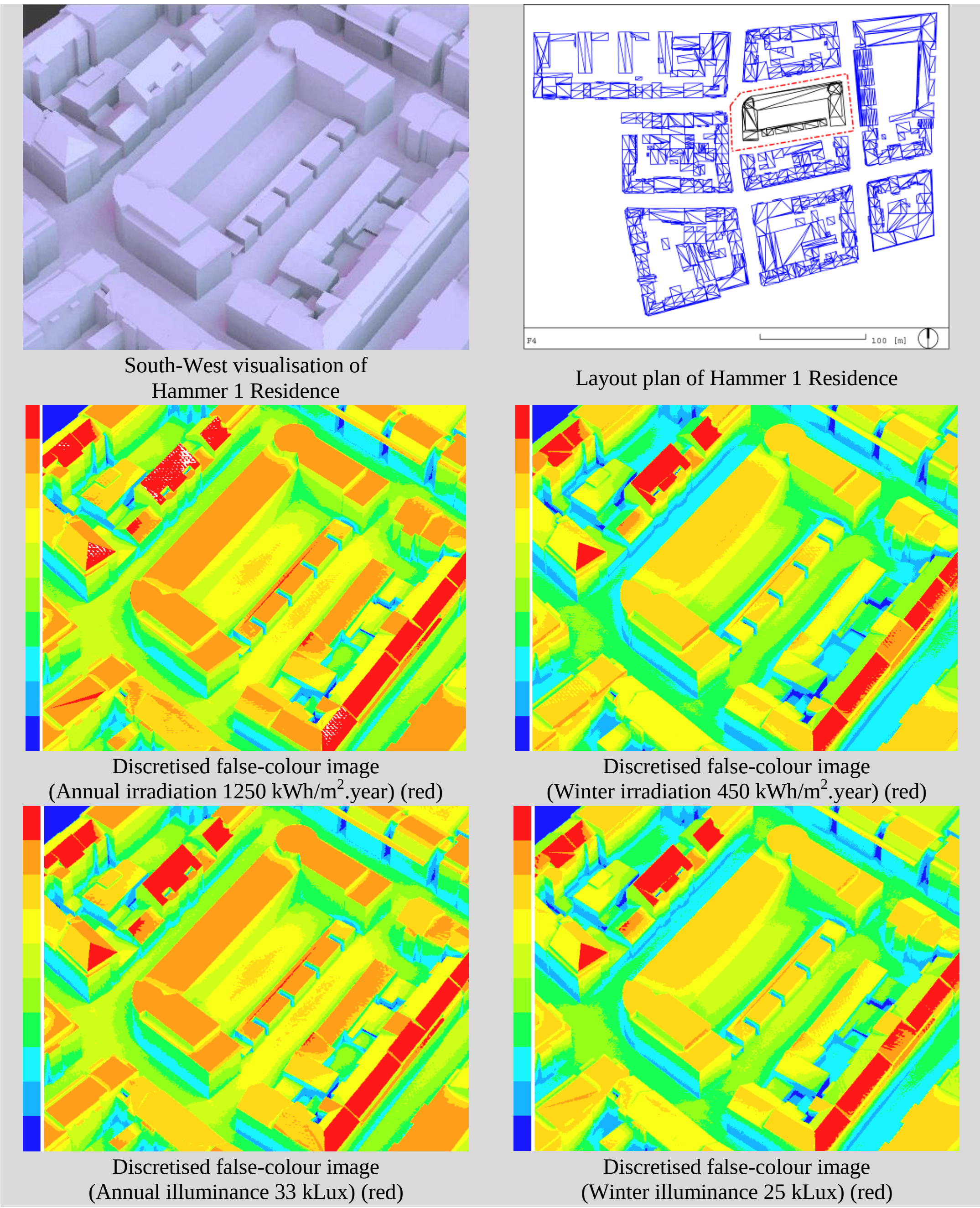
Following discussions with Prof. Compagnon (Compagnon 2000; Compagnon and Raydan 2000; Compagnon 2004) and solar experts, a series of thresholds of annual solar irradiation for façades and roofs has been identified (Table 13 on top and Figure 74 and Figure 75), beyond the latter a given solar technology is likely to be economically viable for that location and based on the following assumptions:

- the minimal Winter vertical solar irradiation required for passive solar leads to a positive energy balance for state-of-the-art glazing in Basel (167 kWh/m^2.year for a heating season);
- assuming an 500 lux indoor required illuminance on the workplane and a utilisation coefficient of 0.05 – typical of a vertical opening – the daylighting threshold for façades and roofs is equal to a 10’000 lux annual average;

[34] The solar reflectance is the ratio of the radiation reflected from a surface to the radiation incident on that surface. For instance, a 100% reflectance means that the surface of interest reflects all of the solar energy toward the atmosphere and absorbs no fraction of it.

- for solar thermal collectors the lower figures of 400 and 600 kWh/m^2.year were adopted for façades and roofs respectively, owing to the generally reduced cost of this type of collector. The rationale behind the differential between façades and roofs is similar to that for BiPV;
- regarding photovoltaics (BiPV), thresholds of 800 and 1000 kWh/m^2.year were adopted for vertical façades and roofs respectively. The lower figure for façades reflects the economic advantages of utilising the PV panels as a form of cladding and also the relative ease of integrating services into this location.

These values can easily be modified or adapted to very specific techniques in order to reflect future technological improvements.



South-West visualisation of Hammer 1 Residence

Layout plan of Hammer 1 Residence

Discretised false-colour image (Annual irradiation 1250 kWh/m^2.year) (red)

Discretised false-colour image (Winter irradiation 450 kWh/m^2.year) (red)

Discretised false-colour image (Annual illuminance 33 kLux) (red)

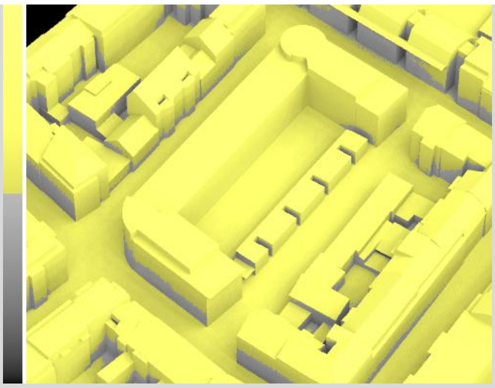
Discretised false-colour image (Winter illuminance 25 kLux) (red)

Figure 74: Hammer 1 Residence from Diener&Diener (1978-1981) in Matthaeus district (Basel). False-colour images.

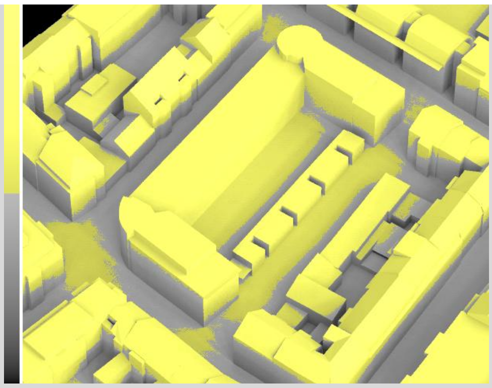
Active solar systems are characterized by very low running cost: once the technical installation is set up, energy is produced from solar radiation, which is costless. Nonetheless, the investment and maintenance costs of the device must be taken into account.

The use of solar thermal collectors in order to produce solar domestic hot water makes definitive sense in Central Europe. The overall costs of solar generated kWh are generally lower that those produced by the way of electric heaters and offer substantial saving of fossil fuel and mitigation of GHG emissions (Comtat&Allardet and Aubade 2008).

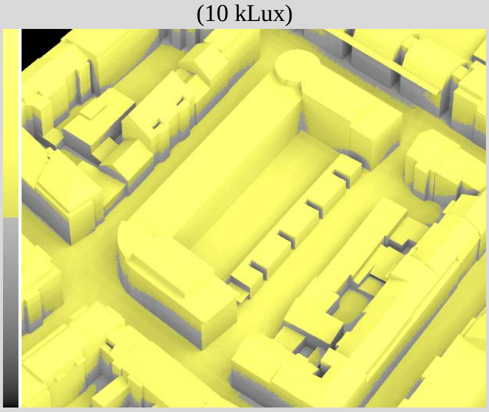
On the other hand, as far as photovoltaics is concerned, investments costs are rather high, though research is still in progress. Several countries (such Germany and Spain for instance) have set up incentive programmes and electricity feed-in tariffs for renewables which foster the integration of PV solar panels within buildings (Comtat&Allardet and Aubade 2008).



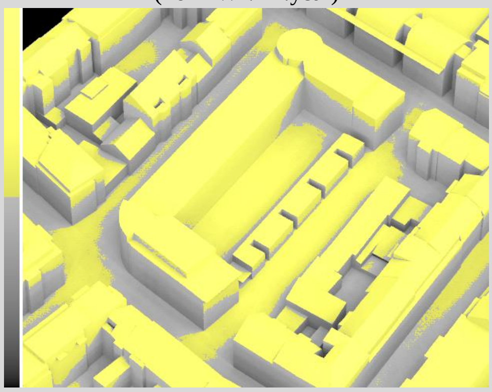
Thresholded image relating to daylighting (10 kLux)



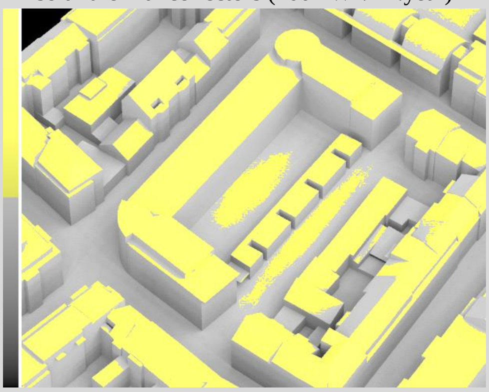
Thresholded image relating to passive solar gain (167 kWh/m^2.year)



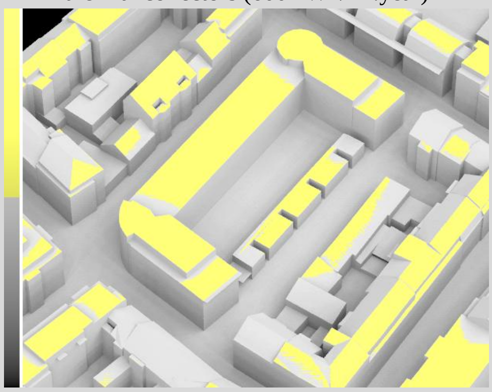
Thresholded image relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



Thresholded image relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)



Thresholded image relating to façade-integrated BiPV (800 kWh/m^2.year)



Thresholded image relating to roof-integrated BiPV (1000 kWh/m^2.year)

Figure 75: Hammer 1 Residence from Diener&Diener (1978-1981) in Matthaeus district (Basel). Thresholded images using a Boolean filter.

In conclusion, this performance assessment methodology was made particularly efficient by means of image processing achieved by the computer rendering of urban sites. By defining minimal annual or Winter solar irradiation thresholds, optimal areas for the implementation of different solar technologies on façades and roofs can be identified by means of computer simulation. However, different orientations and view angles allowed for the identification of favourable (or unfavourable) areas for a given solar technology on the façades of each building - another important advantage of the approach from a practical perspective.

3.3.2 Improvement of the modelisation procedure

The method adopted for most of digital models consisted of modelling buildings with AutoCAD, prior to export the digital data toward PPF software. The modelling of Les Pâquis district blocks 1&2 was however directly carried out with 3D Studio Max: this made it possible to improve the overall procedure and to achieve a more efficient implementation of the numerical models. This is the reason why the corresponding 3D digital model was prepared more rapidly than those of the Bellevaux district, Luz and Barra Funda districts and Eastern Quarry development. The computer digital data made available to the thesis by the Land Register and Surveying Office of Canton Basel-Stadt (Grundbuch und Vermessungsamt) made it possible to achieve high-quality renderings and to obtain very accurate results for the Matthaeus district in Basel; 3D GRID–DTM and GRID–DOM data obtained from *Système Service d'Information du Territoire Genevois* (SITG) of the Canton of Geneva were not detailed enough to provide such an accurate 3D digital model for the Meyrin site.

In any case, an evaluation of needs must be made for any urban planning project before undertaking a time-consuming modelling procedure and/or acquiring expensive digital data. However, the development of a home-made urban model leads to a careful study of the corresponding buildings details, which results in higher modelling accuracies. Nevertheless, a constant criticism is the low accuracy of certain digital models (compared to scale models) in the case of building volumes simplification: this is generally justified by the limited availability or quality of data on the corresponding site, as well the limited time devoted to modelling. Radiance processing of the final Tower Works's site project shows however a degree of details, which was never reached before by a model during the assessment of solar utilization potential of urban sites (e.g. presence of apertures, supporting pillars, balconies, overhang parts, etc.).

The characteristics of the various digital models encountered in this work are summarized in Table 14:

Table 14: Characteristics of the digital models

Digital model	Buildings	3D FACES		File sizes
Matthaeus	1,116	35,000		10,872 kB
Bellevaux	240	4,000	(1)	119,699 kB
Les Pâquis (street block 1, existing)		3,789		1,237 kB
Les Pâquis (street block 1, raised buildings)		3,476		1,125 kB
Les Pâquis (street block 2, existing)		12,928		3,972 kB
Les Pâquis (street block 2, raised buildings)		12,670		3,899 kB
Tower Works (preliminary)		130		50 kB
Tower Works (final)		822		281 kB
Eastern Quarry		7,481	(2)	4,534 kB
Barra Funda	189	1,767		503 kB
Luz	269	2,436		3,060 kB
The Contemporary City		11,568		5,012 kB

(1): 580 polygons
(2): buildings: 5,537 / 3D FACES; terrain: 1,944 / 3D FACES

Usually, the file size is variable and depends upon the model type desired as far as accuracy, number of buildings and number of generated 3D Faces are concerned. Table 14 shows the ratio between file sizes (kB) and number of faces which varies between 0.8 and 3.5: it goes from 50 kB for Leeds 1 to 119,699 kB for Bellevaux. It depends on the 2D cadastral plan used to virtually "raise" the buildings' façades (DXF, DWG, JPEG, TIFF formats, etc.) and thereafter if it were finally removed or not.

The estimated duration requested for setting up these models (excluding the conception time for the Leeds and Eastern Quarry projects strictly speaking) is as follows:

- Matthaeus : unavailable data;
- Bellevaux: 550 hours (including document retrieval time);
- Meyrin : unavailable data;
- Les Pâquis 1 : 30 hours (without document retrieval time);
- Les Pâquis 2 : 25 hours (without document retrieval time);
- Tower Works 1 (preliminary design project): 8 hours (without design project);
- Tower Works 2 (final project): 50 hours (without design project);
- Eastern Quarry: 135 hours to transform the SOLID 3D model into a 3DFACE formatted file (without design project);
- Barra Funda : 50 hours to transform the SOLID 3D model into a 3DFACE formatted file (without document retrieval time and the creation of the existing model used as a basis);
- Luz: 70 hours to transform the SOLID 3D digital model into a corresponding 3DFACE formatted file (without document retrieval time and the creation of the existing model used as a basis);
- The Contemporary City: 180 hours (without document retrieval time).

The estimated time for setting up these models will however vary from one person to another according to his or her knowledge in modelling.

Unfortunately, data involving computer processing time for most of the models were not kept or calculated. Furthermore, this largely depends upon the computer type and the number of tasks launched simultaneously. These simulations were carried out on a "cluster" of PC/Pentium 4, set up in 2002. For a district of 1,116 dwellings such as Matthaeus, without outer reaches, approximately 165 hours were necessary (real time: 165 hours, user time: 63 hours, calculation efficiency: 38%).

The use of 3D digital models in architecture, urban planning and environmental studies is about to become a necessity. One of its immediate applications for the interested parties is the visualisation of a given or alternative project within a certain area. Reading of 2D architectural plans is very difficult for non-trained people, such as inhabitants or clients of the project. They do not have the "sharp-eyed views" of professionals who can identify building shapes and spaces at a glance; new ways of representing architectural objects in three dimensions makes their understanding and interpretation far easier. These new rendering techniques require new skills from building designers and scientists, including a deep knowledge of Computed-Aided Design (CAD), 3D digital modelling, synthetic image rendering, video editing, image animation and computed simulation. Numerous softwares have been developed over the past few years and can be chosen for any objective, computer environment or budget: their diversity can be applied to a whole range of projects.

However, each object must be described in a faithful way if one wants to build up an appropriate 3D digital model: this encompasses the buildings' façades and roofs, as well as the terrain. Assembling numerical information, which is often diffusely located, is a difficult task requiring the use of different complex software. Collecting data and building up the different digital models used within this thesis, have proved highly time-consuming. Nevertheless, it is an investment of time that might be rewarded if the various models created for that purpose are used in the future for other urban planning design and/or research projects.

Chapter 4: Global solar performance of case studies

4.1 Introduction

This study focuses on the relatively large scale of the urban district. It differs from past studies that have tended to focus either on elementary building typologies or on local urban neighbourhoods (of the order of 1 Ha, i.e. 2,471 acres). The latter is interesting in that by simplifying the building geometry it reduces the impact on the results of the urban complexity and thus can deepen the understanding in terms of relationships between building typologies and solar energy potential (Steemers, Baker et al. 1997; Compagnon 2000; Compagnon and Raydan 2000; Compagnon 2004). However, generally most studies suffer from ignoring direct and diffuse shadings due to buildings located beyond the boundary of the case study. Partly to blame is the small size of the group of buildings considered within the city, for which relatively little effort has been invested to derive insights from the real building forms, in particular to identify whether and to what extent vernacular design has responded to climate[35].

The present chapter begins by reviewing the context in which the selected districts were chosen and by introducing the diverse research institutions as well as the key people who participated in these research projects. It is followed by a site description of each case study and a description of the 3D modelling techniques which were chosen to represent the different urban sites. The related modelling results and associated solar performance indicators are also presented in order to account for the overall solar potential of façades located in the various urban areas for passive and active solar technologies, daylighting and photovoltaic electricity generation (BiPV).

Selection of case studies

Three Swiss urban sites - the district of Matthaeus in Basel, Bellevaux in Lausanne and the Meyrin Estate in Geneva - were chosen in collaboration with the Swiss Federal Office of Energy (SFOE). They were the main objects of study of the SOLURBAN research project (Solar Energy Utilisation Potential of Urban Sites) initiated at EPFL (Prof. J-L Scartezzini) in collaboration with the EIAF/University of Applied Sciences Western Switzerland (Prof. R. Compagnon) (Scartezzini, Montavon et al. 2002; Montavon, Scartezzini et al. 2004; Montavon, Scartezzini et al. 2004; Robinson, Scartezzini et al. 2005; Robinson 2006; Montavon, Robinson et al. 2007).

The SOLURBAN project aimed to promote an urban architecture, that adheres to the principles of sustainable development, by assessing the solar energy utilisation potential (passive and active solar systems, daylighting and building integration of photovoltaics) of three urban sites representative of Swiss cities; the latter are expected moreover to cover the range of latitudes of the country, as well as the variety of buildings and morphological typologies of different urban sites in Switzerland. The following features predominantly characterized the three urban sites:

- pre-war residential buildings for Matthaeus;
- post-war tenement social housing for Bellevaux;
- a relatively new multiuse district for Meyrin.

The desire to examine urban sites with the potential for successful refurbishment justifies the selection of the districts of Matthaeus located in the north of Basel, Bellevaux in the centre of Lausanne and the Meyrin Estate in the southern part of Geneva.

Moreover, four different types of representative urban forms in Basel or in the other European cities were used to compare theoretical building shapes leading to higher urban density on the daylighting availability, as well as on the solar utilisation potential of the site.

[35] Although some clear results were obtained from comparisons of different hypothetical new building design proposals within part of an existing neighbourhood.

A collaboration with Prof. B. Marchand, from the *Laboratoire de Théorie et d'Histoire* (LTH2) of EPFL, allowed for the evaluation of the solar performance of the street block Pâquis 1 & 2 in Geneva (Marchand, Montavon et al. 2008).

This architectural project corresponded to the second phase of specifications drawn up by the *Service d'Urbanisme de la Ville de Genève* for an "expertise related to the potential for densification of the city of Geneva". It has the two following objectives:
- to clarify the notion of qualitative density, particularly in the context of Geneva;
- to assess the conditions needed for the improvement of the current urban fabric.

The work was supervised by the *Service d'Urbanisme de la Ville de Genève* (G. Doessegger and J. Urfer). The urban plan was drawn up by K. Bossy of the DeLaMa architecture office in Geneva (Devanthéry-Lamunière-Marchand Urbanisme, EPFL FAS SIA FSU architects).

Other urban sites were selected during an academic sojourn at the Martin Centre for Architectural and Urban Studies at the University of Cambridge (Prof. K. Steemers) thanks to the support of the Swiss National Science Foundation. Two South American districts - Barra Funda and the Luz districts in São Paulo (Brazil) - were also chosen in the course of the international project *Sustainable Urban Spaces: a case study in São Paulo, Brazil.* In addition, a remote collaboration with the Martin Centre enabled the candidate to cooperate on various urban planning projects, primarily *Tower Works Project* and *Testing the Masterplan, as well as An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley* sponsored by Land Securities. Generic models (Cheng, Steemers et al. 2006), plus a conceptual urban plan conceived by Le Corbusier in 1921 -1922, *The Contemporary City of Three Million Inhabitants* (Montavon, Steemers et al. 2006), were also considered.

The project *Sustainable Urban Spaces: a case study in São Paulo, Brazil,* funded by The British Academy, gathered teams of environmental designers and researchers from The Martin Centre (Prof. K. Steemers and V. Cheng, Ph.D. Student), the Universities of São Paulo (Prof. D. Duarte and J. Goncalves), The School of Architecture and Visual Arts, the University of East London (Dr S. Hagan), the University of Applied Sciences of Western Switzerland (Prof. R. Compagnon) and the EPFL (M. Montavon, Ph.D. Student). This made it possible to develop and assess sustainable urban design projects for São Paulo (Cheng, Steemers et al. 2006; Cheng, Steemers et al. 2006; Duarte and Gonçalves 2006).

The research work carried out in this framework makes it possible to compare the daylighting availability and solar potential of Barra Funda and Luz districts. In a second step, the features of a set of urban blocks located in Barra Funda and Luz, two town centre districts of São Paulo, were analysed in order to establish urban planning design rules.

Testing the methodology used in this thesis through current urban design projects was also considered an important goal. The general procedure, adopted for the *Tower Works Project* in Leeds (England), consisted of evaluating its solar utilisation potential (solar radiation and daylight flux) starting from the preliminary urban design phase to the final planning. Several technologies for direct use of solar energy (passive and active solar energy, daylighting and photovoltaics) that can supply heat, light and/or electricity to the buildings, were taken into account as a function of the orientation of the buildings main façades (Wilson 2006).

The overall project team was composed of the following private companies: Carey Jones Architects (J. Wilson), Town Centre Securities PLC (J. Sutcliffe, Glyn Akesson and R. Dunn), Yorkshire Housing (J. Morgan), EDC Architects (M. Elton), Gillespies (M. Sharp), ARUP (M. Mayfield), AYH plc (R. Morris). The following academic institutions were also involved in the project: the University of Leeds, the Academy for Sustainable Communities, the University of Cambridge (Prof. K. Steemers, V. Cheng and M. Ramos, Ph.D. students) and the EPFL (M. Montavon at the invitation of Prof. K. Steemers).

The urban analysis *Testing the Masterplan: An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley* was undertaken by Prof. K. Steemers and developed in collaboration with his Ph.D. students Vicky Cheng and Fernanda Sa Oliveira. Prof. R. Compagnon of the University of Applied Sciences in Western Switzerland and M. Montavon from the EPFL, who was invited to join the Martin Centre at the University of Cambridge for that purpose (Barton 2006; Steemers, Montavon et al. 2007), were also involved in this project.

This part of the work addressed the environmental performance of an urban development project for Eastern Quarry in Ebbsfleet Valley. It focuses primarily on the modelling of the suggested urban project by analysing key microclimatic parameters. The aim was to proceed to the evaluation of the masterplan on the basis of computer simulations, by analysing its energy and environmental performance and by looking for possible improvements. The team composed of the following private companies created the masterplan: Barton Willmore (Town Planning and Masterplanning Consultancy), Gillespies (Landscape and Public Realm Consultancy), Middlemarch Environmental (Ecology Consultancy), ARUP (Engineering and Land formation Consultancy), PBA (Transport Consultancy) and Land Securities (Land Owner and Master Developer).

Finally, Le Corbusier's architectural concepts and urban planning design were also invaluable for this study: his own principles are still guiding today's architects and urban planners in the course of their own professional activities. One of the main objectives of this work was to analyse Le Corbusier's proposition concerning the "solar theory" he applied to urban projects by the way of a rational approach. *The Contemporary City of Three Million Inhabitants* designed in 1922 was studied for that purpose by means of computer simulations; its solar utilisation potential was compared to the urban blocks of the city of Paris, that were so much criticized by Le Corbusier in his own time (Montavon, Steemers et al. 2006).

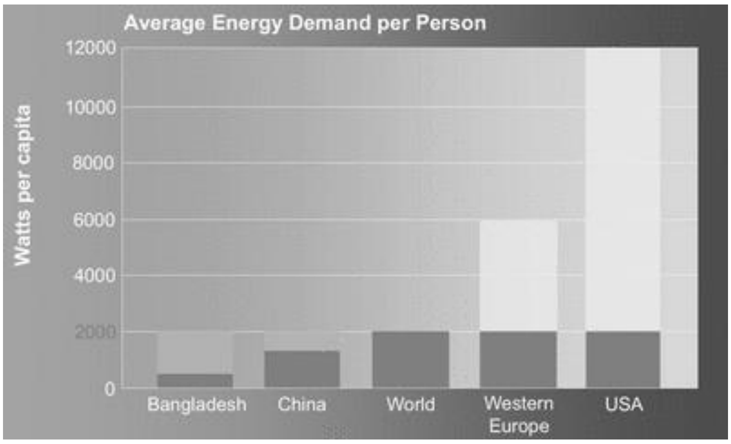


Figure 76 (left): Energy consumption per capita. A person needs 17,500 kilowatt-hours a year on global average. This corresponds to a continuous requirement of 2,000 watts. In Switzerland the figure is three times higher, i.e. 6,000 watts per person. People in some Asian and African countries only need fractions of that on average.

Figure 77 (right): Matthaeus layout plan, 2002 ©Basel-Stadt, Grundbuch und Vermessungsamt.

Source Figure 76: [online] URL: http://www.societe2000watts.com/index.php/home/historique.html (Consulted on June 13nd, 2008).

Figure 78: Views of Matthaeus district. Feldbergstrasse-Klybeckstrasse (top left), Dreirosenstrasse (bottom left), Matthaeusstrasse (top right), Hammerstrasse (bottom right), 2002.

4.2 Matthaeus district, Basel, 47.55 latitude (Switzerland),

This district area was considered because it is characterised by one of the highest population densities of all the Swiss cities and was used as a pilot site within the framework of an ambitious energy savings' incentive programme. The innovative energy policy adopted by the Canton of Basel-Stadt earned its selection as a pilot site for the implementation of a *2000 Watt Society* programme[36], a clear objective within the framework of the "Strategy for Sustainable Development" of the Council of the Swiss Federal Institute of Technology. Faced with the prospect of massive climate changes, this "Strategy for Sustainable Development" aims at drastically reducing the energy consumption of different districts by cutting down the average yearly power per inhabitant from the present value of 6,000 Watts down to 2,000 Watts (e.g. the current average power consumption per capita for the whole planet, see Figure 76 (Basel-Stadt 2001). On a purely technical level, such a *Factor* 4 (von Weizsacker, Lovins et al. 1997) reduction in energy consumption can realistically be achieved in the building sector: its average power consumption (1,600 watts for housing heating and electrical appliances in Switzerland) can be reduced to 450 Watts with the use of current energy saving and solar technologies (Scartezzini, Montavon et al. 2002). The Matthaeus district was considered in this study in order to estimate its solar energy utilisation potential.

4.2.1 Description of case study

The district of Matthaeus is located near the city centre of Basel adjacent to the River Rhine. It was established in the nineteenth century outside the old ramparts and close to the *Kleinbasler Altstadt*. Around 1870, there were only a few scattered houses in this district; a strong development activity took place later on during the industrialisation period of Basel before World War II in order to accommodate the chemical, pharmaceutical and watch industries.

The residential district was mainly built between 1890 and 1900 to provide housing for Basel's industrial workers. The fast growing building process resulted in typical row constructions, which formed the main scheme of the site. Many streets were designed as a whole and built simultaneously. Since the 1960's, some streets have been demolished and/or rebuilt, resulting however in a predominantly orthogonal layout orientated along the North-South/East-West axis; the main streets of the district remained parallel to the River Rhine. New nameless buildings have replaced some of the demolished working-class housings (see Figure 77).

Original building constructions are still standing with ground floors occupied by shops, bars or restaurants; numerous workshops can be found in their backyards. It must be emphasized that the residential and industrial character of Matthaeus is still alive today. Of the overall cantonal population of 402,000 inhabitants, 190,800 (48%) live in the city of Basel, whose area is equal to 37 km^2. Owing to the constraining limits forbidding any extension, the possibility of developing the Matthaeus district is very limited. As a consequence, every refurbishing project is considered with care, seeking optimal refurbishment solutions. The city of Basel (the so called Basel-Stadt Canton) wants to increase the availability of flats by modifying its own cantonal property: this means reinforcing the studio flats and designing new, large four-room flats (85% of Matthaeus' flats have 3 rooms or less). The city of Basel hopes that this strategy will become a model for private investors and will convince them to renovate their own blocks of flats in the same way.

With an area of 59 hectares (145.8 acres) for an overall population of 15,300 inhabitants, the urban site of Matthaeus represents one of the highest population densities of Switzerland - most of the buildings are 4-5 storeys high. It can be emphasized that the district of Matthaeus is short of available space:

[36] The *2000 Watt Society* refers to a growth rate of the GDP of 1.3%. 2 000 watts was the average consumption per capita in Switzerland in 1960. It is also the current world average, however with immense disparities: an inhabitant of the United States consumes 10,000 watts, a Swiss 6,000, an Abyssinian 500.

consequently, the refurbishment or demolitions of existing housing (if the law allows it) are the only possibilities left to the interested parties of the district (see Figure 78).

4.2.2 Description of 3D digital model

The Land Register and Surveying Office of Canton Basel-Stadt (Grundbuch und Vermessungsamt) own a numerical 3D model of the entire Canton. The reference database of this 3D digital model stems from different sources, in particular from the *Cadastral Survey of Switzerland* (CS) (e.g. elevations, communication towers, vegetation, urban networks, etc.).

The 3D digital model of Basel city was prepared with MicroStation (see below step by step) and a raster processing programme according to the following procedure (Meier 2008):
- terrain modelling with superimposition of raster images (land use);
- elaboration of 3D building models adapted to roofs and bridges (vector format);
- generation of 3D oblique sights with projection of shades;
- production of raster files for oblique views of the site with projection of shades;
- final processing of raster data for appropriate formatting and labelling (streets names, image, etc.).

The roof surfaces have been keyed-in using photogrammetric techniques and regular aerial surveys over the whole canton. The roofs processed through this method were first lowered to the ground. The buildings shapes, whose extent corresponds to the maximum roof expansion, were generated in this way. The digital modelling of buildings and other 3D morphological objects was achieved using the VR-GI Modeller developed by Markus Meier of the University of Manitoba in Winnipeg and via AutoCAD or Micro Station. The latter software is a collaborative engineering or computed-aided design (CAD) programme. Contour lines were also acquired using photogrammetric techniques and completed zone by zone at ground level for bridges and underpasses. Contour lines, points of raster images or triangular meshes were derived using Micro Station; the VR-GI Modeller employed a triangular mesh for the terrain model (Meier 2008).

Gables and flat roofs have been differentiated. Data extracted for roofs, façades and ground floor levels were separated. These three raw data sets were split up into separated files whose breaking lines were refined. Turrets, balconies and canopies (larger than 3 m × 3 m) have also been included. The accuracy of their location and height corresponds to an error range of 15 to 30 cm. The degree of details can be adapted to the user's wish for 1:200 to 1:1000 scales (Grundbuch- und Vermessungsamt 2005).

The Land Register and Surveying Office of Basel offered some samples of their own 3D digital model elaborated in 3DFACE facets or 3DPolyline plan both in the AutoCAD DWG/DXF and Intergraph DGN exchange formats. The first format was selected, after several trials undertaken with PPF software, the files turning out to be perfectly readable and editable with this programme: DXF format is an exchange format between different CAD systems (e.g. AutoCAD, ArchiCAD, VectorWorks). As ArchiCAD or VectorWorks do not describe buildings using 3DFACE facets, but rather as blocks, the latter were useless. The same applies for the 3DPolyline and Intergraph DGN versions: 3DPolyline is an entity with points of different elevation (series of lines linked to another in order to create a single object). Intergraph is not a commonly used piece of software in the urban planning field.

The PPF software was modified in order to be able to recognize 3DFACE entities and layers of the Basel digital model. All AutoCAD objects are characterised by geometrical and non-geometrical properties (called “attributes”), which distinguish or help to classify them. There are five non-geometrical properties:
- the layer number (to which the object is attached);
- the object colour;
- the object line type;
- the scale of the line type;
- the line thickness.

Whether visible or not, each layer contains AutoCAD objects; when an object is created, it is stored in a previously designated layer. Prior to that, the 3D digital drawing must be cleared using AutoCAD by removing all useless layers. The terrain, façades and roofs were classified in three different layers, so that individual surfaces could be distinguished from each other. Unfortunately, all the façades and roofs associated with a building could not be stored in a distinct layer: this would have allowed a separate assessment of the solar utilization potential of each building. Thus, the corresponding figure was determined on the district scale or at best on a block scale (made of buildings groups bounded by streets).

The first extensive modification of PPF software was the implementation of *get3df* function in order to be able to import 3DFACE entities. The latter translates the corresponding modelled 3DFACE objects into RADIANCE compatible format, by distributing them among three data types:
- terrain description;
- façade description;
- roof description.

However, objects had to be previously attached to suitable layers according to these types, before proceeding to the translation into a Radiance compatible format.

The second modification of the software was the implementation of a 3DFACE recognition algorithm (for external façades and roofs); the latter enabled PPF to look for the proper orientation of façades and roofs. This was required in order to be able to evaluate the quantity of solar energy received by a given building surface according to its orientation and tilt angle. The triangular mesh digital terrain model (DTM) did not require any specific modification of the software.

One of the most tricky modifications of PPF was related to the importation of 3DFACE sloped roofs. The challenge was to modify the software so that sloped roofs with complex geometries could be converted into PPF format (this requires the recognition of the roof shape and position, as well as splitting it up into surfaces). Before this modification, only flat roofs could be recognized by means of PPF software.

Finally, to overcome an internal error in the Linux library, a RADIANCE optimization procedure had to be modified. The latter was simply a shortcut to enable RADIANCE to deal with a complex 3D digital model, such as the one of Matthaeus/Basel; this could have been avoided with more available computer memory.

The high quality of this 3D digital model lies in the fact that a vector format is used to reduce the amount of data to the essential information. In the near future, all of the “single object” information layer will be integrated within the 3D digital model. The data of this model are available among others in DXF format (Drawing eXchange Format). The latter, created using Autodesk facilitates data exchange during computer-aided drafting or design. It was initially conceived for 3D digital models issued from AutoCAD. DXF is a file format used to transfer vector-like data; DXF files can be formatted in ASCII (DXF) or in binary format (DXB) (see Figure 79 to Figure 82).

Figure 79: Matthaeus district (AutoCAD/3DFACE/DXF format) ©Basel-Stadt, Grundbuch und Vermessungsamt.

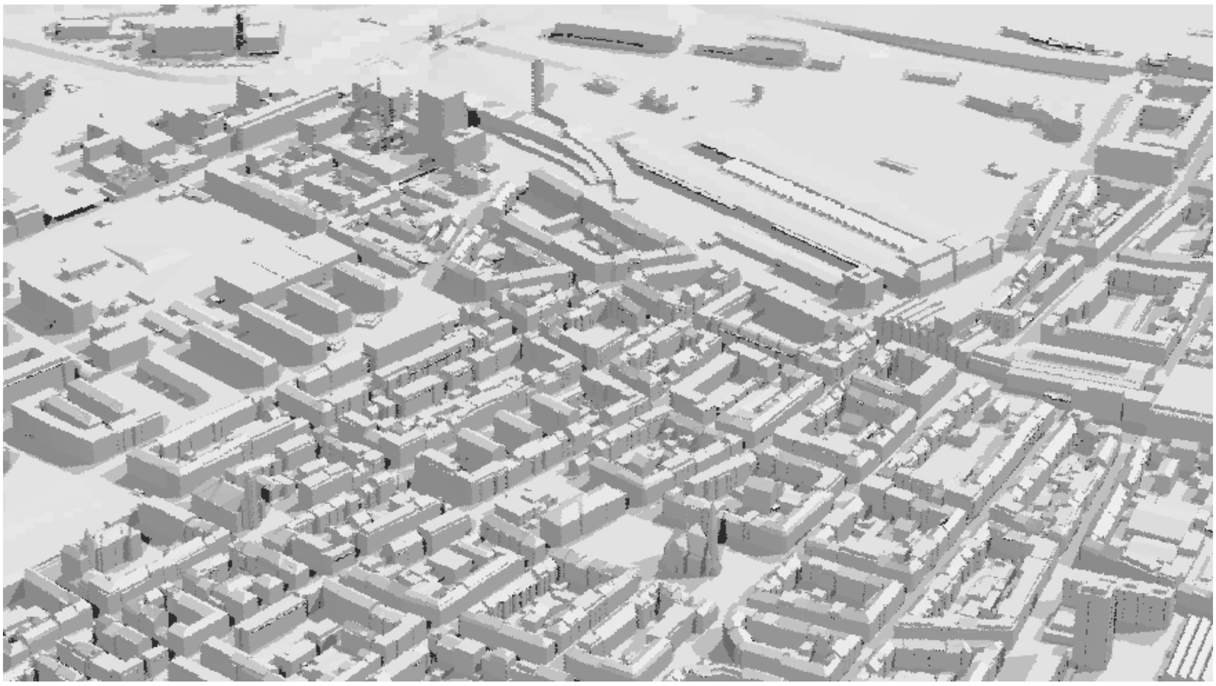


Figure 80: West view of Matthaeus district (RADIANCE rendering).

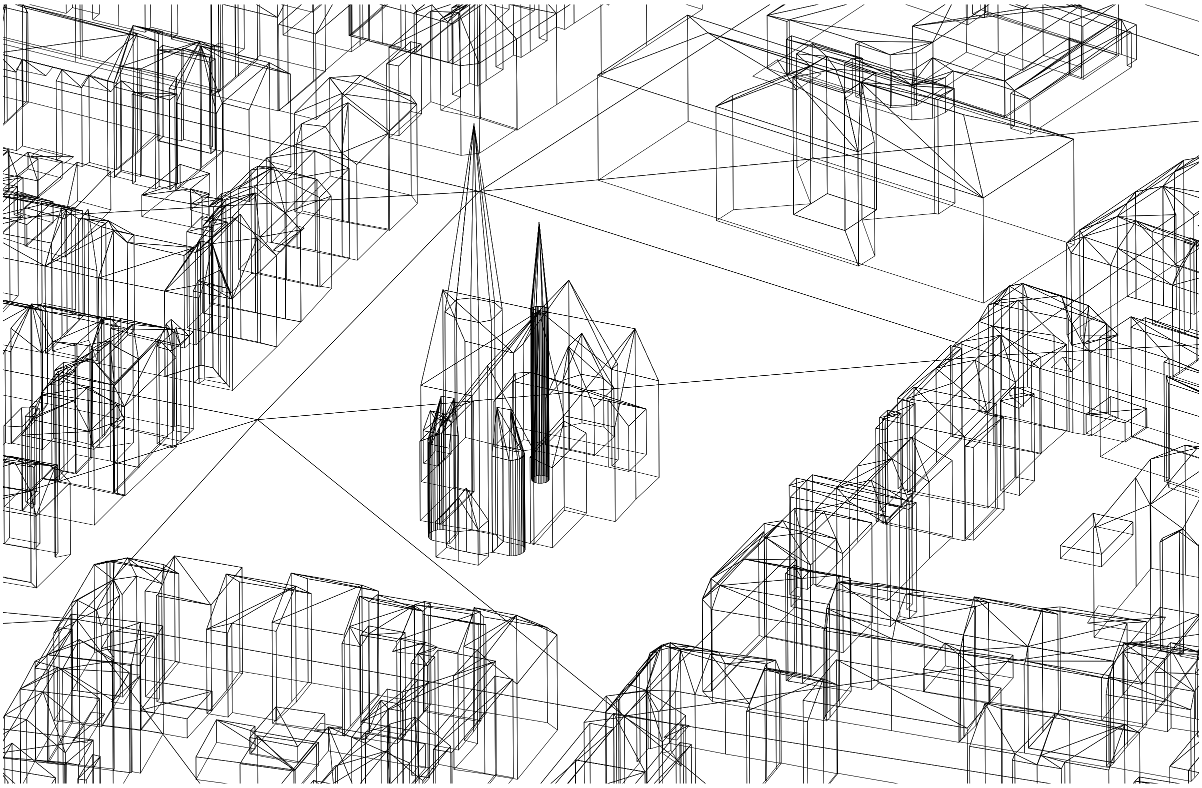


Figure 81: Matthaeus district. Matthaeuskirche[37] (AutoCAD/3DFACE rendering) ©Basel-Stadt, Grundbuch und Vermessungsamt.

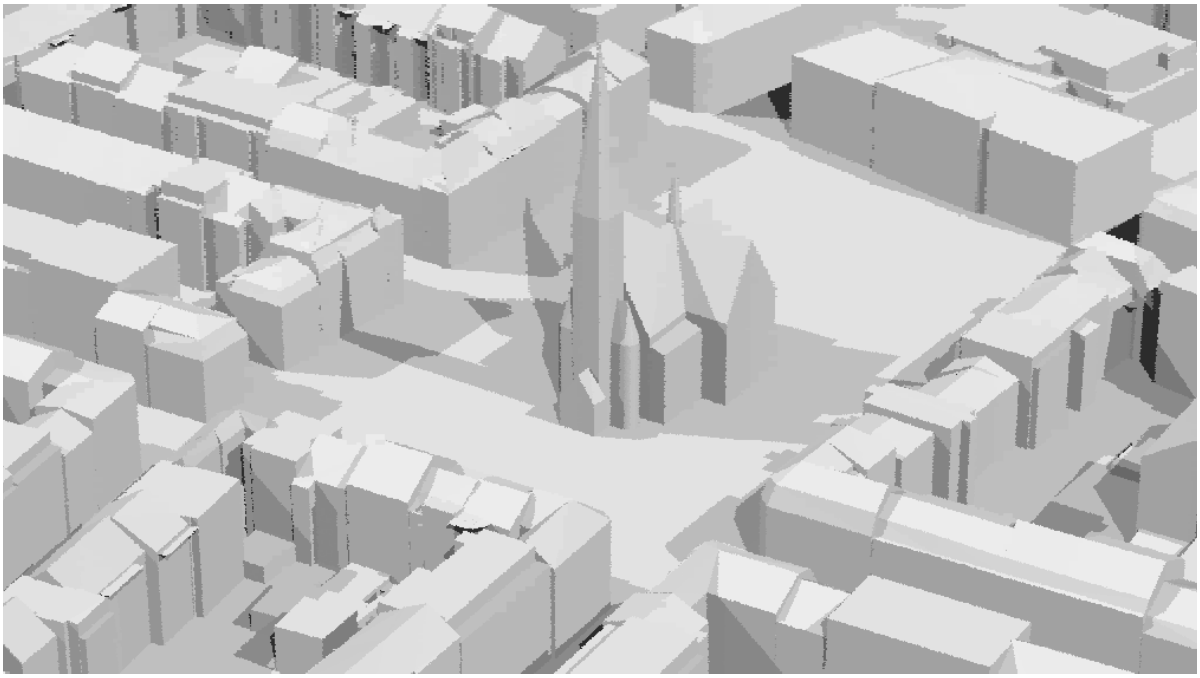


Figure 82: Matthaeus district. Matthaeuskirche (RADIANCE rendering).

[37] Matthaeus church.

4.2.3 Solar performance indicators

As noted earlier, the aim of the SOLURBAN project was to provide concrete information to the partner municipalities in Basel, in order to back-up their strategies to improve the environmental performance of their building stock (Scartezzini, Montavon et al. 2002; Montavon, Scartezzini et al. 2004; Montavon, Scartezzini et al. 2004; Robinson, Scartezzini et al. 2005; Robinson 2006). Spatial distributions of solar irradiation and daylight fluxes over the overall building façades and roofs were calculated using ray-tracing simulation techniques to determine the appropriate placement of different solar technologies (passive and active solar, photovoltaic and daylighting). Several performance indicators were used to assess the solar utilisation potential of this urban site (e.g. statistics of sky view factors and daylight factors) in order to determine the optimal solar strategies for this urban context (Compagnon 2000; Compagnon and Raydan 2000; Compagnon 2004). The simulation was carried out using typical Winter sky conditions of Basel.

Sensitivity study of the thresholds

The sensitivity study of the thresholds was carried out on a street block type denoted "A4"[38] (see Figure 83) to compare the influence of the thresholds on a fraction of surface suitable to passive solar gain and to the thresholded images in relation to the different solar technologies. Table 15 represents the different thresholds variable according to their utilisation factor η and the corresponding average irradiances.

The simulations carried out within the framework of this thesis were realized according to a series of thresholds of annual solar irradiation for façades and roofs presented in Table 13 in Section 3.3.1 with a η[39] factor of 70% (η = 0.7) for passive solar viability, because choosing a utilisation factor η = 1 would have been a far too optimistic. However, this part makes it possible to appreciate the relevance of this choice

Figure 83: Layout plan of Matthaeus district (left) and A4 street block view @2009 Google (right).

[38] Identifying name assigned by M. Montavon.
[39] η is a factor of utilisation of the solar gains.

Table 15: Threshold values proposed for the sensitivity study of the thresholds

Solar techniques	Irradiation/Daylighting thresholds	Parameters	Corresponding irradiation average[4]
Passive thermal heating			
- façades[1]	117 [kWh/m^2.year]	η = 1.0 (UF)	59.5 [kWh/m^2]
	167 [kWh/m^2.year]	η = 0.7 (UF)	85.0 [kWh/m^2]
	235 [kWh/m^2.year]	η = 0.5 (UF)	119.0 [kWh/m^2]
Daylighting systems			
- façades[2]	10 [kLux]	E = 500 Lux, CU = 0.5	90.9 [kWh/m^2]
	8 [kLux]	E = 400 Lux, CU = 0.5	72.7 [kWh/m^2]
	6 [kLux]	E = 300 Lux, CU = 0.5	54.5 [kWh/m^2]
Solar thermal collectors			
- façades[3]	400 [kWh/m^2.year]	½ IrrVerMax	92.7 [kWh/m^2]
	500 [kWh/m^2.year]	-	116.0 [kWh/m^2]
	600 [kWh/m^2.year]	-	139.0 [kWh/m^2]
- Roofs[3]	600 [kWh/m^2.year]	½ IrrHorMax	139.0 [kWh/m^2]
	700 [kWh/m^2.year]	-	162.0 [kWh/m^2]
	800 [kWh/m^2.year]	-	185.3 [kWh/m^2]
Photovoltaic systems			
- façades[3]	800 [kWh/m^2.year]	Threshold set by experts	185.3 [kWh/m^2]
	700 [kWh/m^2.year]	-	162.0 [kWh/m^2]
	600 [kWh/m^2.year]	-	139.0 [kWh/m^2]
- Roofs[3]	1000 [kWh/m^2.year]	Threshold set by experts	231.6 [kWh/m^2]
	900 [kWh/m^2.year]	-	208.5 [kWh/m^2]
	800 [kWh/m^2.year]	-	185.2 [kWh/m^2]

[1]Calculated on the basis of a daily Winter period of 1,967 hours
[2]Calculated on the basis of a daylighting efficiency of 110 [Lm/W]
[3]Calculated on the basis of a daily annual period of 4,317 hours
[4]Corresponding data within PPF program (filtering value areas)

The photovoltaic yield and productivity of thermal solar panels depend on the quality and type of solar collector. Furthermore, the annual global yield of a solar installation depends on other factors than simply the collector choice. The geographic situation - more specifically the latitude, the orientation and the inclination of the collectors or the walls, the solar masks –can also reduce their energy performance and economic assessment A balance between the estimated energy needs, the number of square meters of solar collectors, the storage tank and the regulation will provide the optimal techno-economic solution and offer long-term profitability.

Table 16: Summary of results for Matthaeus district and A4 street block

Basel	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Matthaeus district (η = 1.0 (UF))	51.1%	26.9%	**48.7%**	92.2%	46.7%	49.4%	1.3%
Matthaeus district (η = 0.7 (UF))	**51.1%**	**26.9%**	**31.9%**	**92.2%**	**46.7%**	**49.4%**	**1.3%**
Matthaeus district (η = 0.5 (UF))	51.1%	26.9%	**14.3%**	92.2%	46.7%	49.4%	1.3%
Street block A4 (η = 1.0 (UF))	61%	39.2%	**57.8%**	95%	56.6%	45.1%	1.3%
Street block A4 (η = 0.7 (UF))	**61%**	**39.2%**	**41.9%**	**95%**	**56.6%**	**45.1%**	**1.3%**
Street block A4 (η = 0.5 (UF))	61%	39.2%	**26.8%**	95%	56.6%	45.1%	1.3%

Table 16 shows the results of the passive solar viability for the Matthaeus district, as well as those of the A4 street block with the different utilisation factors η and their corresponding HT[40] values. The parameter HT is calculated using the following formula:

$HT = 24*DD*U/(1000*g*\eta)$

The result is given directly in kWh/m2

DD is the number of degree-days of the place under consideration.
Basel DD=2808 [K days]

U is the specific heat loss coefficient of a state-of the-art window (low-e insulated glazing): U=1.3 [W/(m2K)]
g is the SHGC of the window: g=0.75 [-]
η is a factor of utilisation of the solar gains: η=0.7 [-]

As a result, the following thresholds values were obtained:

If η = 1.0 HT = 117
If η = 0.7 HT = 167
If η = 0.5 HT = 235

By using a Boolean filter, so that only pixels exceeding a given value are coloured, surfaces of the building envelope which are viable for a given solar technology can be visually identified a priori, ensuring that installations respond correctly to the available energy. Figure 84 present thresholded images of this type specifically for the refurbishment, by the architectural firm of Viridén & Partners AG in Zürich, of an 1896 building located at 4-6 Feldbergstrasse situated in the A4 street block and which won the 2009 Solar Prize[41] (see Figure 85).

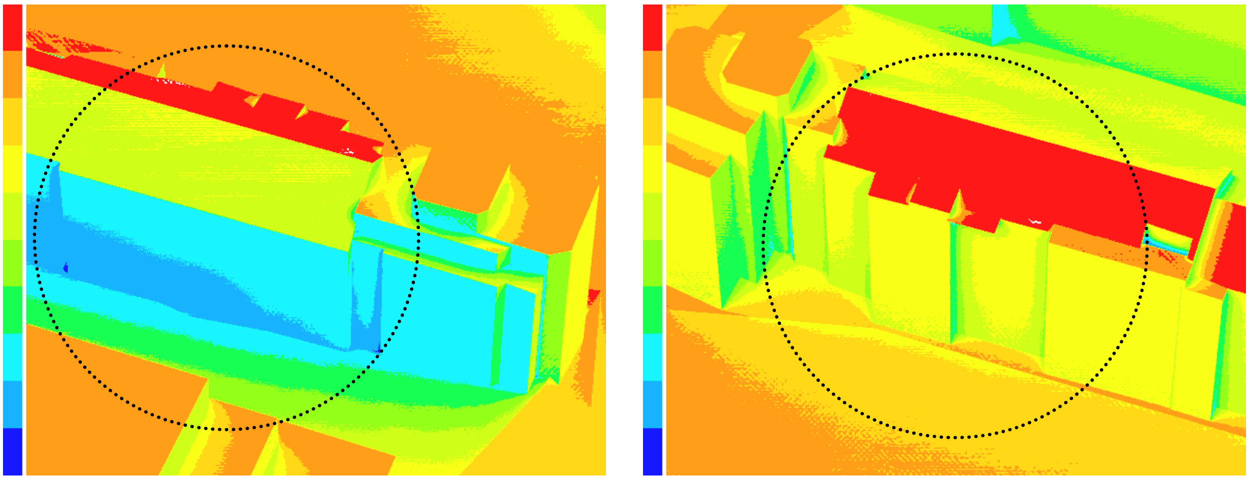


Figure 84: Feldbergstrasse N°4-6 in the Matthaeus district. Discretised North (left) and South (right) false-colour images (with 100 kWh/m2 subdivisions) relating to the annual irradiation.

[40] HT= irradiation limit for passive applications (kWh/m2) Default=151.
[41] In 1991, what was then ARGE Solar 91 (today the Agence Solaire Suisse) inaugurated the Swiss Solar Prize. Under the auspices of this national project, townships, private enterprises and private dwellings were encouraged to build solar installations and explicitly without recourse to green belt areas. Since 1991 the Swiss Solar Prize has been awarded every year.

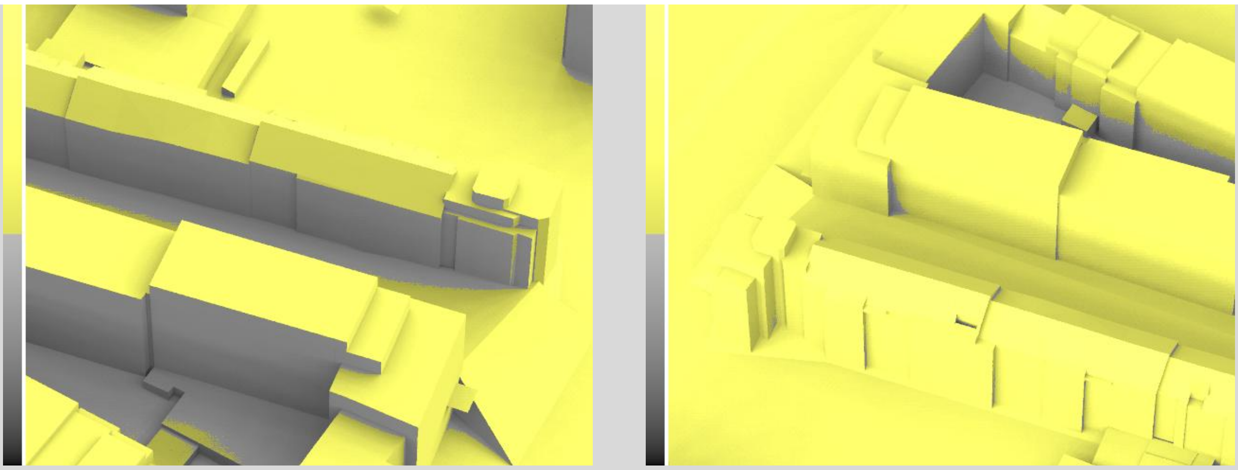
The challenge presented to Viridén & Partners AG was to provide a full supply of solar energy to a six storeys high block of flats comprising 12 dwellings located in a protected city zone and which necessitated 40% less energy than that envisaged in a *2000 Watt Society* programme. All the heat requirements (water, heating, ventilation of the dwellings and supplementary energy) are met exclusively by the solar installations placed integrated into the roof. It was possible to reduce the total energy consumption used prior to the transformation by 93%, going from 223,000 kWh/year to a mere 15,800 Wh/year. In other words, the requirements now represent only 7% of what they had been before. If the 1.5 million buildings which Switzerland comprises were renovated the same way, in line with current technologies, the total energy needs for all of our real estate would decline from 125 TWh/year to some 9 TWh/year (SOLAR Agentur 2009).

The figures for the passive solar gains of the A4 street block from Table 16 are much more "telling" than the filtered images (see Figure 86 to Figure 91).

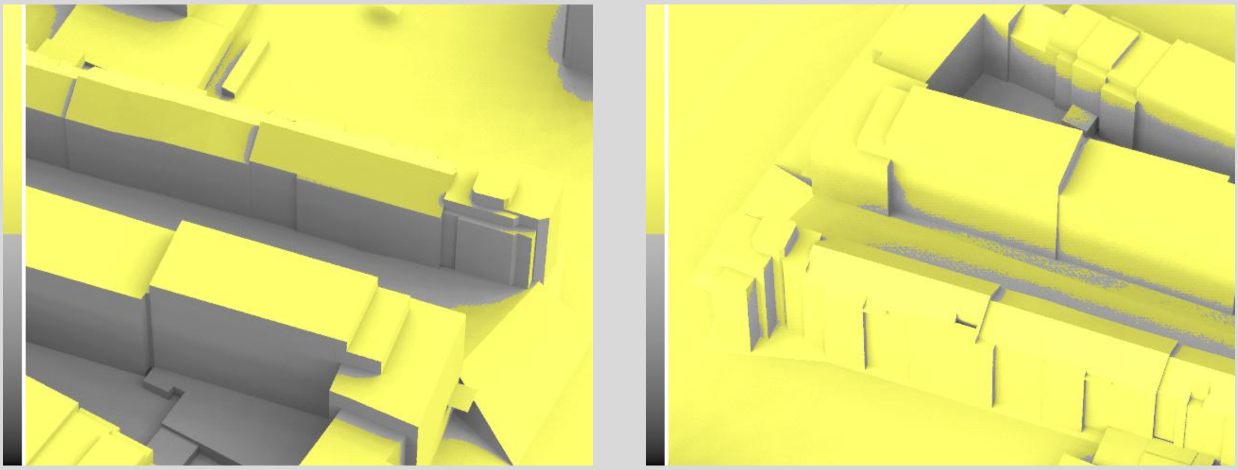
It is difficult to offer a global picture by taking only the thresholded images into account: each building is unique and has its own obstructions. One particular façade will appear in a certain way with a particular threshold and for a specific case. One only has to modify one parameter in order to change this image.

Figure 85: 4-6 Feldbergstrasse in the Matthaeus district. Main façade view (top left), rear façade view (bottom left) and views of the roofs (top and bottom right).

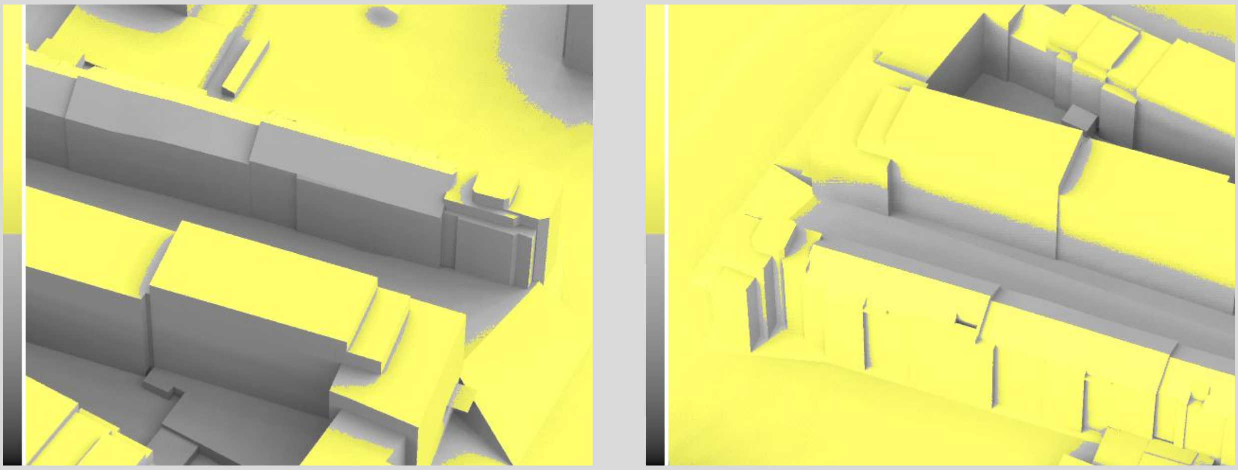
Source: [online] URL: http://www.viriden-partner.ch/umbau_sanierung/mehrfamilienhaeuser.cgi (Consulted on December 8, 2009).



Thresholded North (left) and South (right) views relating to passive solar gain (117 kWh/m^2.year)



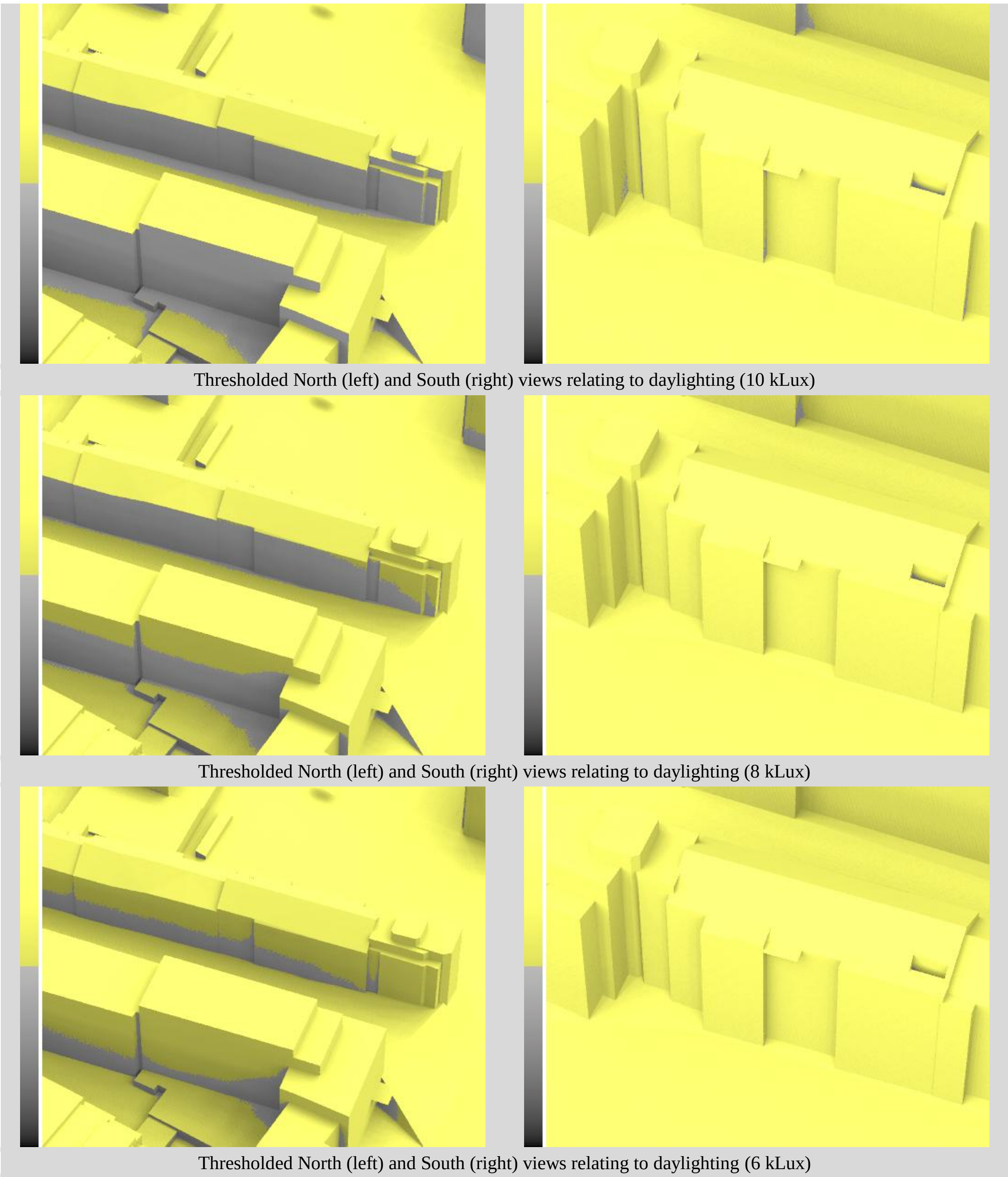
Thresholded North (left) and South (right) views relating to passive solar gain (167 kWh/m^2.year)



Thresholded North (left) and South (right) views relating to passive solar gain (235 kWh/m^2.year)

Figure 86: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

During the Winter season the passive solar gains are located mostly on the South and West façades. At worst, there is a slight deterioration of passive solar “response” at the bottom on the ground floors of buildings with a threshold of 167 and 235 kWh/m2.year.



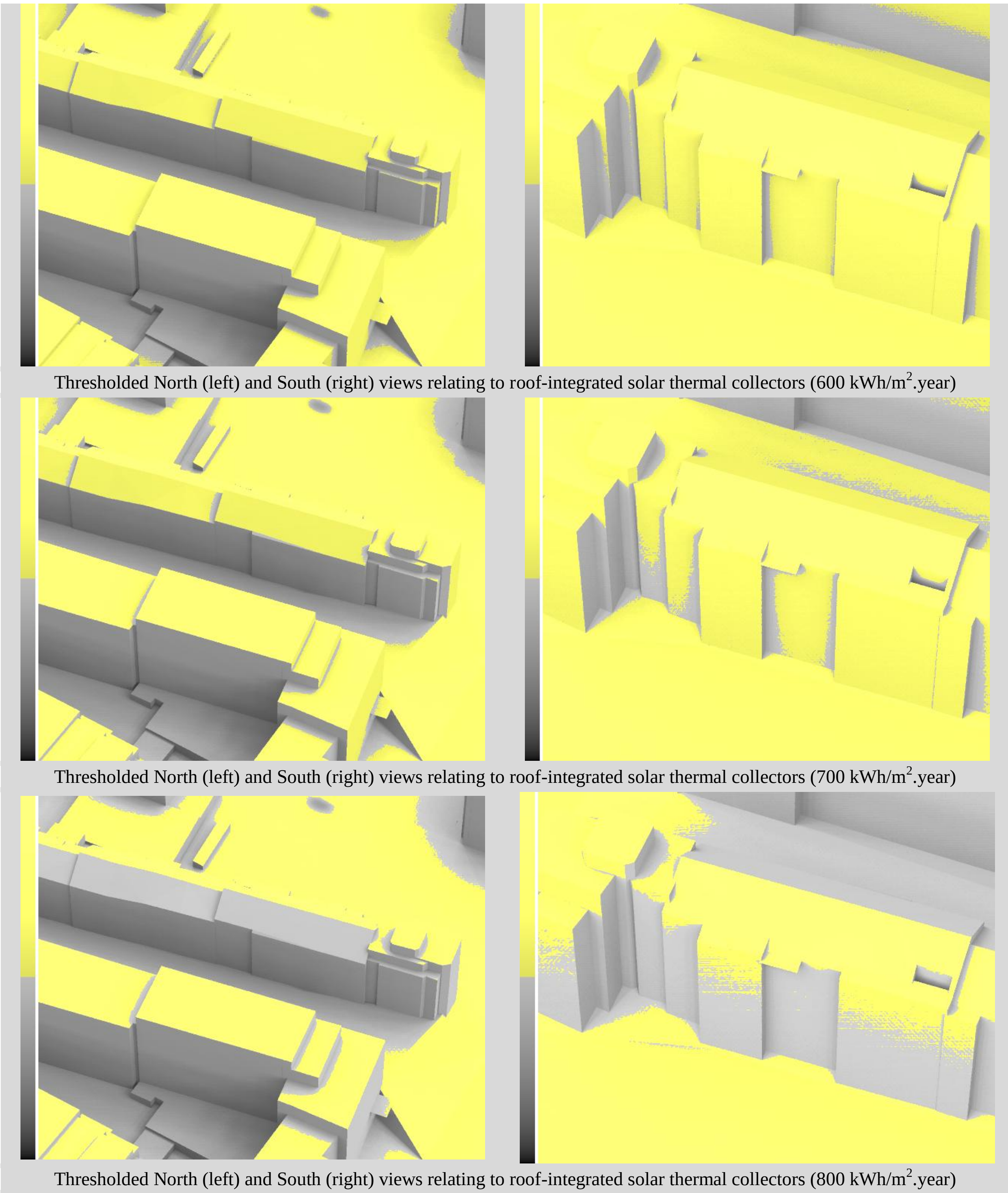
Thresholded North (left) and South (right) views relating to daylighting (10 kLux)

Thresholded North (left) and South (right) views relating to daylighting (8 kLux)

Thresholded North (left) and South (right) views relating to daylighting (6 kLux)

Figure 87: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

Putting aside the North façades, all façades perform quite well for daylighting with the three different thresholds. A threshold of 6 or 8 leads a better "response" of the North façades. At most, there is a slight deterioration of daylighting on the ground floors of buildings with a threshold of 6 kLux.



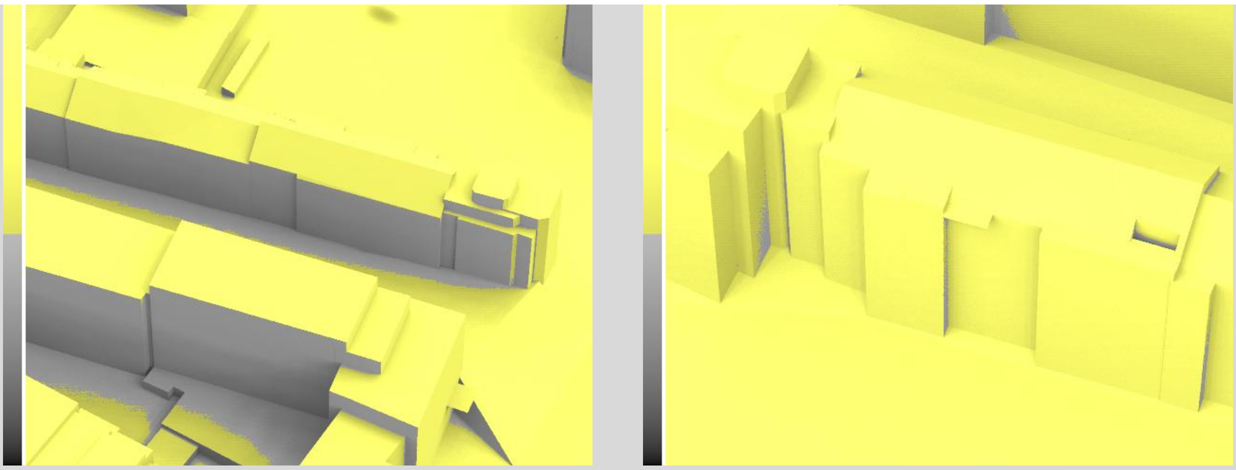
Thresholded North (left) and South (right) views relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)

Thresholded North (left) and South (right) views relating to roof-integrated solar thermal collectors (700 kWh/m^2.year)

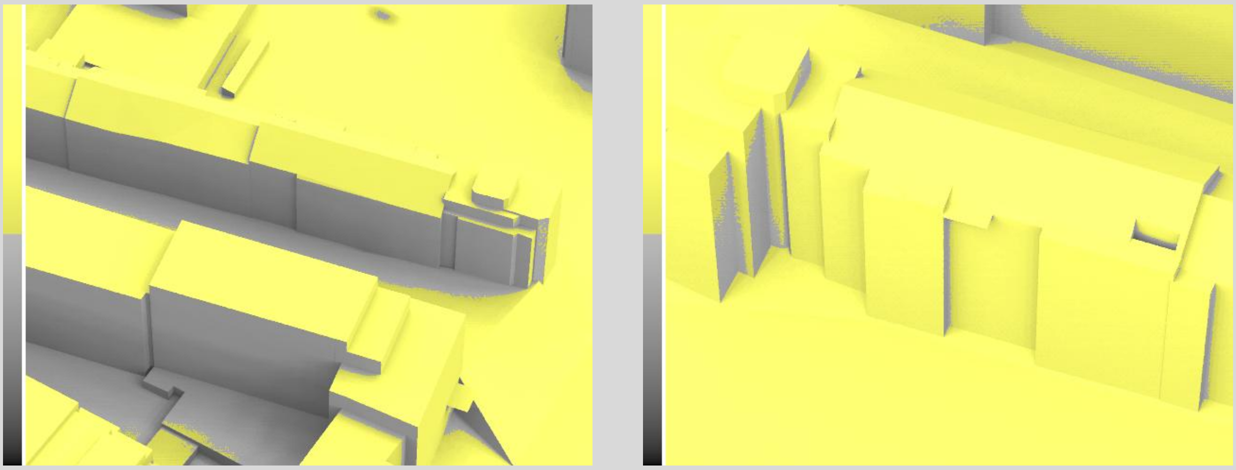
Thresholded North (left) and South (right) views relating to roof-integrated solar thermal collectors (800 kWh/m^2.year)

Figure 88: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

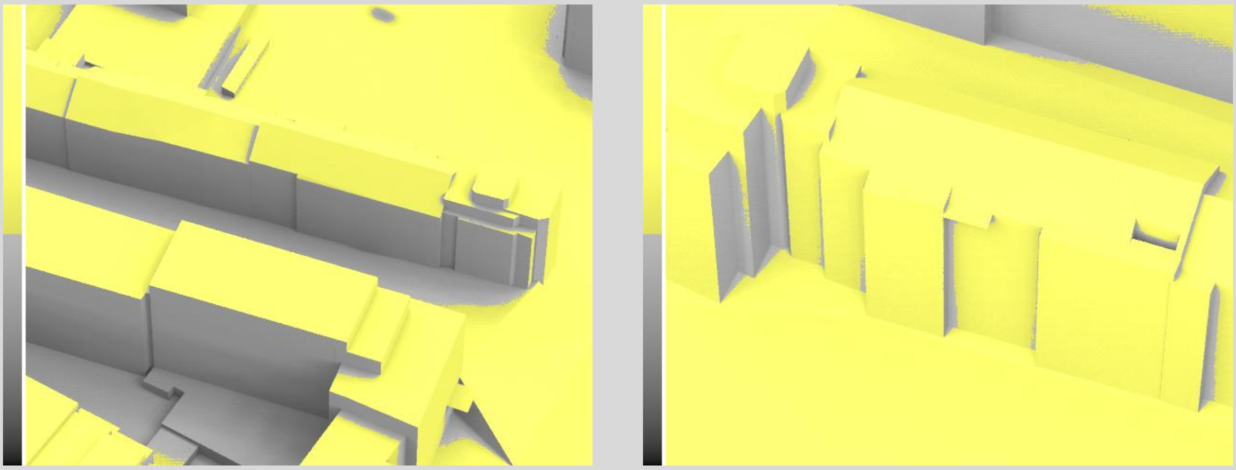
Sloping roofs with a North orientation are not appropriate for solar thermal with a threshold of 800 kWh/m2.year. On the other hand, the South, East and West orientations as well as flat roofs, are appropriate for solar thermal collectors with the three different thresholds.



Thresholded North (left) and South (right) views relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



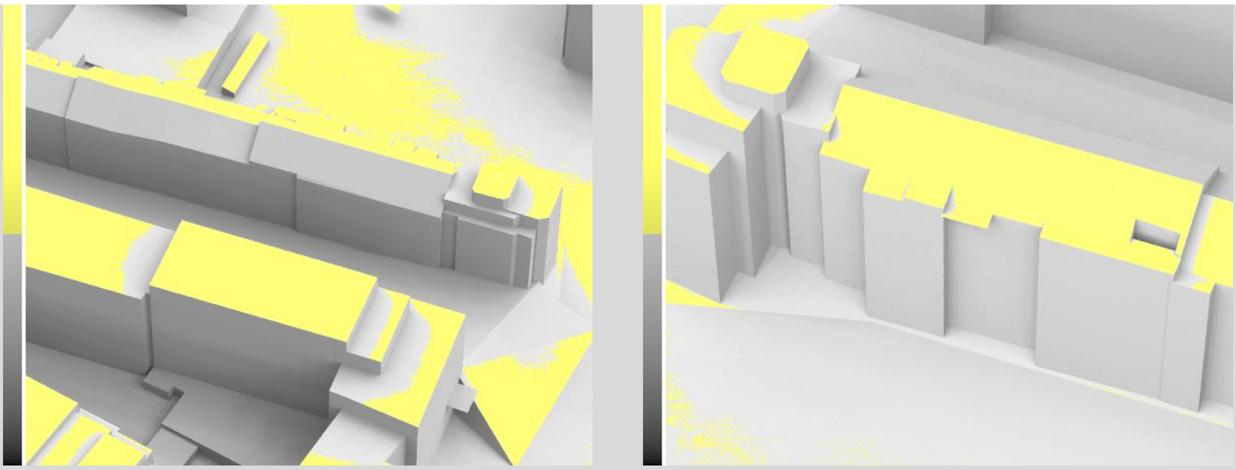
Thresholded North view relating to façade-integrated solar thermal collectors (500 kWh/m^2.year)



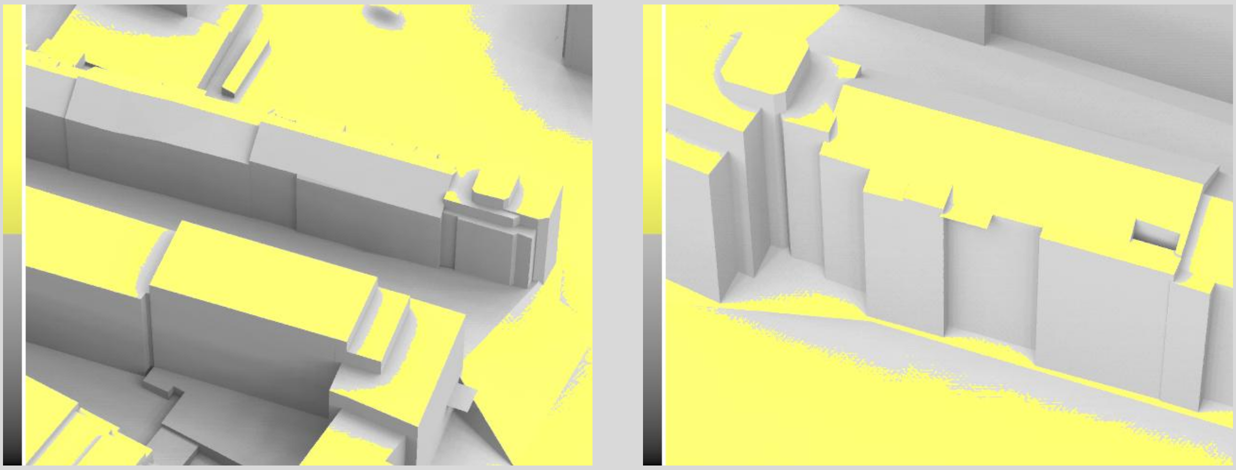
Thresholded North view relating to façade-integrated solar thermal collectors (600 kWh/m^2.year)

Figure 89: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

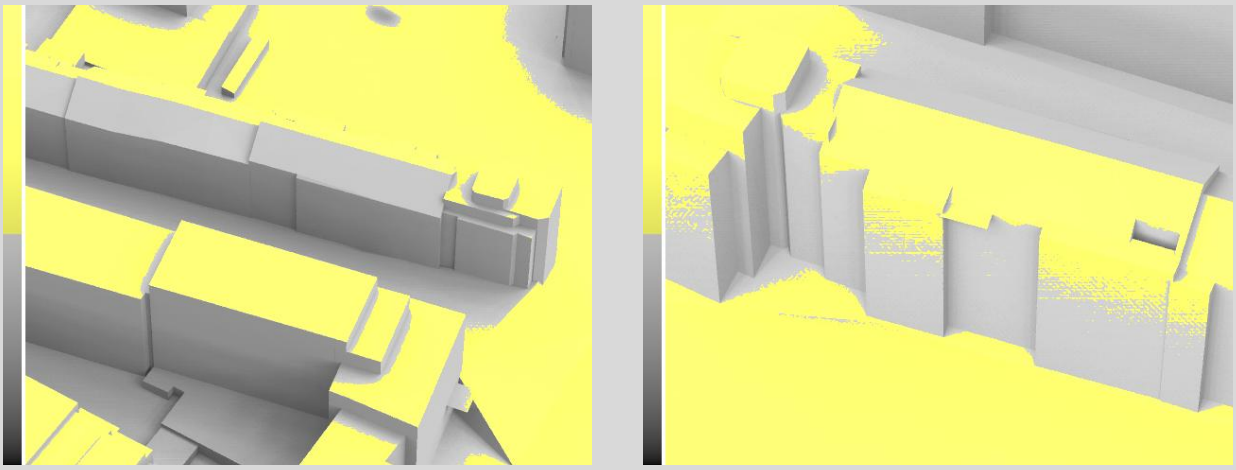
The North façades are again not suitable for solar thermal collectors; the South, North and East façades perform very well. On the other hand, with a threshold of 500-400 kWh/m^2.year, the East façades are no longer appropriate at all.



Thresholded North (left) and South (right) views relating to roof-integrated BiPV (1000 kWh/m^2.year)



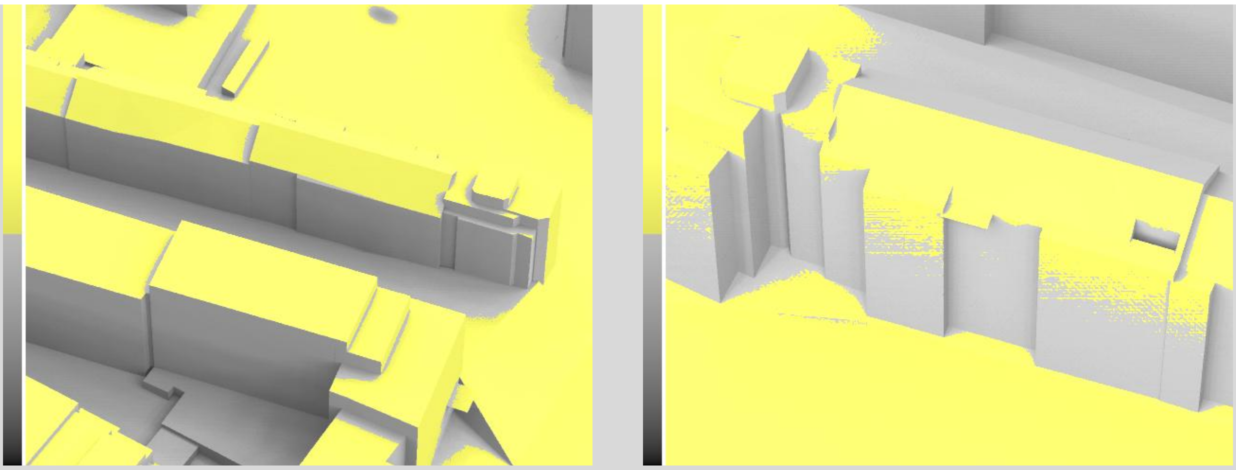
Thresholded North (left) and South (right) views relating to roof-integrated BiPV (900 kWh/m^2.year)



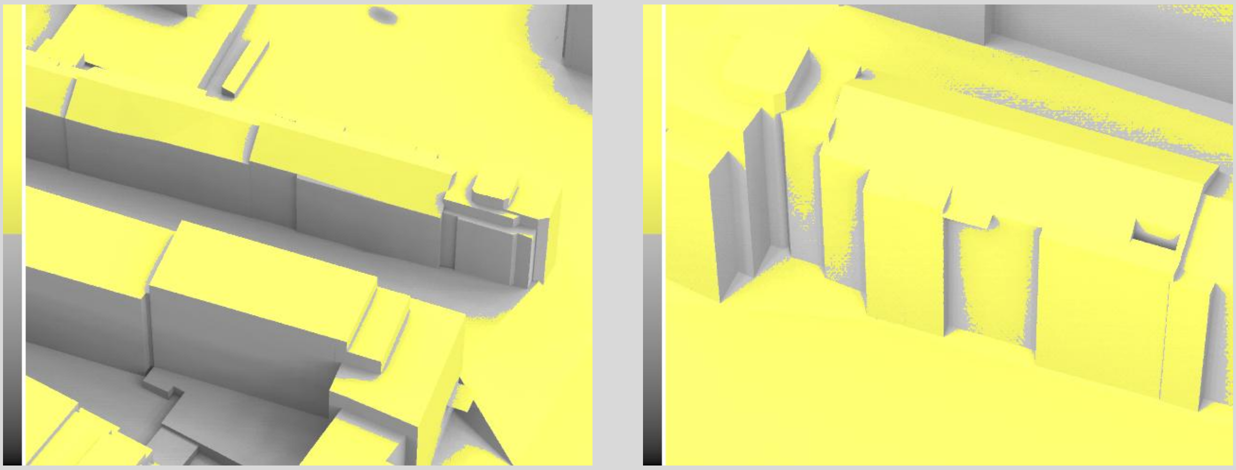
Thresholded North (left) and South (right) views relating to roof-integrated BiPV (800 kWh/m^2.year)

Figure 90: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

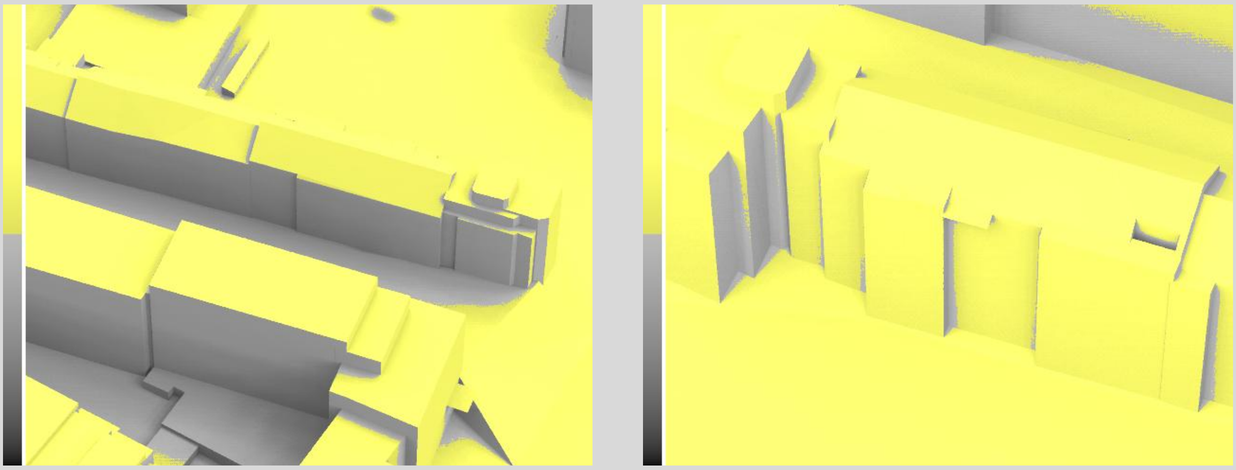
As far as the BiPV on roofs is concerned, the South sloping roofs “respond” in a positive way with the three different thresholds, in contrast to the North sloping roofs, which “respond” negatively for all cases. The flat roofs do not seem especially affected, apart from a few surfaces located near recessed areas, which are certainly shading the roofs.



Thresholded North (left) and South (right) views relating to façade-integrated BiPV (800 kWh/m^2.year)



Thresholded North (left) and South (right) views relating to façade-integrated BiPV (700 kWh/m^2.year)



Thresholded North (left) and South (right) views relating to façade-integrated BiPV (600 kWh/m^2.year)

Figure 91: 4-6 Feldbergstrasse in the Matthaeus district. Thresholded images using a Boolean filter.

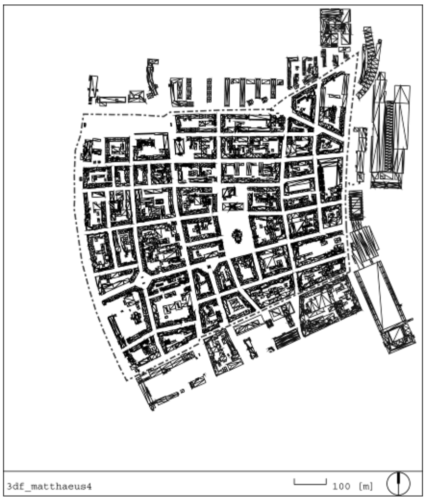
The North and East façades are not suitable for BiPV, even with a threshold at 600 kWh/m^2.year. Conversely, one is aware of a dramatic improvement (+80%) on the South façade, when moving from a threshold of 800 to 600 kWh/m^2.year. This thesis permitted the comparison of theoretical building shapes for the purpose of analysing their impact on a few parameters depending on the urban density — such as the site coverage ratio[42] and the plot ratio[43] — on the availability of daylight, as well as on the solar utilisation potential of the site.

[42] The site coverage ratio is the building footprint of the total site area. It gives an idea of the land use.

Layout of the urban site

The solar potential of a urban site for collecting solar irradiation and illuminance depends on the main orientation of its buildings. The orientation rose appearance mostly reflects the rectangular shape of buildings and their regular arrangement on the site (see Figure 92). The orientation rose, suggested by Compagnon, depends on the façade area oriented towards each cardinal direction, as well as on the obstruction due to neighbouring buildings. These areas are summed up and aggregated into several azimuth sectors (typically 15° wide). The sectors showing the largest areas of façades indicate the main orientations in which irradiances and illuminance will play a predominant role.

The Matthaeus rose indicates that the site is slightly more influenced by North-South/East-West azimuths; the dominance of the East-West road axis is however more marked than the North-South with figures respectively of 25% against 21%. Globally, the façades occupy the South-East and North-West quadrants regularly; the North-East and South-West sectors have been less exploited showing an area of only 24% of raw façades. Furthermore, the street blocks average for Matthaeus site calculated by PPF is four storeys (4.23 precisely).



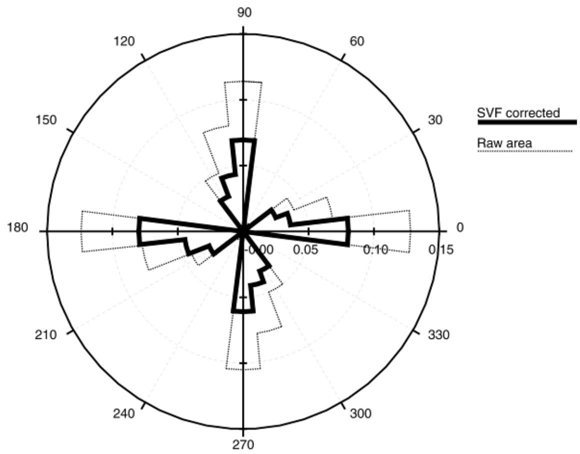


Figure 92: Layout plan for the Matthaeus district (left) and an illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (right).

Daylight and Sky view factors

The outdoor daylight factor and the Sky View Factor (SVF) are used to assess the potential of an urban site in the absence of climate data. These two parameters allow a self-evaluation of the urban shape in a way which is independent of a specific geographical context (see Figure 93).

The outdoor daylight factor for Matthaeus computed using a CIE standard overcast sky model has a pyramidal shape, which begins gently at 0%, peaks at 40% and abruptly falls again at 50%. The daylight factor computed by PPF also accounts for reflections in-between buildings. Approximately 44% of the façades have an outdoor daylight factor equal or higher to the threshold of 40%. The peak value at 40% is certainly due to the clearance of the façades in the West of the district, along the Rhine and around the Matthaeuskirche Square. The presence of innumerable courtyards also plays a decisive role.

[43] The floor area ratio (FAR) also called the plot ratio or the floor space index is the most significant measure for housing and other building types. The plot ratio defines the total floor area of buildings permitted to be erected on a site. A plot ratio is calculated by dividing the net floor area of all buildings on the site by the net site area. It helps to determine the urban density.

As indicated earlier, the site is rather intensely occupied, with a population density of 260 inhab./ha and a plot ratio of 2.44. The density of urban areas has a considerable impact on the Sky View Factor (SVF): this is confirmed by the orientation rose, on which their cooling and daylighting potential depend. The urban feature of Matthaeus is responsible for a significant reduction of the sky fraction viewed by the buildings' façades; most of the building façades (and roofs) are subject to rather unfavourable conditions. The façades are heavily obstructed at the rate of 40%: consequently, SVF values lie between 0.2-0.5 for the façades and 0.8-1 for the roofs of Matthaeus with an important peak between 0.85 and 1. The most obstructed façades are located in the South-East and North-West sectors. One should observe on the orientation rose a large difference in obstruction between West and East given the fact that the entire West side of the Matthaeus district is built in the vicinity of the Rhine, and consequently free of obstruction. Nevertheless, the difference between these two orientations is only 1%.

Obstruction Illuminance Multiplier

Obstruction Illuminance Multiplier (OIM) distributions computed for all surface orientations (see Figure 94) are an alternative method to assess the effect of urban form on daylight access. These graphs show that the Matthaeus district is affected by obstructions. All façade surfaces have an OIM lower than 1 with a peak in the ranges of 0.9 and 1 for roofs. During the heating season, when the sun elevation angle is low and on high surface reflectance, the OIM increases from 0.4 up to 1 for some façades. This indicates that their surrounding obstructions act poorly as effective reflectors for façades in contrast to the roofs whose peak increases considerably in Winter. However, the number of façades areas showing an OIM value larger than 1 is higher during the heating season compared with the annual calculation. This is also an indication of a positive effect of the inter-reflections over surrounding buildings.

Irradiation and illuminance distributions

A key results from PPF is the calculation of the solar irradiation and illuminance histograms shown in Figure 95, with black areas relating to façades and grey to roofs. PPF determines, by accounting for inter-reflections and for each part of the envelopes, the irradiation (measured in kWh/m^2) and the illuminance (measured in lx) impinging the buildings envelope. All these values, averaged over an appropriate time period are grouped within histograms, which give the areas of the envelope elements in different classes of irradiation or illuminance. The histograms of solar irradiance allow the assessment of photovoltaic systems and solar thermal collectors; the histograms of solar irradiance assessed during the heating season allow the assessment of passive thermal heating.

Annual façade irradiation is fairly normally distributed around 400 kWh/m^2.year with a weak peak in the ranges of 100-200 kWh/m^2.year. The average global irradiation for the façades is equal to 390 kWh/m^2.year, which is rather low. In contrast to the façades, the roofs of Matthaeus are relatively unobstructed, with the highest fraction of surfaces receiving 1,100 kWh/m^2.year and an average irradiation of 925 kWh/m^2.year. However, the histogram has a long tail towards the end of the irradiation scale, suggesting that some low roofs are heavily obstructed. The trend is similar for the annual illuminance distribution for façades and roofs, with peaks in the ranges 6-8 kLux and 28-30 kLux.

In Winter, the irradiation distribution has a sharp peak located between 0-100 kWh/m^2.year; it ends with a long tail towards the low end of the irradiation scale at 400 kWh/m^2.year with a Winter average of 136.4 kWh/m^2.year. On the other hand, the roofs see a little more sun with an average of 289.2 kWh/m^2.year. In both cases, the Winter average is weak. The pattern of Winter illuminance is less "squeezed" than the Winter irradiation. It shows two peaks between 4-6 kLux and 18-20 kLux and reaches up to 22 kLux for the façades.

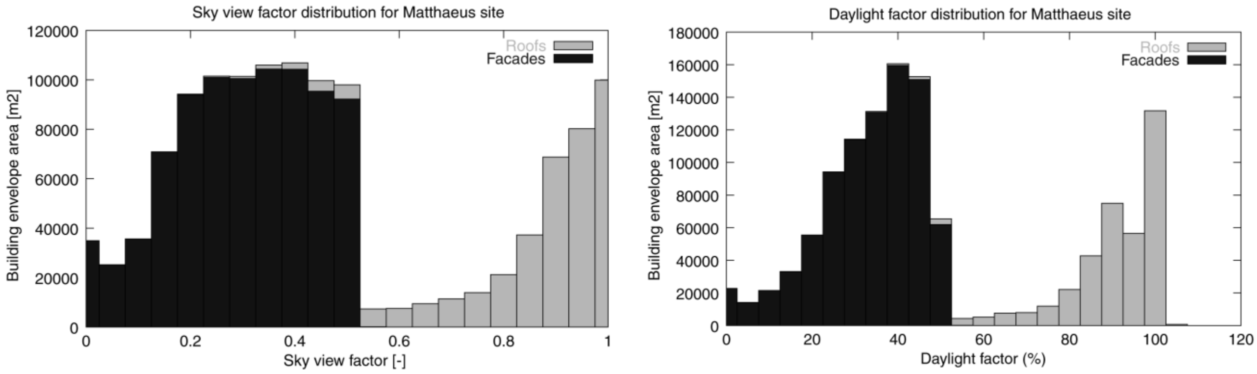


Figure 93: Sky View Factor distribution (SVF) (left) and outdoor daylight factor (right).

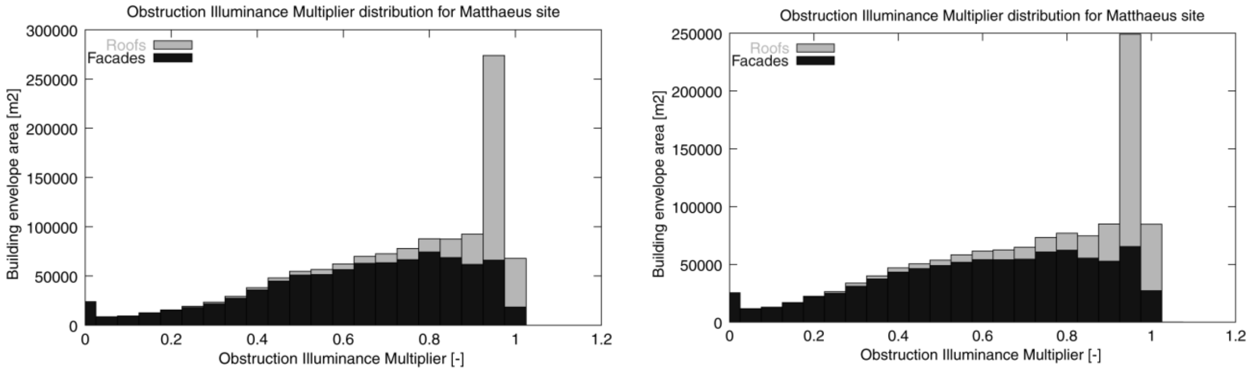


Figure 94: Obstruction Illuminance Multiplier (OIM) distribution during the entire year (left) and during the heating season only (right).

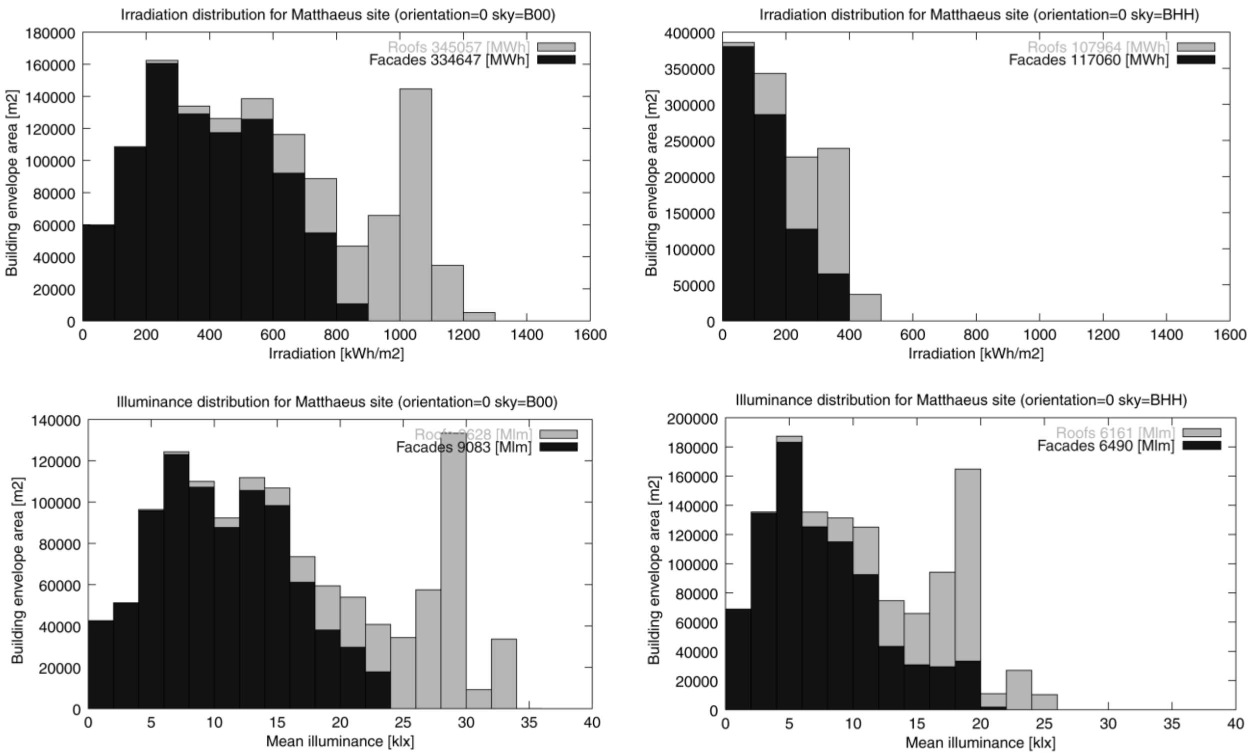


Figure 95: Statistical distribution of yearly irradiation on the building façades and roofs (top left) and statistical distribution of Winter irradiation on the building façades and roofs (top right), Statistical distribution of yearly illuminance on the building façades and roof (bottom left) and statistical distribution of Winter illuminance on the building façades and roof (bottom right).

Sensitivity of solar potential

The sensitivity of the different solar potentials, according to the threshold values, is shown on the cumulative distributions of the annual and Winter irradiation on the building façades and roof. These figures show (on their vertical axis) the percentage of the building envelope area that is lit by an irradiation or an illuminance larger or equal to the corresponding thresholds shown on the horizontal axis (see Figure 96).

The annual curve of the façades subsides gently, but then rapidly starting at 100 kWh/m^2.year. The annual curve of the roofs reacts differently and presents several rifts immediately before and after 1,100 kWh/m^2.year, another one after 1,000 kWh/m^2.year and a fourth one before 1,200 kWh/m^2.year. The Winter curve of the façades reveals fairly rapidly a strong decrease after 50 kWh/m^2.year. A similar annual curve can be observed for the roofs and falls rapidly after 200 kWh/m^2.year. Both annual and Winter cumulative distributions confirm that the roofs are distinctly more unencumbered than the façades which show significant obstructions.

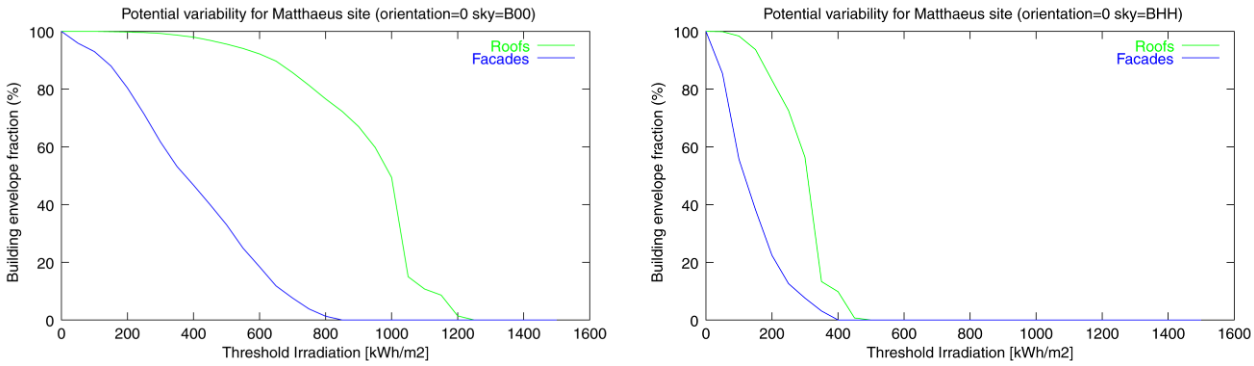


Figure 96: Cumulative distributions characterising the façades' solar irradiation of the Matthaeus district. Annual solar irradiation serves to assess the potential for building integrated photovoltaic systems and solar thermal collectors (left); heating season irradiation serves to assess the potential for passive solar heating techniques (right).

Overall daylighting performance and solar potential

The evaluation of the solar potential of the district (see Table 17) indicates that the latter developed by itself without taking the access to solar radiation into account: however with a plot ratio of 2.44, 31.9% of the façades are suitable for passive heating. This value rises up to 51.2% for daylighting on an annual basis and to 26.9% for Winter. The solar gains during wintertime are rather low and consequently a multitude of façade openings will not generate the required indoor illuminance. As far as solar thermal collectors are concerned, 92.2% of the roof area and 46.7% of the façades are suitable for solar hot water production. Photovoltaic panels show a lower solar potential, with only 49.4% of the roofs'surfaces and 1.3% for the façades being suitable for them. These values reflect the uniformity of building heights and the high density of the site.

Table 17: Comparison of percentage of surfaces available for energy exploitation in the proposed Matthaeus centre

Basel	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Matthaeus	51.2%	26.9%	31.9%	92.2%	46.7%	49.4%	1.3%

Implementation of solar energy technologies

Closer views of the blocks, which correspond to the 55 Matthaeus city blocks, were produced through visualisation techniques involving 3D colour rendering of the buildings with appropriate view angles (see Subsection: Sensitivity study of the thresholds). Implementation of the different solar technologies in the operational field are expected to be facilitated by these visual tools, contributing to improve the dissemination of sustainable technologies in favour of a “2000 Watts Society” (as an example, see Figure 97).

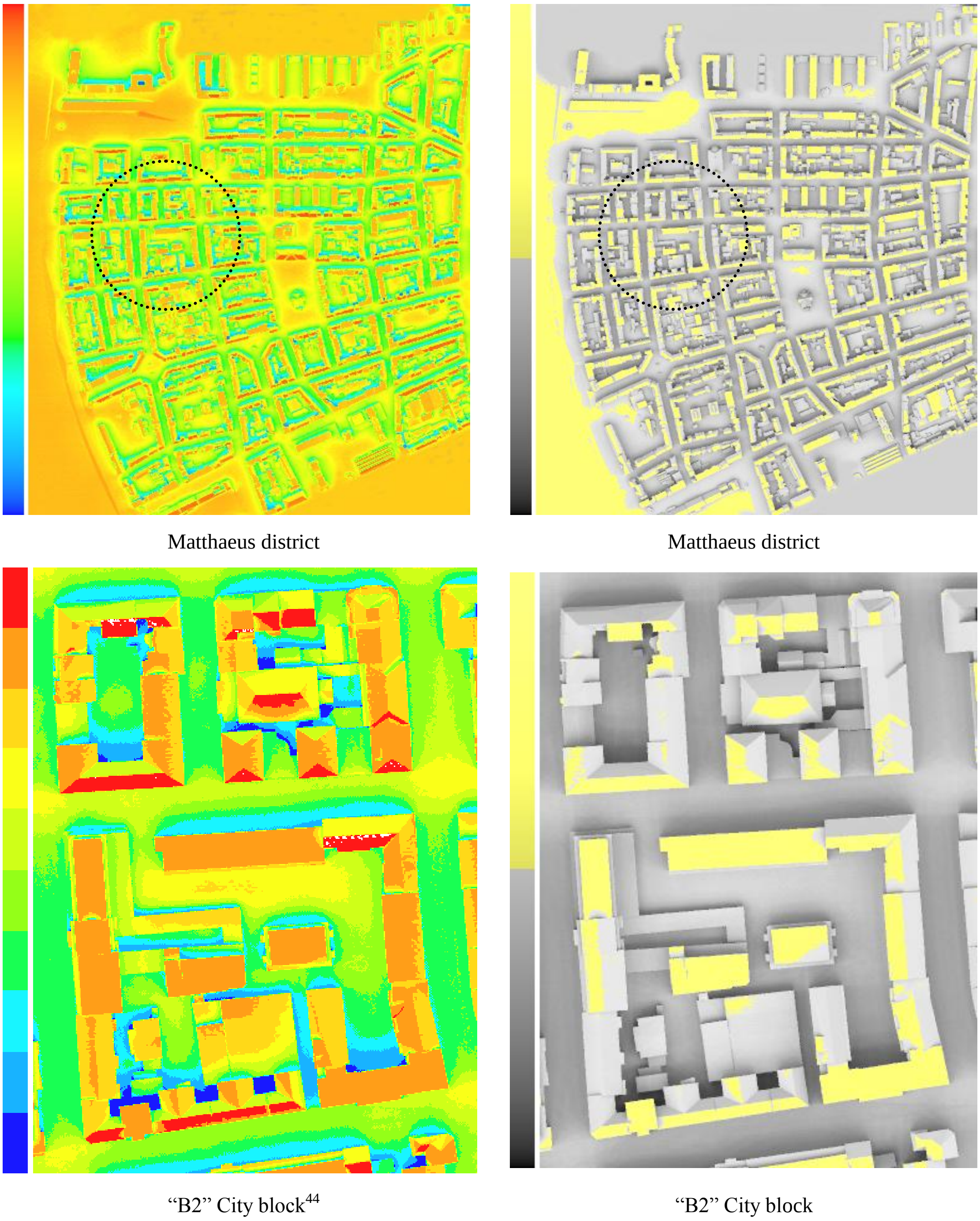


Figure 97: False-colour images and thresholded images using a Boolean filter. Continuous false-colour (top left), discretised false-colour (with 100 kWh/m2.year subdivisions) and threshold images relating to roof areas appropriate for photovoltaic applications of the Matthaeus district (top and bottom right).

[44] Identifying name assigned by M. Montavon.

Balance of the Matthaeus district analyses

Matthaeus district has very large façade and roof areas (covering 858,000 and 373,000 m^2 respectively – 9,235,435 and 4,014,938 sq ft), which open up good prospects for the utilisation of solar energy. As the high density of the urban site reduces the sun and daylight access to the buildings, part of the area does not benefit from yearly average solar irradiances and daylight illuminances that are technically and economically appropriate for direct solar technologies. However, assessment of the relative fraction of suitable façades and roofs, based on the minimum required irradiation and illuminance thresholds, shows that a very significant part of these areas remains appropriate for solar technology operations, despite the urban character of the site. It indicates that about half of the façade areas can reasonably be used for passive and active solar heating, as well as daylighting of buildings; the same figure is obtained for photovoltaic electricity generation on the roofs, and an even higher value was observed for active solar collectors. As a consequence, the prospects for the Matthaeus district to achieve the goals of the "2000 Watts Society" project are promising.

Generic urban forms' studies

Four different types of representative built forms in Basel and in other European cities were compared. The purpose was to explore the role of built form parameters – in terms of shape, orientation and level of surrounding obstructions, compactness index, solar energy efficiency, etc. – regarding their solar potential (see Figure 98). The latter were embedded into an existing square in the centre of the Matthaeus district. These buildings have been designed with standard dimensions of 10-14 m (32.8-45.9 ft) depth and 11-13 m (36-42.6 ft) width in compliance with the site regulations. These dispositions were chosen to maximize daylight inside the apartments.

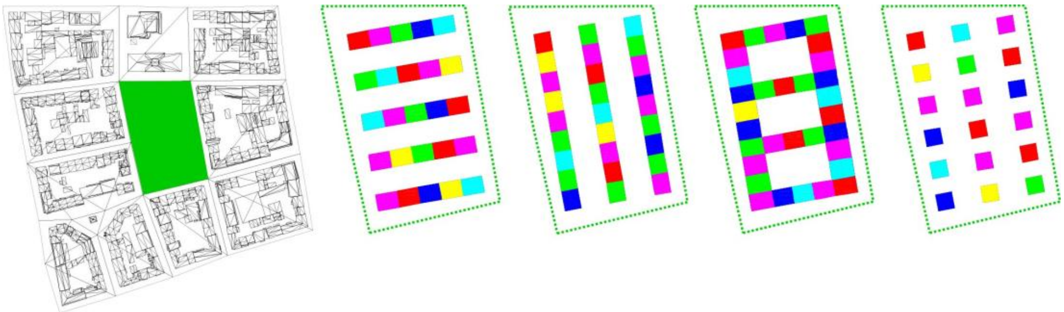
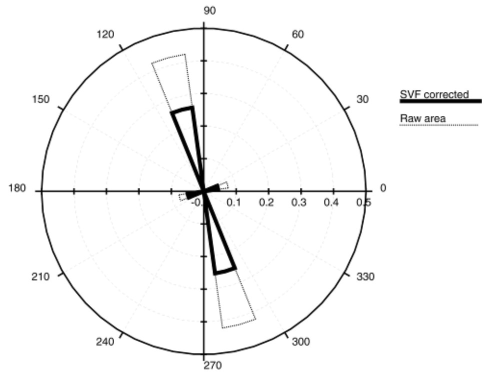


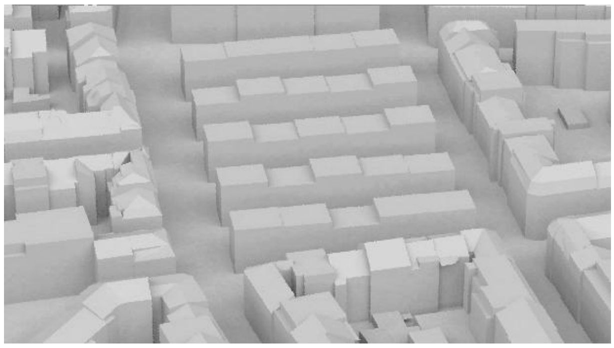
Figure 98: Layout surroundings in the Matthaeus district of the potentially buildable area and four typical urban built forms studied: respectively "Terraces" Flat Roofs, "Slabs" Sloped Roofs, "Blocks" (2 sided-roofs) and "Pavilions" (4 sided-roofs).

Layout of urban sites

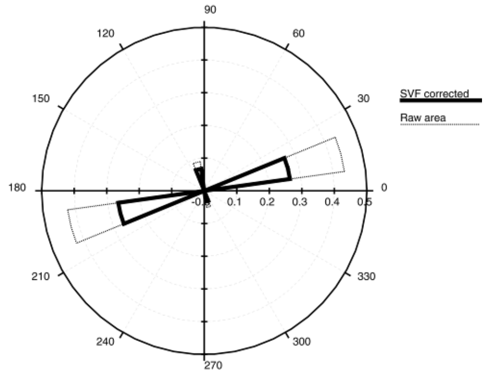
Generic urban forms were designed and parameters defined during this study in order to minimize the energy consumption of buildings using evolutionary algorithms (Kaempf, Montavon et al. 2009). As a first approximation, minimizing the energy consumption of urban built forms can be achieved by maximizing the net balance between their solar gains and their thermal losses: this was carried out at EPFL in the course of the Ph.D. thesis of Dr Jerôme Kaempf. The final resulting urban forms, whose parameters were defined by means of *genbuil*[45] and remodelled in the course of this study, as well as the PPF analyses, are presented in this section. The results are surprising and the integration of these forms is quite realistic, especially as far as the "Blocks" are concerned. However, the "Pavilions" seem to be the urban forms, which are more poorly integrated into this district from an architectural perspective.
Figure 99 shows the orientation roses of these forms along with their corresponding computer rendering.

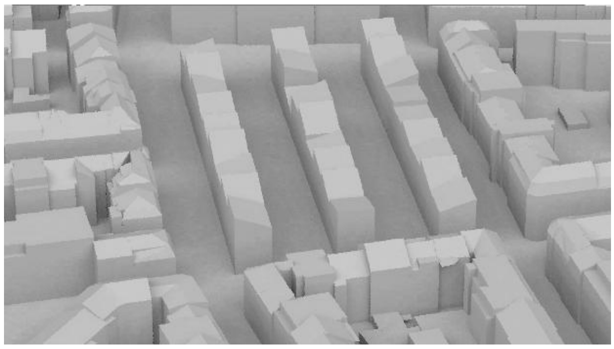
[45] New C++ software *genbuil* was developed to determine the solar potential and the thermal losses of each vector representing a potential candidate for the best energetic building configuration.



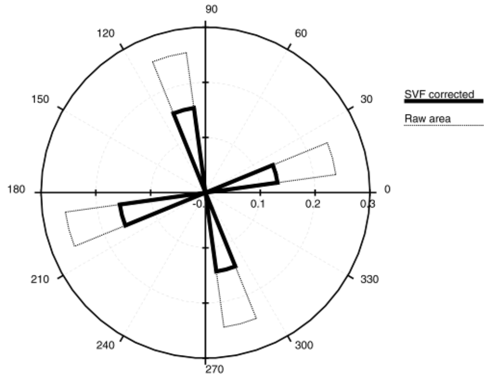


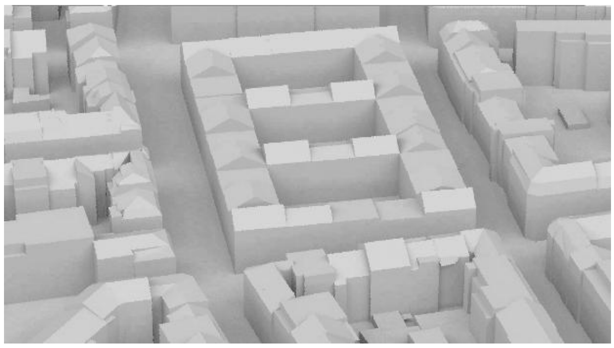
“Terraces”



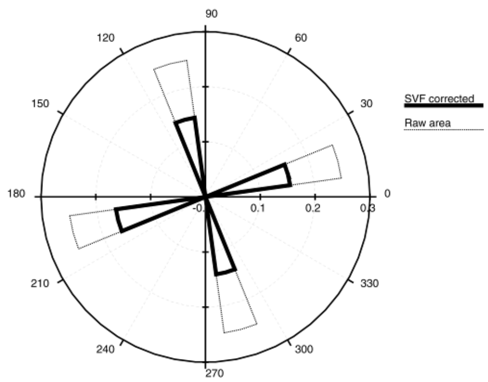


“Slabs”

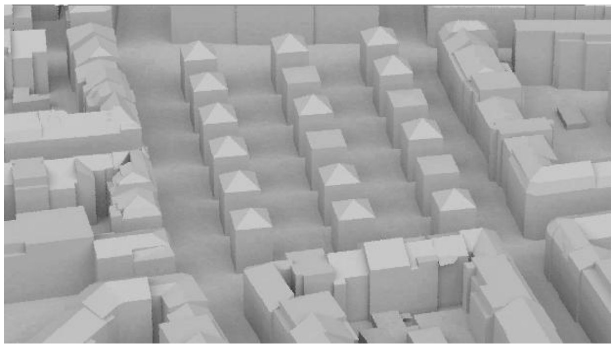




“Blocks”



“



“Pavilions”

Figure 99: Illustration of the orientation roses of the four analyzed generic urban models (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (left) and visualizations of urban forms (right) (RADIANCE renderings).

The orientation roses of the generic urban forms show that the façades of the “Terraces” are 84% North-South oriented and slightly veering towards the West-East; the East-West orientation veers slightly towards the South-East and predominates at 86% for the “Slabs”. These two forms are completely different in terms of orientation. Surprisingly, the two orientation roses of “Blocks” and “Pavilions” are comparable. Although these two forms are completely different conceptually, they are however similar regarding their orientations. This similarity extends even to their obstructions in relation to their façades. The latter are almost identical for both and are located at 41% for “Blocks” and at 30% for “Pavilions”. Globally, the façades have the main orientations North-South/East-West with a slight veering to the West. The 4 projects demonstrate more or less the same relative fraction of obstructions.

Overall daylighting performance and solar potential of the urban forms

The assessment of these urban forms places “Pavilions” in a good position with 65.3% of the façades suitable for daylighting (see Table 18); “Terraces” has a lower potential with only 52.8% of its façades favourable to this technology. On the other hand, for the Winter period, it occupies the top position with values reaching 29.5% and likewise in the case of the passive solar 32.9%. “Pavilions” takes over the lead again for solar thermal, 100% of the roofs and 56.1% of the façades being usable. Conversely, its BiPV results are low compared to the other forms with only 46.8% of the roofs being exploitable. “Terraces” reveals an excellent potential with 89.3% of the roofs being viable, which is impressive considering that the average for the Matthaeus district is characterized by a value of 49.4%. Once again, it must be emphasized that the only negative features of “Blocks” is the solar thermal value with 47.7%.

Daylighting, solar potential and urban density

To increase the reliability of this study, other factors were taken into account in order to determine the optimal urban form (see Table 19).

Densities were examined in three ways: i) plot ratio, ii) compactness index of built form and iii) compactness index of built form related to site. Plot ratio is defined as the ratio of total floor area to site area; the compactness index of built form is the ratio of envelope area to volume and the compactness index of built form related to site is the ratio of floor area to site area divided by the building footprints to site area.

The plot ratio provides a first impression of the urban shape, but the view of the final shape is comparable to a rough model executed by a sculptor (Allain 2004). The index of compactness indicates the degree of compactness of the form on its own without the influence of the site. The index of compactness of the built volume related to site indicates the degree of integration of the form in relation to the site. A higher value will indicate that the built form has completely “espoused” the terrain into its surface as well as into the dimensions authorized by the building regulations.

It is not surprising that the plot ratio of “Blocks” is superior to the others and even 2.5 times superior to “Pavilions”. The index of compactness of this built form is the weakest with 0.23. This signifies that “Blocks” is not a compact form in itself, in contrast to “Pavilions” which is by far the most compact with a value of 0.45. The index of compactness of the built volume related to site of “Blocks” indicates that it is close to the average with 4.41 compared to the other forms; this accounts for the fact that the maximum rating for the site is at 5. Once again, “Pavilions” is well placed with a rating of 4.41. At this point, things start to deteriorate for “Pavilions”.

Table 18: Comparison of percentage of surfaces available for energy exploitation for a range of selected urban forms in the proposed Matthaeus centre

Basel	Daylighting viability		Passive solar viability	Solar thermal viability		BiPV viability	
	Façades (annual)	Façades (Winter)	Façades (Winter)	Roofs (annual)	Façades (annual)	Roofs (annual)	Façades (annual)
Matthaeus	51.2%	26.9%	48.7%	92.2%	46.7%	49.4%	1.3%
“Terraces”	52.8%	29.5%	32.9%	99.6%	49.3%	89.3%	0%
“Slabs”	63.4%	13.7%	22%	93.8%	51.3%	68.5%	0.2%
“Blocks”	54.9%	20.7%	27.3%	96%	47.7	47.2%	0.5%
“Pavilions”	65.3%	21.7%	28.6%	100%	56.1%	46.8%	0%

Table 19: Comparison for “Pavilions”, “Slabs”, “Terraces” and “Blocks”

Matthaeus centre	“Terraces”	“Slabs”	“Blocks”	“Pavilions”
Obstructed façades (%)	39.28%	36.61%	41.04%	39.19%
Plot ratio Raw floor area (m^2) / Site area (m^2)	1.14	1.31	1.84	0.73
Compactness index of built form (Envelope area/Volume)	0.31	0.30	0.23	0.45
Compactness index of built form related to site (Floor area/Site area) / (Footprint/Site area)	3.80	4.35	4.41	4.41
Envelope area (m^2)	13220.3	14452.7	15787.3	12067.3
Volume (m^3)	42363	47611	67089	26778
Raw floor area (m^2)	12392	14166	19931	7933
Covered ground area or footprint - (m^2) - (%)	 3260 30.22%	 3251 30.14%	 4522 41.91%	 1800 16.69%
Non-built area (%)	69.77%	69.86%	58.09%	83.31%
Site area (m^2)	10786	10786	10786	10786
Annual irradiation (MWh)	7353	7976	8997	6156
Annual illuminance (Mlm)	205	219	248	169
Irradiation per unit of external surface (kWh/m^2)	556.2	551.9	569.9	510.2
Illuminance per unit of external surface (kLux)	15.52	15.14	15.73	14.01
Irradiation per floor area (kWh/m^2)	593.33	563.03	451.14	777.59
Solar energy efficiency index (Annual irradiation (MWh) *1000) / (Irradiation per external surface (kWh/m^2) x Site area (m^2))	1.22	1.33	1.46	1.11

Indeed, its illuminance and irradiation per unit of external surface are only located at 14.01 kLux and 510.2 kWh/m^2.year, whereas for "Blocks" they "culminate" at 15.73 kLux and 569.9 kWh/m^2.year. The differences are small, but have a significant impact. The pavilion type (detached house, one-family housing, etc.) no longer has to be taken into account if one manages to obtain similar illuminance and irradiation with a form that is less compact than the "Pavilions" type. It occurs again for the raw floor area (m^2) and the solar energy efficiency index: the "Blocks" type makes it possible to create 19,931 m^2 of commercial and habitable surface whereas with the "Pavilions" type it is located at 7,933 m^2 (namely 2.5 times less).

To pursue this further, the solar energy efficiency index of these different urban forms was determined in this study and is defined as:

(Annual irradiation (MWh) *1000) / (Irradiation per unit of external surface (kWh/m^2.year) x Site area (m^2))

The study of the generic urban forms case reveals even more the complexity of the issue. The conclusion is that the most efficient urban form in terms of daylighting and solar potential is ultimately "Blocks" (1.46), followed by "Slabs" (1.33), "Terraces" (1.22) and "Pavilions" (1.11). However deeper investigation turns out to be essential to confirm that the optimization of the urban form through the evaluation of the solar potential is heading in the right direction. In addition, the urban form "Blocks" allows one to address the crucial problems which are crying out for a solution in the towns: namely an alarming lack of dwellings and the necessary densification to safeguard the green belts of the town periphery.

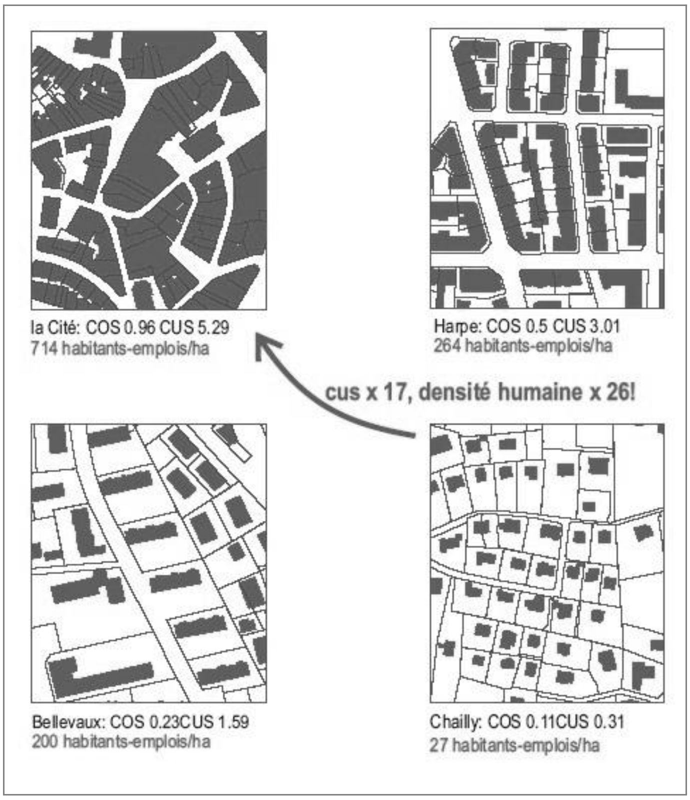


Figure 100: Examples of district densities in Lausanne. The Bellevaux district (bottom, left) is not very dense in comparison to the Cité and La Harpe districts.

Source: [online] URL: http://www.tribu-architecture.com (Consulted on March, 2005).

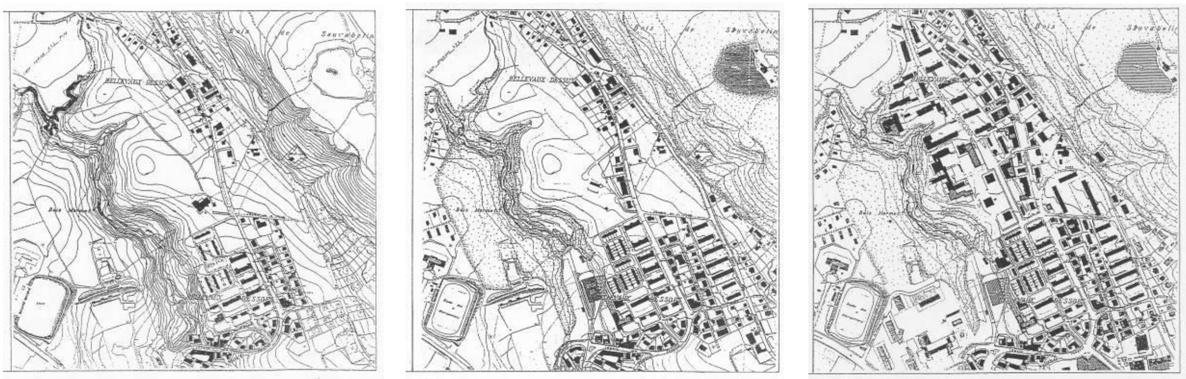


Figure 101: Evolution of the district: situations in 1937, 1959 and 1975.

Source: Gay, J.-B., M. Montavon, et al. (2004). Quartiers durables BaLaLuZh, Quartier Bellevaux - Lausanne, Rapport final de la phase 1. Lausanne (Switzerland), Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL).

4.3 Bellevaux district, Lausanne, 46.51 latitude (Switzerland)

This study was carried out in the Bellevaux district selected during the SOLURBAN project (Montavon, Scartezzini et al. 2004; Robinson, Scartezzini et al. 2005) for the following reasons:
- its slightly 6% sloped ground (interest for the project to test PPF on a sloped urban site);
- the diversity of its building largely directed east-west which, in the near future, will probably be refurbished or demolished to allow for the reconstruction of multi-family apartment buildings, for the sake of sustainable development (Gay, Montavon et al. 2004);
- its potential for densification in the spirit of the hygienist thinking[46] of former times.

The city of Lausanne currently suffers from a severe housing shortage whose causes are manifold (migratory fluxes, high increase in the housing area per inhabitant, attraction of the Lémanic Arc, etc.). Moreover, 70,000 jobs for new inhabitants are expected within the Lausanne urban area by 2020[47]: to respond to this, densification becomes unavoidable. The Bellevaux area has an attractive potential; it was therefore interesting to assess the solar potential of the existing district to see if any densification opportunity is foreseeable in the near future, without lowering the initial quality (see Figure 100).

4.3.1 Description of case study

The urban district of Bellevaux is located in the north of Lausanne about 1.5 km from the city centre. It is bounded on the east and west sides by two wooded areas: the *Bois de Sauvabelin* and the *Bois Mermet*. With an area of 35.6 ha (88 acres) the district of Bellevaux can be considered as a showcase of multifamily housings. A total of 240 buildings cover a built-up area of 81,880 m^2 (881,349 sq ft), corresponding to a site coverage ratio equal to 0.23. These relatively low values have allowed for substantial green areas in the district, which also includes a residual area with low environmental value; the latter could in principle support further densification without negative environmental impact.

The district owes its birth to the hygienist ideas expressed at the beginning of the twentieth century. The urban planning goals of the initial project were only partially realized. The hygienist theories recommended for the site required a low urban density in order to allow "the air to circulate and improve daylight performance". Eventually, the city of Lausanne became industrialized and experienced all the related consequences of that process. To avoid high urban densities, the urban planners favoured the development of public transportation allowing for the expansion of the city of Lausanne.

Since the 12th century, a Cistercian cloister has been located in Bellevaux. However, the current development of the district was initiated at the beginning of the 20th century; in 1908 the first social housing was built in Bellevaux. From then on, numerous social housing projects were undertaken so that their number today represents 42.2% of the housing of the entire district, as a comparison, the social housing of the city of Lausanne currently represents 9.6% of the total of its residential buildings. The site is predominantly made up of three to five storey tenement buildings; over three quarters of which were constructed after World War II (from 1947 to 1970). The architectural style of the buildings varies a lot: a mixture of single dwellings, rows of working-class houses, gangway buildings, towers, shops and craft workshops The district displays a high range of building types: small and big shops, schools,

[46] The hygienist movement is an architectural and urban planning movement that advocates the application of hygienist theories. It was achieved, in the early twentieth century, through the work of various physicians and politicians (in particular the "*Musée social*") who fought against the unhealthiness of the Parisian accommodations and the spreading of tuberculosis. Their goal was to open up intramural districts sometimes bounded by former fortifications. They influenced a large number of architects and decision-makers of urban transformations, such as Rambuteau and Baron Haussmann in Paris.

[47] Projet d'agglomération Lausanne-Morges (PALM). Pour un développement équilibré à l'horizon 2020, Résumé du rapport final, février 2007.

Figure 102: A majority of buildings was built between 1947 and 1970.

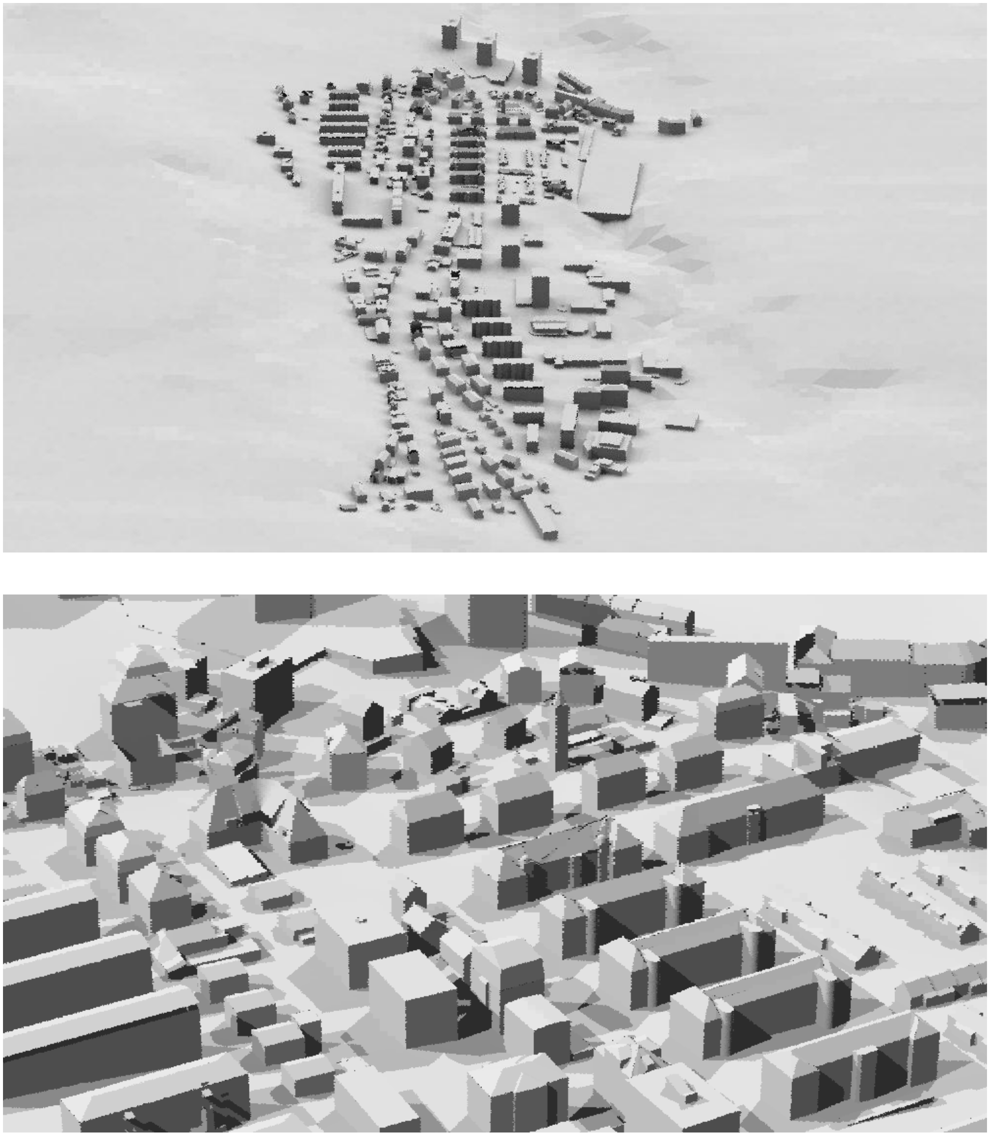


Figure 103: Bellevaux district in Lausanne. North view (top) and Zoom of North view (bottom) (RADIANCE renderings).

sport and leisure-related facilities, light industry and offices exist to satisfy the needs of the inhabitants (see Figure 101 and Figure 102).

The current district population has reached 4,601 inhabitants, a large proportion of whom are young people (22% of the population is less than 20 years old) and a larger proportion of whom are immigrants (43% of the population). The district's inhabitants are made up of workers, craftsmen, artists, students and retired persons. The occupancy of social housing is made up largely of elderly people.

4.3.2 Description of 3D digital model

The Urban Planning Service of Lausanne only owns two-dimensional cadastral data (2D digital model). Topographical data are incomplete: they are exclusively made of contour lines of different elevations. A first attempt, which consisted of using raw terrain and building digital data acquired by means of airborne "laser scans" (DHM[48]/DTM–AV[49] format from SWISSTOPO), turned out to be unsatisfactory. This is due to the fact that elevation data over the Lausanne region were just recently acquired: the DHM/DTM–AV was therefore not interpolated at that time. XYZ data in the files were very irregularly distributed: in some areas, no point could even be found in a circle of 40 m diameter, whereas in others, they were thousands of them. As it was impossible to interpolate these data, the use of DHM/DTM–AV was consequently abandoned, the development of such complex software being out of the scope of this thesis.

Applications that may overcome the difficulty of retrieving elevation models from laser scans are currently under development at the Geographical Information Systems Laboratory (LASIG) of EPFL. One application is able to determine building heights; a second one can provide laser-acquired Digital Elevation Models (DEM) by taking care of joins, aggregates and cut-out data meshes. Some promising work, dedicated to the analysis of the shape of buildings roofs acquired from laser scans, was also undertaken by Maas (Maas 1999; Maas 1999). This new software application should make it possible to refine 3D digital urban models in the near future. By projecting different vectorial data (cadastral plans for instance) on a laser-acquired DEM, it would be possible to create 3D databases from the currently existing documents and data.

A digital terrain model (DTM), providing elevation data in GRID–ASCII[50] format for terrain models, was supplied by the LASIG; the latter has been available throughout Switzerland since the end of 1996. DEM25 is computed from elevation data of the nationwide 1:25 000 Swiss map (CN25, Carte Nationale 1:25 000). It contains the raw data of the terrain, without constructions and/or vegetation. Land use is not taken into account; lakes' sole data are their overseas altitude. Two kinds of digital terrain models exist:

- A Base Model (made of digitized CN25 elevation data) with vector elevation curves, vector lake outlines and individual digitized elevations;
- A Raster Model (made of a 25 m raster mesh issued from CN25) with 701 × 481 elevations representing 337,181 altitudes.

The raster model is derived from the base model of a given terrain.

A 2D digital model cadastral plan was supplied by the Urban Planning Service of Lausanne in order to configure the buildings of Bellevaux district. It was used to virtually "raise" the building façades of the district. A 3D digital model of the Bellevaux district was generated later on by using microfilm recorded data prepared by the *Archives de la Construction Moderne* (ACM) of EPFL, as well as from the *Service d'Architecture* of the city of Lausanne (Architecture Office).

[48] The DOM or DHM models reproduce the shape of the earth's surface including all permanent and visible landscape elements such as the vegetation, forests, buildings and other civil engineering structures.

[49] The DTM-AV model represents the earth surface topography without vegetation and buildings.

[50] American Standard Code for Information Interchange: the most renowned and compatible digital character encoding standard.

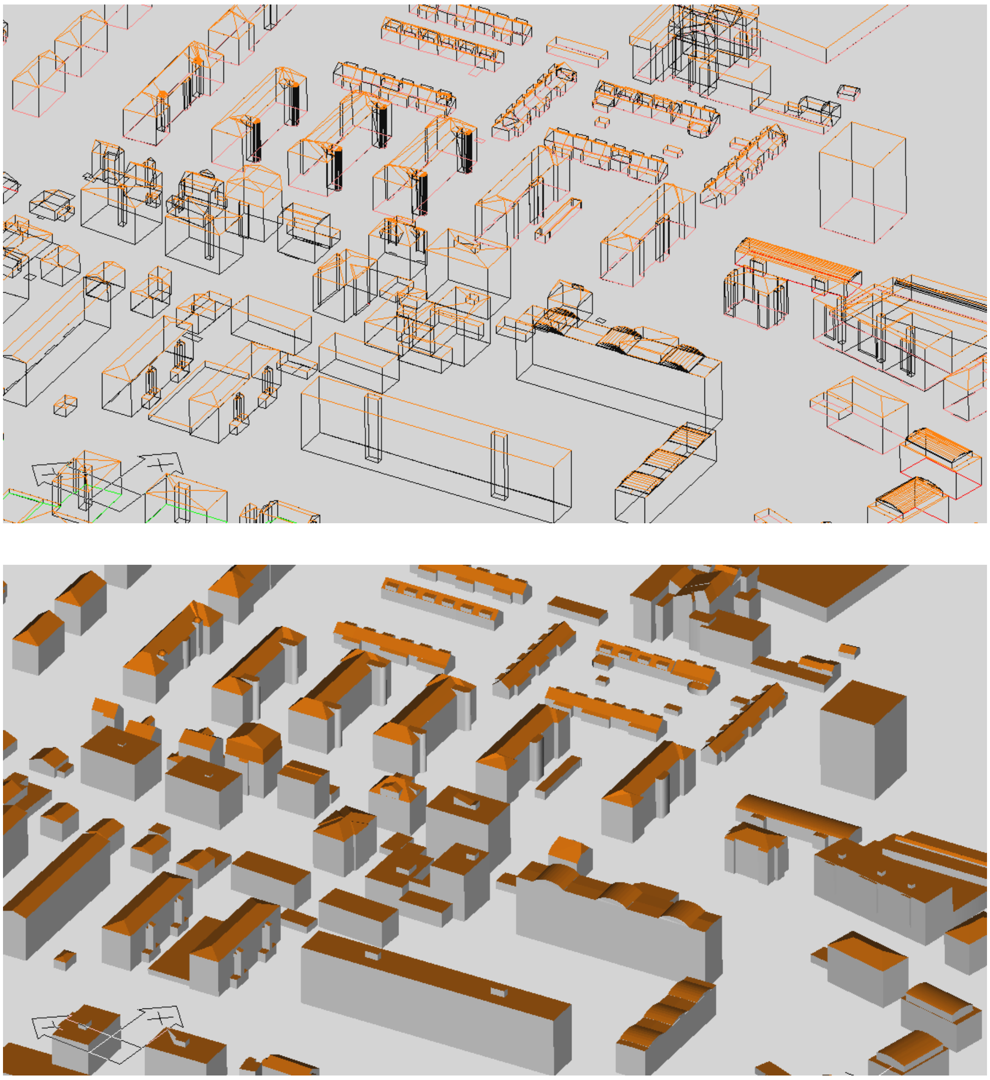


Figure 104: Bellevaux district in Lausanne. North view (top) and Zoom of North view (bottom) (AutoCAD/3DFACE renderings).

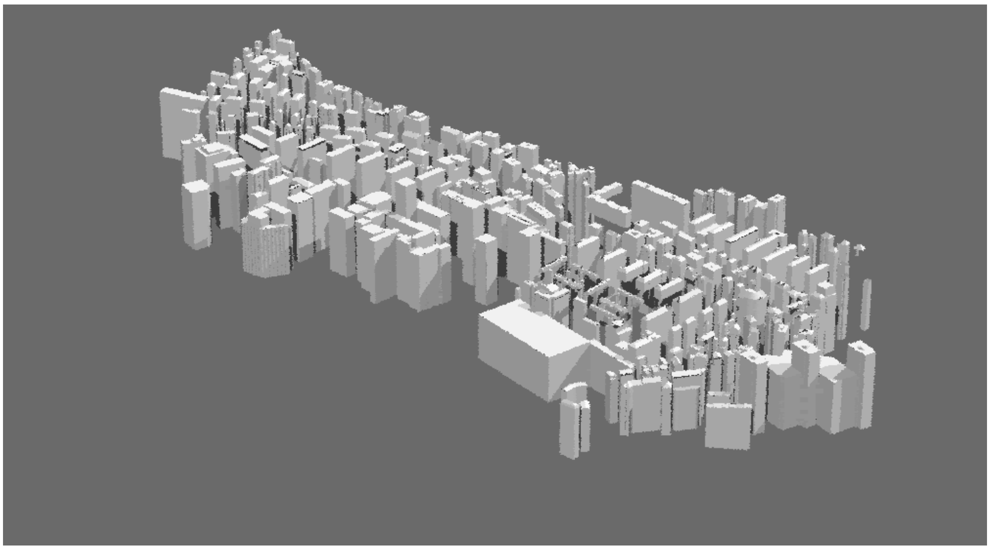


Figure 105: Façades automatically lowered towards the ground to an altitude of ±00.0 (RADIANCE rendering).

The digital model, developed using AutoCad (POLYLINE/3DFACE), is shown on Figure 103 and Figure 104. Buildings' façades were generated from original footprints using the POLYLINE/thickness command; straight segments, arc segments or a combination of both were created. A thickness corresponding to the height of each building was included in the POLYLINE application. This semi-automated handling allows all the façades to be raised up during a single operation. Modified polylines become faces; roofs were modelled using 3DFACE facets. The elaborated 3D urban digital model is extremely accurate (it has an accuracy of 1 cm). The entire set of flat, sloped and rounded roofs was modelled, including the hanging parts (overhanging flagstones) and superstructures (dormer windows, elevator shafts, blower rooms).

In order to meet this important challenge, the following practical operations were necessary:

- district surveys to identify the whole buildings set (sketches, photographs);
- analysis of architectural plans of all buildings using the relevant archives (City of Lausanne, ACM);
- clearing up of the 2D cadastral plan layers;
- keying-in of the buildings digital data issued from cadastral plans (polylines) and architectural drawings (plans and sections);
- modelling of building roofs using the architectural drawings (plans and sections);
- data modification according to the numerous refurbishment works occurring on the buildings (not shown on the original drawings) using photographs and building permit applications;
- validation of the 3D digital model by rendering of the buildings (using PPF software);
- merging of buildings' digital model with those of the terrain model (DTM 25).

The software had to undergo several modifications in order to be able to interpret POLYLINES/façades (polylines with a given thickness) and DEM25 relief data. 3DFACES, representing buildings roofs, were not modified, a command having already been adapted at the time (for the interpretation of Basel's 3D digital model).

The new function *get3dfn* was programmed for reading the corresponding files and converting it into a PPF-readable format. A computational routine was written to modify the data files of the Bellevaux district which contain terrain, façades and roofs data, so that individual surfaces could be distinguished from each other. This was required in order to be able to quantify the solar irradiation received by a given building surface according to its orientation and tilt angle.

As for the translation of DEM25 data into a PPF data format, a function *getxyz* had to be written. The latter reads elevations of geometrical files (.xyz files) and transfers them to PPF on a user-defined sized mesh. One of the main difficulties was the handling of buildings in the sloped topography of the Bellevaux district, expressed in the DEM25 terrain model. Buildings were first modelled on a flat terrain. All façades were automatically lowered to the ground to an altitude of ± 00.0 m (see Figure 105); they were than automatically raised back to an altitude corresponding to the lowermost cutting of their façades with the terrain. The latter was then extruded underneath each building footprint and intersected with it. The results were stored in such a way that each building could be individually identified and support standalone analyses if required. (see Figure 106 and Figure 107).

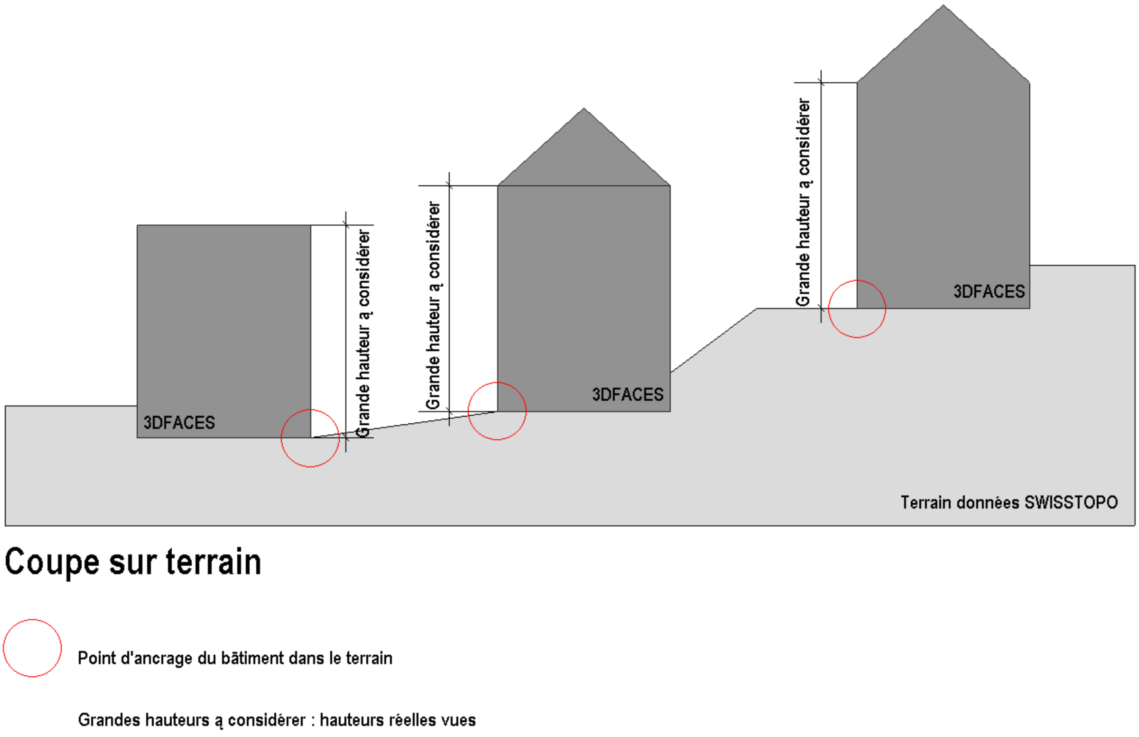


Figure 106: Cross section of the site. Input of the buildings in the sloped topography: Anchorage point in the building of the site (red circle) and larges elevation to be considered.

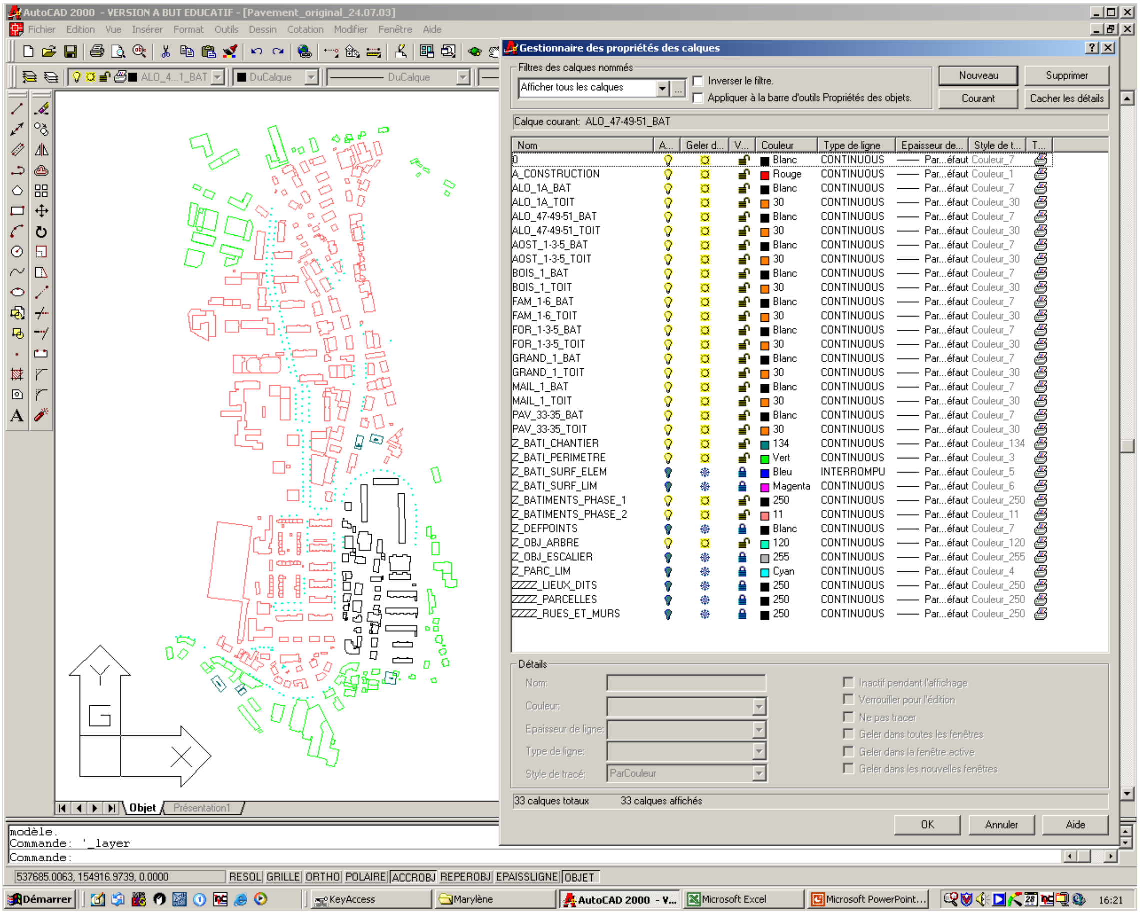


Figure 107: Storage of the 3DFACE in the appropriate AutoCAD layer so that each building could be individually located.

4.3.3 Solar performance indicators

Tribu'architecture[51] wrote: […] "*The question of densification, particularly diffuse densification, is a complex one that cannot be solved by waving a magic wand. But the acute housing shortage is such that today it is becoming a matter of urgency to offer solutions that are genuinely effective* […]". A fundamental aim of the SOLURBAN project was to evaluate the solar potential of the existing district in order to ascertain if densification would be possible without degrading the quality of the original site.

Using heating degree-days of 3,061 DD for Lausanne, the threshold for passive solar gain reaches 182 kWh/m^2.year. Assuming an indoor required illuminance of 500 lux and a utilisation coefficient of 0.05 – typical for a vertical opening – it corresponds to that fraction of façade area, which receives on average annually, 10,000 lux or more. For solar thermal collectors the lower figures of 400 and 600 kWh/m^2.year were used for façades and roofs respectively. Thresholds of 800 and 1,000 kWh/m^2.year were used respectively for photovoltaics. The simulations were carried out using the typical winter sky conditions of Lausanne (Compagnon 2004).

Layout of the urban site

The Bellevaux rose (see Figure 108) indicates that the North-South/East-West azimuths have a dominant influence on the site: the dominance of the East-West road axis is even more marked than the North-South with respectively 40% against 36%. Globally, the façades occupy the North-East and North-West quadrants regularly both 25% with a slight predominance of 3% for the direction South-West (28%). The South-East sector has been less exploited with an area of only 22% of raw façades.

The Sky View Factor (SVF) corrected surface shows that the façades are obstructed at a rate of 25%, which is fairly weak but sound enough to meet the initial urban planning goals. The first development layout of parallel blocks to be constructed was clearly on the North-South axis; as the district filled up this axis it deviated towards the East-West. If one takes the corrected SVF into account, the North-South axis becomes predominant once again to +6% compared to the East-West axis.

The most obstructed façades are located in the North-East sector (30%) and the least obstructed in the North-West (20%): as for the South-East and South-West, they are obstructed at the rate of 28% and 22% respectively. Once again, one can see that the largest obstruction is the hill on the *Bois de Sauvabelin,* which is located to the East of the district.

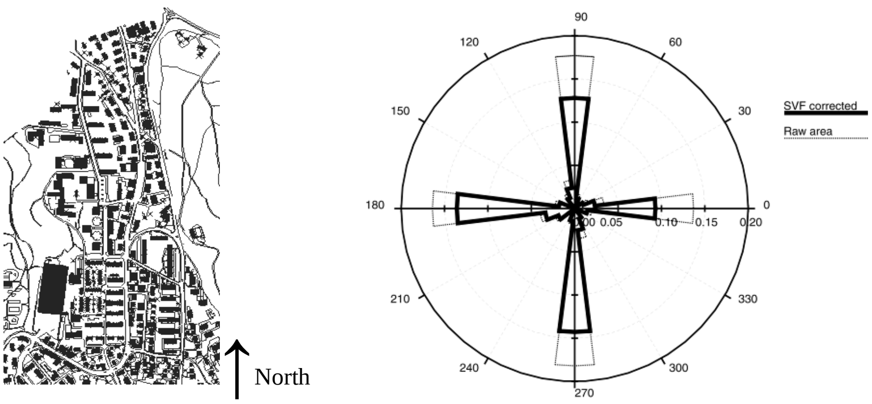


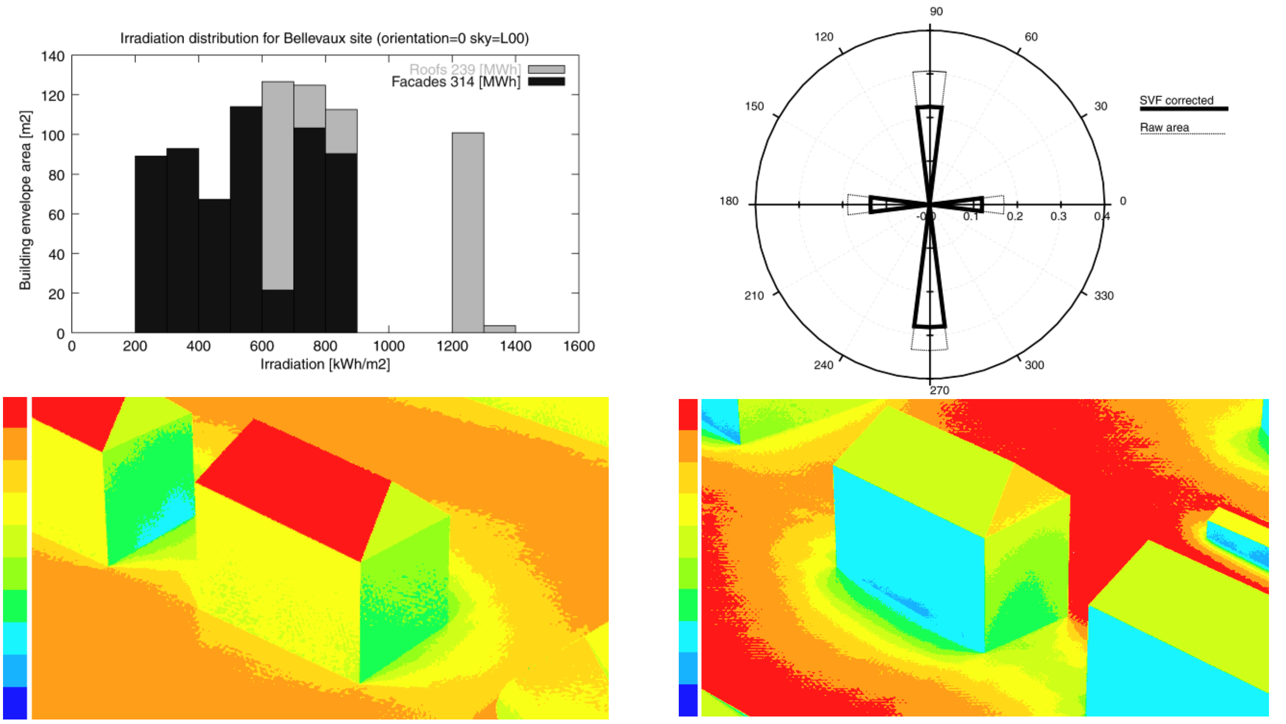
Figure 108: Layout plan of Bellevaux district (left) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (right).

[51] Tribu'architecture is a society founded in March, 2000 by three EPFL architects, [online] URL: http://www.tribu-architecture.com (Consulted on March, 2005).

Table 20: Summary of results for Bellevaux district and selected buildings

Lausanne	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Bellevaux district	69.5%	51.3%	57.3%	96%	68%	65.4%	10.6%

Figure 109: Aloys-Fauquez buildings. Layout plan (left) and South-West view (right).



Discretised South-East false-colour image
(with 100 kWh/ m2 subdivisions) relating to the annual irradiation

Discretised North-West false-colour image
(with 100 kWh/m^2 subdivisions) relating to the annual irradiation

Figure 110: Aloys-Fauquez buildings N°29-3. Irradiation distribution (top left), illustration of the orientation rose of building façades (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (top right) and false-colour irradiation images (bottom left and right).

Overall daylighting performance and solar potential

Table 20 indicates that 57.3% of the façades are suitable for passive heating; this value rises to 69.5% for annual daylighting and recedes to 51.3% for winter daylighting. The façades receive considerably irradiation, so that 68% of the façades are suitable for solar hot water production and 10.6% for the photovoltaic installations (BiPV); however, this rises up respectively to 96% and 65.4% for the roof area.

Pilot building study: "Aloys-Fauquez N°29-31"

This study on the Bellevaux district was particularly focused on the pilot building "Aloys-Fauquez N°29-31" (see Figure 109), in order to compare the building heat demand determined according to the SIA norm 380/1[52] with the calculated solar potential. In addition, an estimate of the performance of the BiPV system of roofing was determined with the help of PVSyst[53] and compared with the PPF data. This was concluded with a succinct analysis carried out on two other sectors in the Bellevaux district, Aoste and Entre-Bois, in order to verify visually for the entire district the distribution of solar radiation and daylight flux on the different façades according to their orientations.

Context

This series of blocks of flats (Aloys-Fauquez N°29-31, 33-35, 37-39 and 41-43) was constructed by the city in 1903 for its own miners. After the Second World War the focus was on freeing up large areas in certain districts of Lausanne which were considered unhealthy: the health services condemned 610 housings. Of the 878 housings that were inspected, 51 were judged satisfactory and in compliance with the regulations of the community. These blocks of flats were renovated in 1994. The repairs consisted mainly of creating two extra flats in the attic areas (8 for a total of 19 occupants) and of installing roughcast insulation. At the present time, heating is provided by oil.

Layout of the building

The orientation rose of "Aloys-Fauquez N°29-31" is similar to the one of the Bellevaux district. Statistically, this building is fairly representative of the look advocated at that period by the hygienists for this district, namely a main façade with an orientation to the South and by definition a rear façade with an orientation to the North. The orientation rose reveals distinctly a rectangular building with a North-South orientation of 64%. The most obstructed façade is located in the North-East (34%) sector and the least obstructed in the South-East (22%). The South-West sector is obstructed at a height of 23% and the North-West one at 22% (see Figure 110).

Irradiation distribution

Façade irradiation has a bi-modal distribution clearly distinguishable, peaking in the ranges 500-600 kWh/m2.year and 700-800 kWh/m2.year, reflecting the dominance of a long South oriented façade on the others façades. This applies also to sloping roofs with peaks in the ranges 600-900 kWh/m2.year and 1,200-1,300 kWh/m2.year reflecting the different South and West, East and North collecting surfaces. At 900 kWh/m2.year, the irradiation stops abruptly to start again at 1200 kWh/m2.year, which indicates a difference of surface inclination and confirms the great potential of the south-oriented 38° sloping roof. The phenomenon is repeated for the illuminance distribution for façades and roofs and confirms this distinction between directions and inclination (see Figure 110).

[52] The SIA norms (the French acronym for "Swiss society for Engineers and Architects") are a collection of rules. They are used in Switzerland to define the correct rules in the area of construction.
[53] PVsyst is a PC software package for the study, sizing, simulation and data analysis of complete BiPV systems.

Heat demand and solar potential

The thermal energy of the building was calculated using the LESOSAI[54] software. Out of 720 kWh/m^2 of irradiation per floor area evaluated by PPF, LESOSAI estimates that the heat gains (i.e. free gains and backup heating) are only 136.4 kWh/m^2 per floor area (490 MJ/m^2) and that the thermal losses are 122.6 kWh/m^2 (440 MJ/m^2: see Table 21 and Figure 111). This means that the heat gains are in reality five times lower than the irradiation per floor area; this value increases to 6 times for the thermal losses. In this case, the heat losses are due in a large measure to the exterior walls, which are made of cinder blocks even though they are covered with roughcast insulation (the building was renovated in 1994): the windows are the second cause of heat loss. The heating intensity is estimated at 91.7 kWh/m^2 (330 MJ/m2). One might say that the target value of SIA 380/1 has not been met and that one is really a long way from the MINERGIE®[55] limit which is equal in this case to 41 kWh/m^2 (147 MJ/m^2), namely half of the present value.

Table 21. Summary of PPF and LESOSAI results for “Aloys Fauquez N°29-31”

“Aloys-Fauquez N°29-31”	**PPF**	**LESOSAI**
Obstructed façades (%)	24	24
Compactness index (Envelope area/Volume)	0.40	0.40
Annual irradiation (MWh)	553	-
Heat gain per floor area (kWh/m^2)	-	136.4
Thermal losses per floor area (kWh/m^2)	-	122.6
Envelope area (m^2)	870	870
Volume (m^3)	2151	2151
Volume SIA (m^3)	5650	5650
Floor area (m^2)	768	768
Covered ground area (m^2)	172	172
Irradiation per external surface (kWh/m^2)	664.8	-
Irradiation per floor area (kWh/m^2)	720	-

Table 22. Total energy requirement for Bellevaux district

Bellevaux district	**Housings**	**Retails and others**	**Total kWh**
Electricity	6,726,250	4,073,513	10,799,763
District heating	1,987,650	6,485,450	8,473,100
Gas	8,156,487	2,559,556	10,716,042
Fuel	20,619,259	5,987,162	26,606,421
Total heat	30,763,396	15,032,168	45,795,563
Total energy requirement	37,489,646	19,105,681	56,595,326

Table 23. Total energy requirement by inhabitant

Bellevaux district	**Housings**	**Retails and others**	**Total kWh**
Electricity	1,462	885	2,347
Heat	6,686	3,267	9,953
Total energy requirement	8,148	4,153	12,301

Table 24. Comparison Swiss consumption

Bellevaux district	**PJ/year**	**kWh/inhabitant**
Electricity	180	6,944
Heat	395	15,239
Total energy requirement	575	22,184

[54] LESOSAI is a programme for thermal energy calculation and certification of buildings comprising one or more heated or cooled zones. It is designed primarily for building and thermal engineers and architects.

[55] MINERGIE® is a registered quality label for new and refurbished low-energy-consumption buildings. This label is mutually supported by the Swiss Confederation, the Swiss Cantons and the Principality of Liechtenstein along with Trade and Industry. The Minergie label may only be used for buildings, services and components that actually meet the Minergie standard.

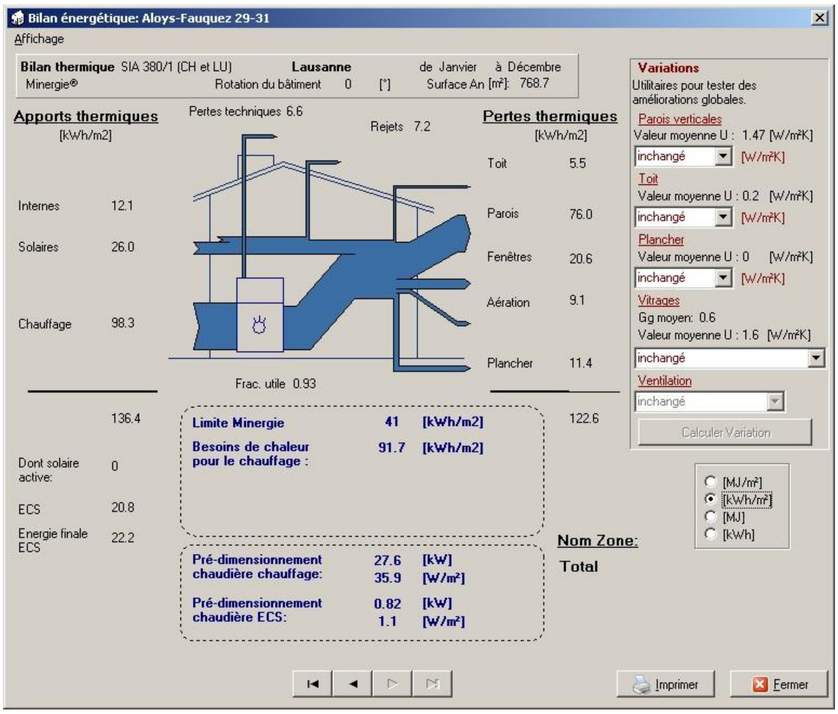


Figure 111: LESOSAI results. Thermal energy balance of “Aloys-Fauquez N°29-31”.

Overall, the total useable solar irradiation that falls on the façades and roofs equates to 720 kWh/m^2 of floor area. This theoretically meets the demand to install solar thermal collectors on the façade. For a deeper investigation of the question, the overall energy intensity E_{tot} of “Aloys-Fauquez N°29-31” has been calculated according to the norm SIA 380/1 in order to verify that the heat gains do offset the total thermal losses:

$$E_{hw} = 293 \text{ [MJ/m}^2\text{]}$$

$$E_h = 516 \text{ [MJ/m}^2\text{]}$$

$$E_{el} = 93 \text{ [MJ/m}^2\text{]}$$

$$E_{tot} \mathbf{= 293 + 516 + 93 = 902 \text{ [MJ/m}^2\text{]}}$$

E_{hw}	: yearly hot water requirements
E_h	: yearly heating requirements
E_{el}	: yearly electricity requirements
E_{tot}	: energy intensity

The overall energy intensity E_{tot} is 902 MJ/m^2 (250 kWh/m^2.year) and the thermal energy is equal to 809 MJ/m^2 (E_{hw} + E_h = 225 kWh/m^2). The irradiation per floor area of 720 kWh/m^2.year (2,590 MJ/m^2) evaluated by PPF is three times larger than the thermal energy, which should cover the yearly hot water and heating requirements for the building.

The energy requirements for all the Bellevaux district are – according to the 2005 consumption data from the *Services Industriels* – 56,595,326 kWh, which corresponds to 56,595 MWh. As the annual irradiation is 166,896 MWh for 213,824 m^2 of floor area, the irradiation per floor area consequently rises to 780 kWh/m^2.year. In other words, it is almost three times larger than the energy intensity of the district (56,595,326 kWh / 213,824 m^2 = 264 kWh/m^2.year). Therefore, this is very close to the result that was determined for “Aloys-Fauquez N°29-31”. It is also noticeable that the total energy requirement by inhabitant at Bellevaux is below the Swiss national average (see Table 22 to Table 24).

Overall daylighting performance and solar potential

Based on these results, evaluations for the solar potential of two other types of buildings were undertaken. The goal was to compare three different forms of buildings with different orientations: North-South for “Aloys-Fauquez N°29-31” and an East-West building orientation for “Pavement N°7-9-11-13-15”.The “Entre-Bois N°11” tower has no special orientation (see Figure 112). The roofs were also considered, a sloping roof in the first case and a flat roof in the second and third block of apartments.

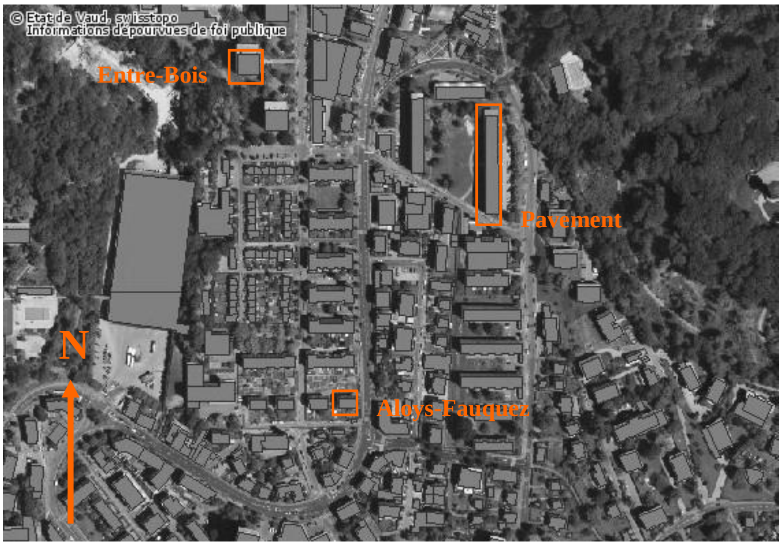


Figure 112: Buildings considered. “Entre-Bois N°11”, “Aloys-Fauquez N° 29-31” and “Pavement N°7-9-11-13-15”.

Table 25 shows that for “Aloys-Fauquez N°29-31”, “Pavement N°7-9-11-13-15” and “Entre-Bois N°11”, passive solar gains are viable for 52.2%, 94.6% and 60.8% of the façades; this value reaches 69.5%, 94.8%, and 77.2% respectively for daylighting over the year and 44%, 92.1%, and 55.3% for Winter. A 15.6% and 41.2% fraction of façades and roofs surfaces respectively are viable for integration of BiPV, though this increases to around 100% and 68.7% of the combined surfaces in respect of solar thermal collectors. The façades of “Pavement N°7-9-11-13-15” receive less solar irradiation, so that the BiPV viable surfaces fractions are 4.7% and 95.2% respectively, increasing to 94.8% and 99.7% in the case of solar thermal technologies. “Entre-Bois N°11” results are 7.3% and 85% for the BiPV and 75.3% and 99.3% for solar collectors.

To sum up these two cases, a building with a North-South orientation shows more efficient façades for solar thermal technologies than BiPV. A building with an East-West orientation shows more efficient façades for passive solar gain and daylighting. As a tower has no main orientation, its performances are located between the first two selected buildings. In each case, a flat roof will be more efficient than a sloping roof if all sections of the roofing are taken into consideration for the calculation (North, South, East and West).

Table 25: Summary of results for Bellevaux district

Lausanne	Daylighting viability		Passive solar viability	Solar thermal viability		BiPV viability	
	Façades (annual)	Façades (Winter)	Façades (Winter)	Roofs (annual)	Façades (annual)	Roofs (annual)	Façades (annual)
Bellevaux district	69.5%	51.3%	57.3%	96%	68%	3.9%	65.4%
“Aloys-Fauquez N°29-31”	69.5%	44%	52.2%	68.7%	100%	1.1%	41.2%
“Pavement N°7-9-11-13-15”	94.8%	92.1%	94.6%	99.7%	94.8%	2.8%	95.2%
“Entre-Bois N°11”	77.2%	55.3%	60.8%	99.3%	75.3%	0%	85%

Electricity needs

To go even further, the electricity needs were also considered for “Aloys-Fauquez N°29-31”. The evaluation of the solar potential with the aid of PPF proves that only the sloping roof with a South orientation is viable for BiPV, whilst the PVSyst provides the following figures for the South and West sloping roof (see Figure 113):

- sloping roof South :nominal power of 10.5 kW, annual yield of 10.6 MWh/year;
- sloping roof West : nominal power of 1.1 kW, annual yield of 0.9 MWh/year.

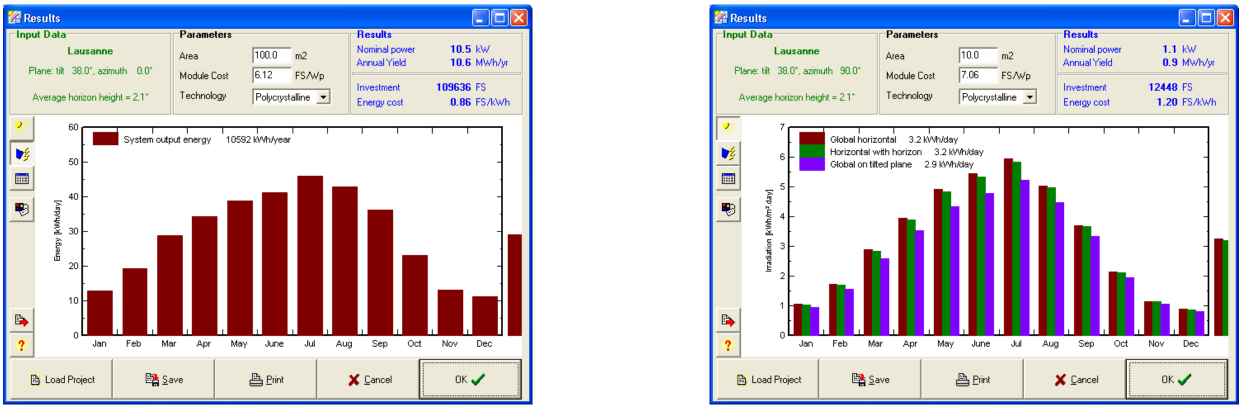


Figure 113: PVSyst results. South sloping roof (left) and West sloping roof (right).

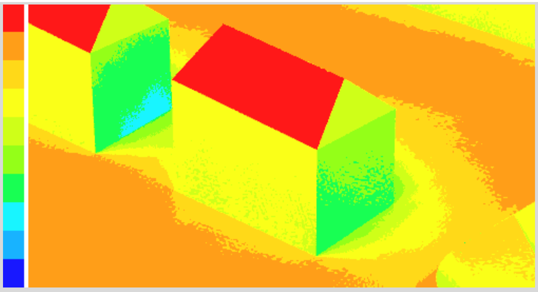
If one takes only the sloping roof with a Southern orientation into account, the irradiation received in the roofing amounts to 136 MWh, which corresponds to 1302 kWh/m^2.year. The planning of the PV power plant using PVSyst provides for the 100 m^2 useful southern roof area a nominal power of 10.5 kW, which corresponds to an annual yield of 10.6 MWh/year.

The solar irradiation received by these panels would theoretically be sufficient to a large extent to meet the electricity requirements for “Aloys-Fauquez N°29-31”. According to the data of the *Services Industriels* of Lausanne, the electricity consumption of the households and the communal premises amounts to 20,065 kWh/year (20.1 MWh/year). Unfortunately, the effective output of the BiPV plant is not large enough to cover the total demand for electricity, which is necessary for the proper functioning of the building. In fact, this demand is twice as large as the output from the BiPV roofing installations. Finally, the investment cost of the installation at Sfr. 109,636.- corresponds to an energy cost of 0.86 SFr./kWh, which is not cost effective without governmental support in view of the current cost of electricity (0.25 SFr./kWh).

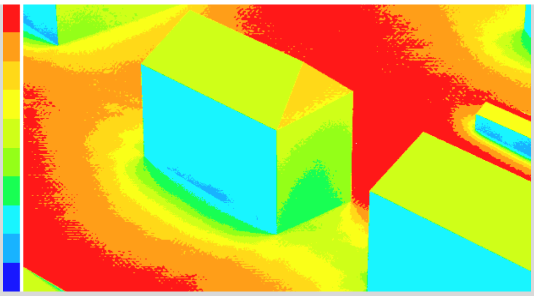
Implementation of solar energy technologies

The images of “Aloys-Fauquez N°29-31”, corresponding to daylighting (see Figure 114 and Figure 115), show optimal South, East and West oriented façades for this solar technology; on the other hand, the North façade is entirely unsuitable. In Winter passive solar gains are predominant on the South façade and on two thirds of the West façade. According to the reconfiguration of the interior plan, all the rooms, including the living room, are facing either towards the South, the East or the West. The stairwell and the kitchen take up all of the North façade. Therefore, the kitchen is the least favourable in the flat, which is a tolerable situation.

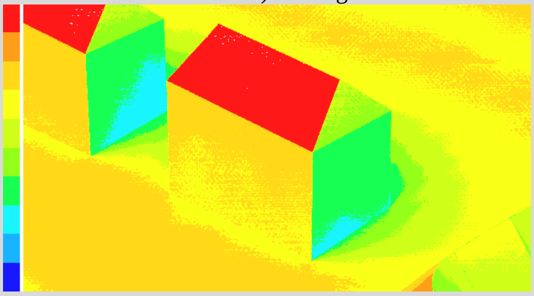
The three North, East and West sections of the sloping roofs are suitable for solar thermal applications, and not for BiPV. On the other hand, the South section of the sloping roof is optimal for both. Most of the South, East and West façades are suitable for solar thermal in contrast to the North façade. Furthermore, the South façade performs very well with a threshold of 600 kWh/m^2.year. The panels of the South façade will presumably compensate for the poor exposure of the North façade. Regarding BiPV, the technical viability (not to mention the economic viability) of the systems is modest, approximately 50% of the South façade being appropriate for photovoltaic use.



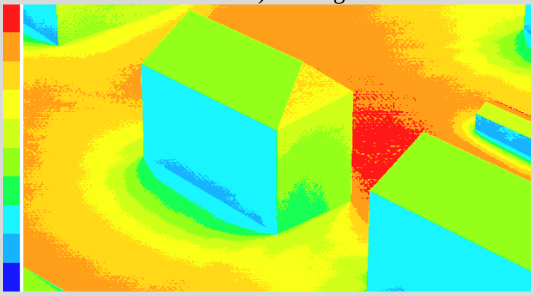
Discretised South-East false-colour image
(with 100 kWh/ m^2 subdivisions) relating to the annual irradiation



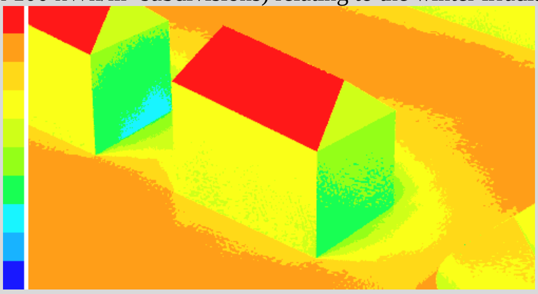
Discretised North-West false-colour image
(with 100 kWh/m^2 subdivisions) relating to the annual irradiation



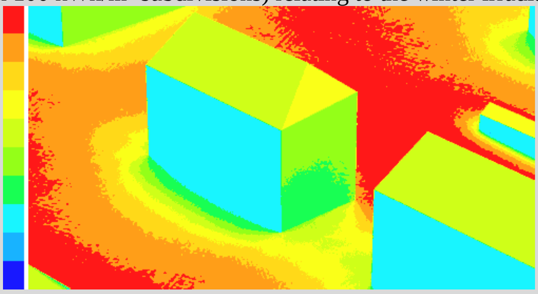
Discretised South-East false-colour image
(with 100 kWh/m^2 subdivisions) relating to the winter irradiation



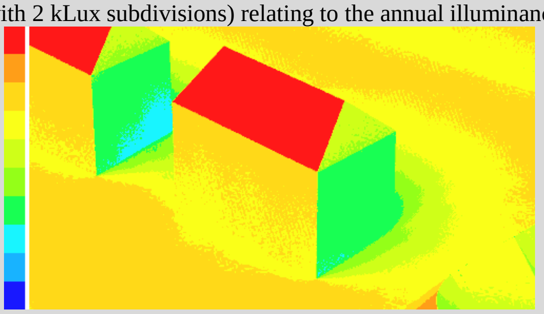
Discretised North-West false-colour image
(with 100 kWh/m^2 subdivisions) relating to the winter irradiation



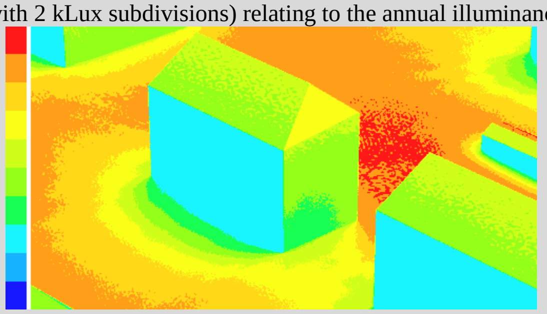
Discretised South-East false-colour image
(with 2 kLux subdivisions) relating to the annual illuminance



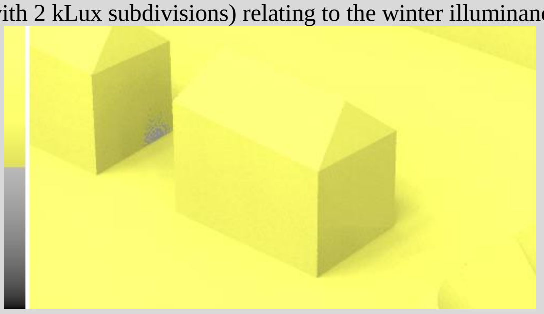
Discretised North-West false-colour image
(with 2 kLux subdivisions) relating to the annual illuminance



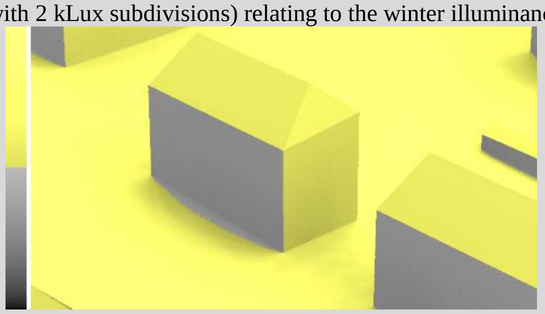
Discretised South-East false-colour image
(with 2 kLux subdivisions) relating to the winter illuminance



Discretised North-West false-colour image
(with 2 kLux subdivisions) relating to the winter illuminance

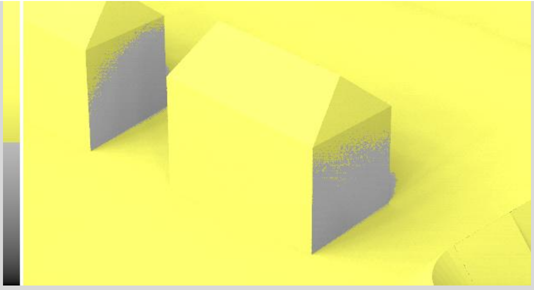


Thresholded South-East view relating to daylighting
(10 kLux)

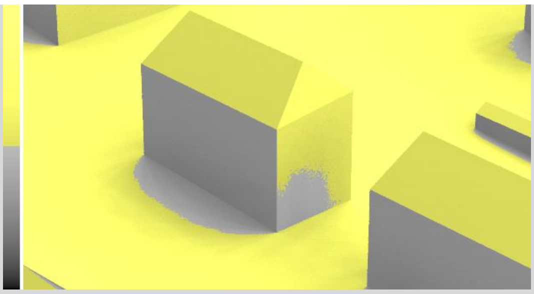


Thresholded North-West view relating to daylighting
(10 kLux)

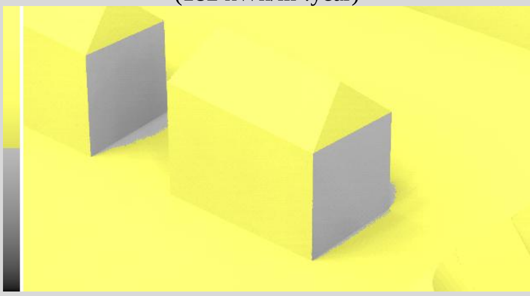
Figure 114: “Aloys-Fauquez N°29-31”. False-colour images and thresholded images using a Boolean filter.



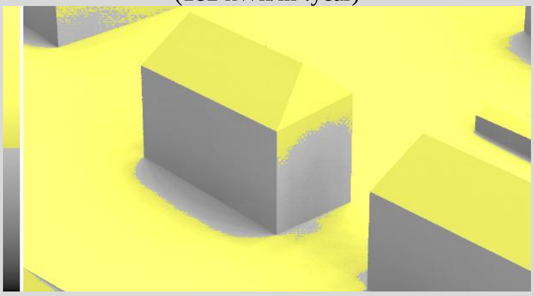
Thresholded South-East view relating to passive solar gain (182 kWh/m^2.year)



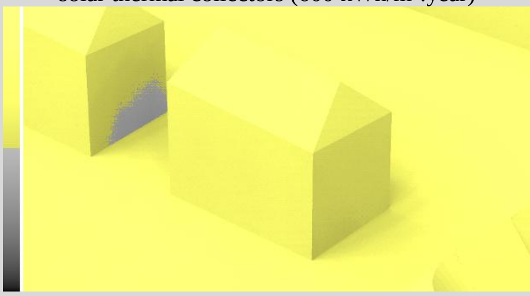
Thresholded North-East view relating to passive solar gain (182 kWh/m^2.year)



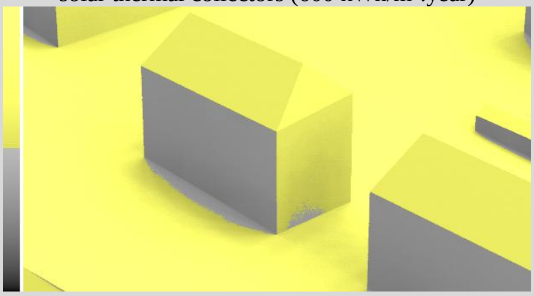
Thresholded South-East view relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)



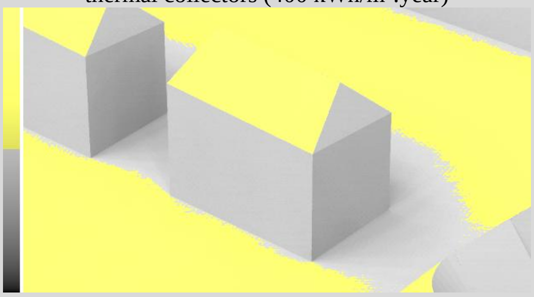
Thresholded North-West view relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)



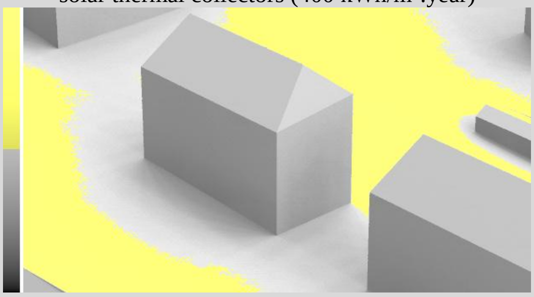
Thresholded South-East view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



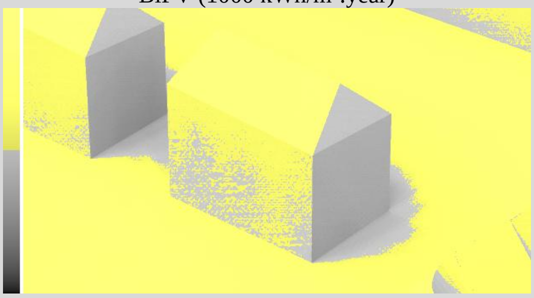
Thresholded North-West view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



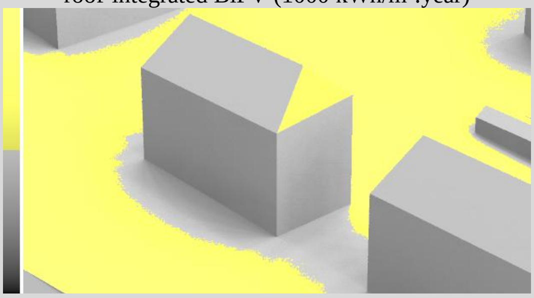
Thresholded South-East view relating to roof-integrated BiPV (1000 kWh/m^2.year)



Thresholded North-West view relating to roof-integrated BiPV (1000 kWh/m^2.year)



Thresholded South-East view relating to façade-integrated BiPV (800 kWh/m^2.year)



Thresholded North-West view relating to façade-integrated BiPV (800 kWh/m^2.year)

Figure 115: “Aloys-Fauquez N°29-31”. Thresholded images using a Boolean filter.

Figure 116: Meyrin site and Meyrin Estate (inside the circle) ©SITG.

Figure 117: Meyrin site. Aerial view (left) and typical view of Meyrin Estate (right).

Source Figure 117 left: EUROPAN 3 (1994). *Chez soi en ville*. Editions Europan, Paris, France.

4.4 Meyrin site, Geneva, 46.20 latitude (Switzerland)

This study was carried out in the Meyrin site selected during the SOLURBAN project (Montavon, Scartezzini et al. 2004; Robinson, Scartezzini et al. 2005). Meyrin Estate was the first satellite town built in Switzerland, which still reflects the hygienist spirit of that time (see Figure 116) and was selected for that purpose. It was created to solve the post-war housing crisis. Couples primarily with children created the typical demand; they constituted the first profile of towns and caused an abrupt change in comparison to the social distribution of cities and villages. In this respect, it was interesting to evaluate the daylight and solar potential of the Meyrin site in order to compare it with the former urban fabric of Geneva and to decide if any densification opportunity is practical in a near future, without lowering the initial quality.

Geneva is currently experiencing a severe housing shortage; due to the lack of space on its site, the elevation of downtown buildings and the densification of the surrounding cities will become inevitable.

4.4.1 Description of case study

Meyrin is located at a distance of 9 km (5.59 miles) from the centre of Geneva and covers an area of 9.95 km^2 (2,458 acres); it was originally designed to serve as a satellite district for Geneva. It is one of the few surviving examples in Switzerland of 1960's functionalist town-planning and architecture (see Figure 117). Meyrin was indeed chosen by the local authorities to host Switzerland's first satellite district to be built according to the urban planning concepts inspired by the Charter of Athens[56]. As far as housing is concerned, the goal is to insert the dwelling into a building unit, which includes shops, health services, kindergarten, etc. Buildings are dissociated from streets and mutually distant in order to offer enough space for green areas: "Introducing the sun is the architect's foremost commitment" according to Le Corbusier. The second function – work – is fulfilled by the principle of linear localization near the transportation axes. The function of recreation – referred to as *work force recovery* by Marxists – is the reason why numerous green areas were planned in Meyrin: "The city must be like a huge park". The need for urban mobility in the district is met by the creation of specific transport ways, whether the traffic concerns pedestrians (4 km/h) or automobiles (from 50 to 100 km/h).

The district of Meyrin, almost exclusively devoted to housing, benefited from the growth of the Geneva urban context. Meyrin, which was just a small hinterland village in 1922, started its growing phase when Cointrin's first aviation runway was built: the airport boosted the municipality. As a consequence it underwent a deep metamorphosis in the 60's, growing from a village of 3,200 inhabitants to a city of 14,000 inhabitants, reaching even 21,000 in 2008 (2,090 inhabitants/km^2). Settlements and infrastructures represent currently 54% of the Meyrin area. In order to maintain the quality of life in the district, Meyrin's authorities encouraged the preservation of the environment (50% of the territory is made up of agriculture and wooded areas).

Built at the edge of the town – between the airport and the European Centre for Nuclear Research (CERN) – Meyrin accommodates a variety of industrial research centres, which represent 26,000 employment positions for an overall population of 20,800 inhabitants. Benefiting from the economic attractiveness of Geneva, the district has experienced intensive growth for more than a decade: it comprises today industrial estates, malls and tenement buildings, more than 70% having been built since 1960. After 1985, the district of Meyrin Estate lost approximately 1,000 residents. Causes are the ageing of the population, the departure of their children, the loss of attractiveness and the obsolescence

[56] In 1933, several architects, gathered together on the occasion of the *Congrès International d'Architecture Moderne* (CIAM), one of whom was Le Corbusier, to write the Charter of Athens. This is the official birth certificate of the modern movement. At the same time critical towards the nineteenth century yet contingent upon the same prescriptive fantasies, the *progressive* or *modern* current (both terms can to a certain extent be seen as synonyms) will take as long as fifteen years to break up the rigid frames of Haussmann's theories and to prevail in architecture.

of some buildings: the cultural centre *Forum Meyrin* is for this reason the only sizeable construction realized since that time.

4.4.2 Description of 3D digital model

The *Service d'Information du Territoire Genevois* (SITG) of the Canton of Geneva provided a GRID – Digital Terrain Model (GRID–DTM) and a GRID – Digital Height Model (GRID–DOM) of Meyrin site, which were obtained by airborne laser scans. The DTM and the DOM include the elevation of each square meter of the Canton of Geneva and allow a 3D display of the latter by means of the relevant applications (MapInfo, ArcView, etc.).

For the GRID–DTM, this elevation stands for the terrain: it is measured from the bottom of the vegetation thanks to foliage-penetrating techniques. It is interpolated under the buildings using their respective bottom altitudes. Profiles can be computed, as well as shaded relief maps. Raster images can be set as background for the 3D digital model. For the GRID–DOM, altitudes stand for the top of the objects on the terrain's cover (vegetation, buildings, supply lines, etc.) or the natural terrain in absence of man-made object. Contour profiles can be calculated on this basis as well as shaded relief maps. Raster images can be set as background for the 3D digital model. By subtracting the DTM from the DOM data, one obtains the height of an object: the height of the vegetation or the buildings can be determined in this way. According to SWISSTOPO, DOM and the DTM–AV data are available in the two following presentations (see Figure 118):

- The "Raw type", a cloud of vector points (x,y,z) with a density of about 0.5 point per m^2 (delivery formats : ASCII X,Y,Z single space);
- The "GRID 2 m type", which has been interpolated from the raw type model as a 2 m wide grid (delivery formats: ASCII X, Y, Z single space and ESRI ASCII Grid).

The planimetry accuracy is about 15 to 40 cm for DTM files with 15 cm (standard deviation) for hard surfaces, 25 cm (standard deviation) for fields and 40 cm (standard deviation) for forests. The grid resolution is equal to 1 m. The same rule applies for the DOM files (except for the forests with 25 cm planimetry accuracy). The ASCII Standard (American Standard Code for Information Interchange) is the most common and compatible digital character encoding standard (see Figure 119).

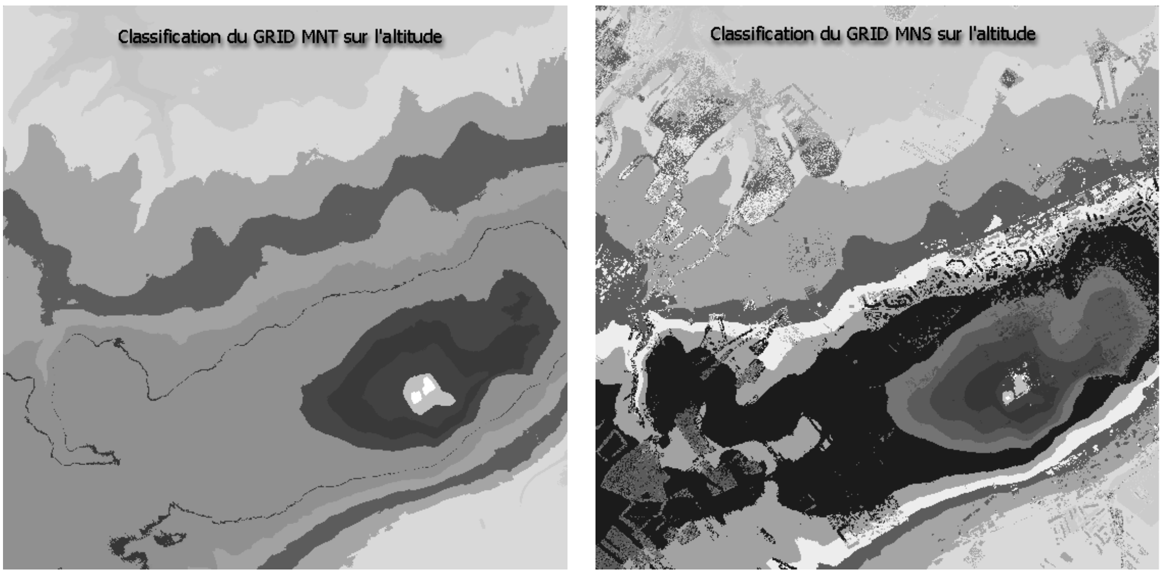


Figure 118: Sample examples. GRID–DTM data (left) and GRID–DOM data (right).

Source: [online] URL: http://www.sitg.ch/ (Consulted on March 15, 2008).

This method allows statistical indicators (gap-type) for the two digital models to be applied, which offers the possibility of calculating an index of reliability for each building. The higher this value, the higher the reliability of the estimated building height (0-50 good reliability). The reliability index can contribute to outline errors as well as inaccurate data.

```
ncols 10
nrows 10
xllcenter 504000
yllcenter 113001
cellsize 1
nodata_value -9999
404.63 404.58 404.52 404.46 404.43 404.36 404.32 404.27 404.25 404.33
 404.25 404.27 404.29 404.27 404.28 404.65 404.57 404.31 404.34 404.41
404.39 404.49 404.16 404.42 404.75 404.40 404.31 404.29 404.30 404.39
 404.40 404.48 404.52 404.54 404.53 404.57 404.47 404.35 404.47 404.36
404.48 404.39 404.31 404.20 404.09 404.11 404.18 404.20 404.24 404.26
 404.30 404.33 404.38 404.41 404.44 404.49 404.51 404.56 404.64 404.66
 404.66 404.67 404.64 404.64 404.76 404.77 404.95 404.70 404.71 404.81
404.82 404.73 404.92 404.87 404.85 405.00 404.95 404.98 404.90 404.95
404.89 404.77 404.86 404.65 405.16 404.92 404.86 405.08 404.95 404.9
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

Figure 119: Sample example of ASCII data.

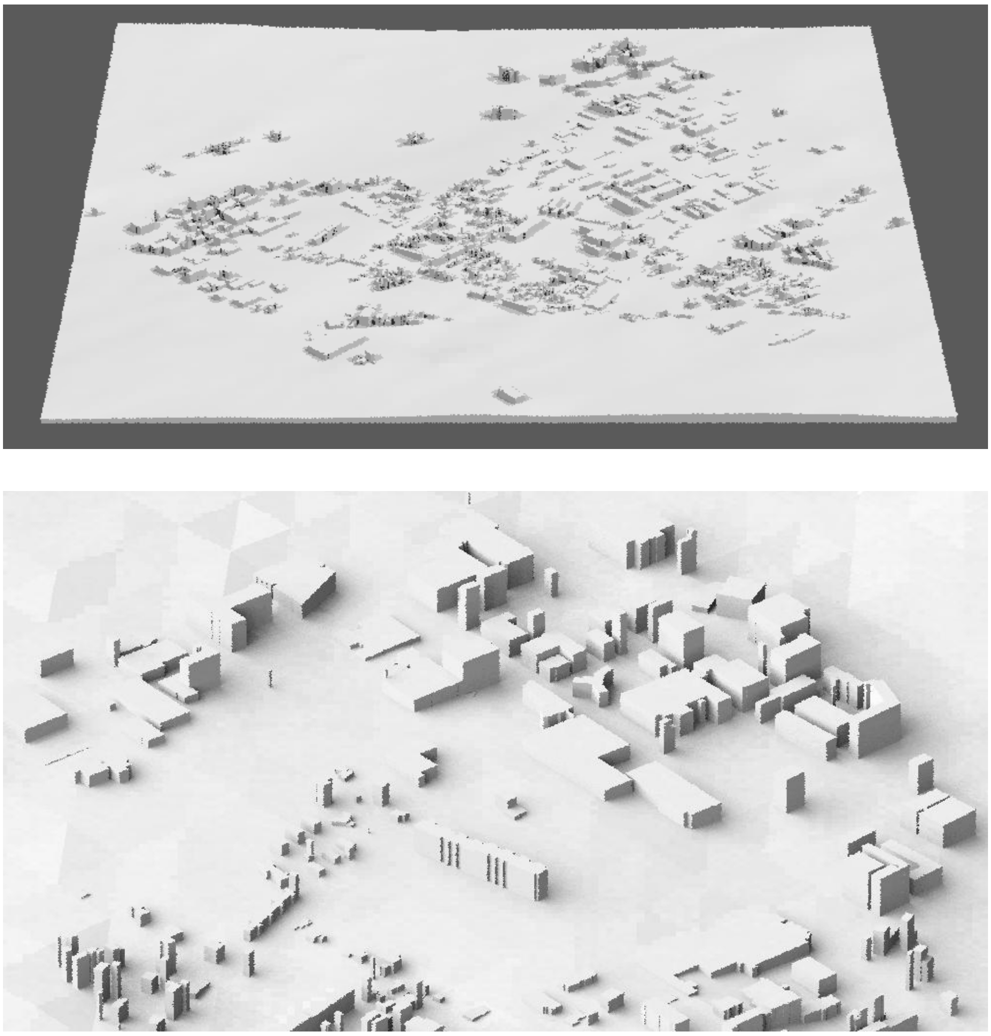


Figure 120: Meyrin industrial zone South view (top) and Zoom of South view (bottom) (RADIANCE renderings).

All buildings having a height lower than 1 meter were deleted. However, this model remains somewhat crude, sloped surfaces of buildings being undefined. An average height was suggested and therefore led to roofs with a flat shape. These buildings can be represented in a 3D space using GIS data or other appropriate software. Fortunately however, most of the buildings in Meyrin Estate have flat roofs, thereby making the solar utilization potential assessment representative enough for the purpose of this study (see Figure 120).

Samples of 3D digital model in the DXF, MIF/MIDDXF and DBF/SHP/SHX exchange formats were offered by LITG/EPFL. The DXF format could have been used, albeit the *dxf2ppf* function should have been modified in order to read each polygon's attributes describing the buildings' outlines (the height is among these attributes). As only a few details were provided in DXF format, it would have been quite difficult to proceed to this adaptation.

The MIF/MID (Map Info Interchange Format) consisting of ASCII data was easily readable by a program such as PPF: it is indeed easy to recognize the building outlines (in the .MIF file), as well as the other attributes (in the .MID file). In order to key-in raw laser points using MapInfo, raw files had to be renamed (by simply replacing the filename extension .xyz with .txt). The .txt corresponding files were imported in .TAB MapInfo format.

MapInfo's export function was than simply used to obtain MID/MIF files, namely the MapInfo Interchange Format (MIF) that describes a MapInfo database. The MIF data file is an ASCII formatted file made up of two sections:

- a heading section, containing the format version and the characters type of the coordinates system;
- a data section that defines the graphical objects.

As for the MID file, it stores attribute information. It is possible to export graphic or data in MIF format. The former are located in a .MIF file, the latter in a .MID file. The .MIF files can be converted into other formats using appropriate programs. The DBF/SHP/SHX files are binary files, which should be avoided when possible. To sum up, the final selection was DTM files for the terrain model and MIF/MID files for the building models.

In order to translate MIF/MID data into a PPF-compatible format, the *getmimi* function had to be implemented in the software. A routine was written to modify the data files of the Meyrin site, which contain the terrain, façades and roofs, so that individual surfaces could be distinguished from each other. This was required in order to be able to quantity the solar irradiation incident on a given building surface according to its orientation and tilt angle.

In October 2005, the Canton of Geneva was delivered new LIDAR data. The latter offered to it 3D digital terrain models with a 20 cm (respectively 15 cm) altimetry accuracy that was canton-wide. A simple survey of the literature from various projects involving 3D digital modelling reveals that these highly valuable data are seldom exploited (the interest of users of large-scale products for the integration of the third dimension into Geneva's GIS data is however high). The cantonal Civil Service launched a pilot study with a view to achieving a 3D digital model of the Geneva land register (Vieira de Mello, 2006). It should allow for more accurate assessment by including LIDAR data into the 3D monitoring campaign of the city of Geneva (Carneiro and Golay 2007).

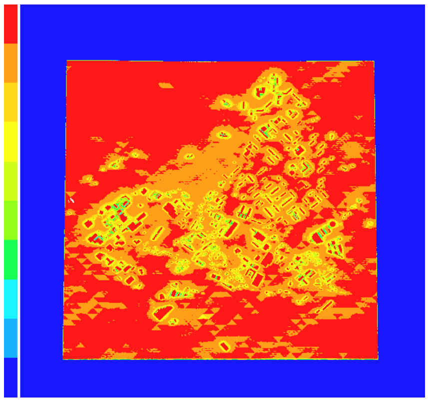
4.4.3 Solar performance indicators

Using heating degree-days of 3,151 DD for Geneva, the threshold for passive solar gain reaches 187 kWh/m2.year. Assuming an indoor required illuminance of 500 lux and an utilisation coefficient of 0.05 – typical of a vertical opening – it corresponds to the fraction of façade area which receives on average annually, 10,000 lux or more. For solar thermal collectors the lower figures of 400 and 600 kWh/m2.year were used for façades and roofs respectively. Thresholds of 800 and 1,000 kWh/m2.year were used respectively for photovoltaics. Simulations were carried out using the typical Winter sky conditions of Geneva (Compagnon 2004).

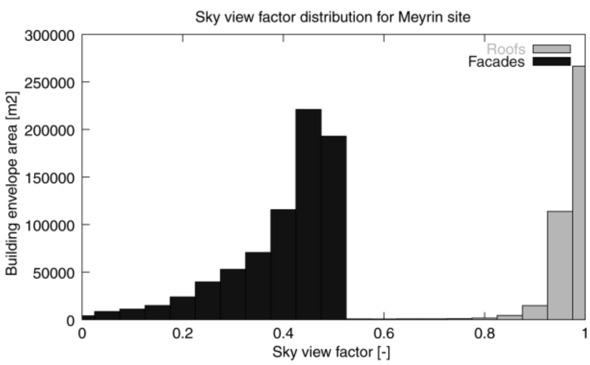
Layout of the urban site

The four directions North-East (24%), South-East (25%), South-West (25%) and North-West (26%) of the Meyrin rose are equally represented (see Figure 121). The two South-East and South-West sectors occupy the same number of façades area, 51% of the buildings being oriented along the North-West/South-East axis. The Sky View Factor (SVF) corrected surface shows that the façades are obstructed at the rate of 20.6%, which is acceptable for a built-up site like Meyrin as far as daylighting and passive solar are concerned. The obstructions for the South-West (26%) and North-West (26%) sectors exceed by 2% the obstructions of the North-East (24%) and South-East (24%) sectors. The orientation of the parallel blocks layout of the Meyrin Estate clustered in groups perpendicular to one another varies with some of the larger buildings located in Meyrin's industrial zones and in relation to groups of detached houses. Furthermore, this layout of parallel blocks shows generally eight storeys and ground floor so that despite the relatively generous spacing there remains reasonable overshading (most of the Meyrin site is five storeys :1,907,990 floor area / 406,765 ground area = ~5 storeys).

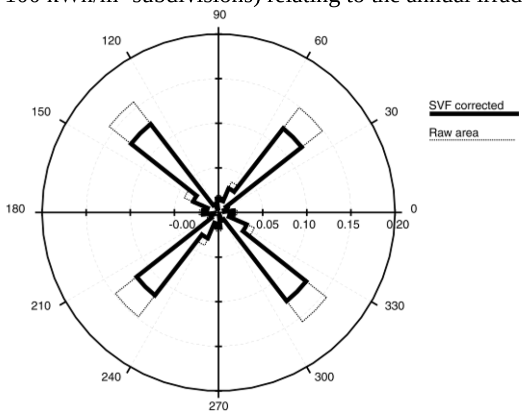
Layout plan of the site



Discretised South false-colour image
(with 100 kWh/m^2 subdivisions) relating to the annual irradiation



Sky view factor distribution

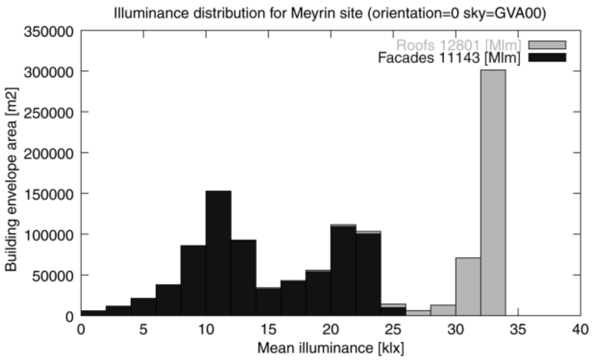


Orientation rose of the overall building façades

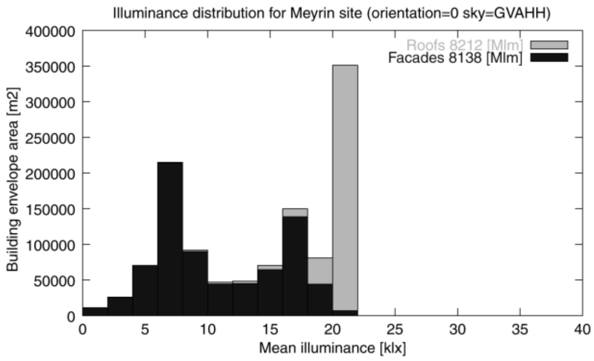
Figure 121: Meyrin site results.

Irradiation and illuminance distributions

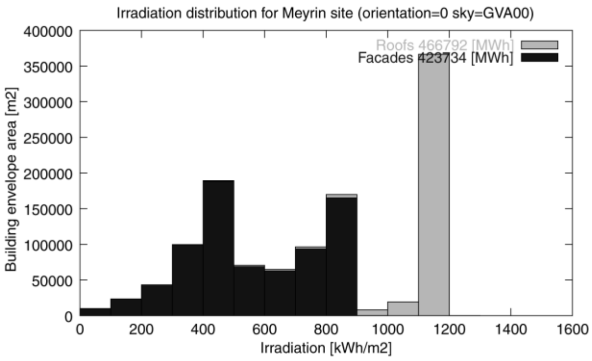
The annual façade irradiation has a bi-modal distribution peaking in the range of 300-400 kWh/m2.year and 800-900 kWh/m2.year, reflecting the dominance of long surfaces oriented 45° to the South and to the North respectively. The trend is similar for the annual illuminance distribution for façades and roofs, with peaks in the ranges 10-12 kLux and 20-24 kLux. The peaks of the Winter façade irradiation are closer to each other than the annual one; they culminate between 100-200 kWh/m2.year and 300-400 kWh/m2.year, whereas the Winter illuminance keeps the same distribution with peaks located between 6-8 kLux and 16-18 kLux. The value of the roofs is not truly representative of the real solar potential of the Meyrin site, it's merely an estimated value. In fact, the simplification of the buildings, modelled with flat roofs, considerably raises the figures of the roofs solar potential to 1,000-1,200 kWh/m2 annually and 300-400 kWh/m2 in Winter for the dominant peaks (see Figure 122).



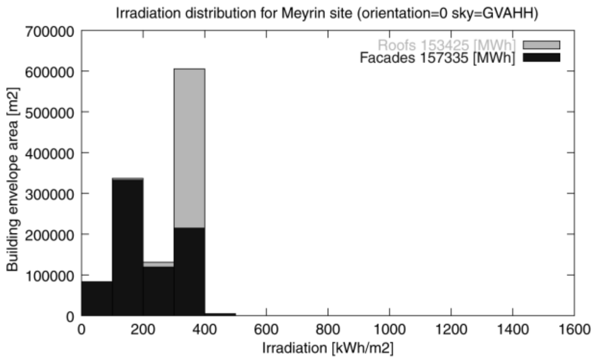
Statistical distribution of yearly illuminance on the building façades and roof.



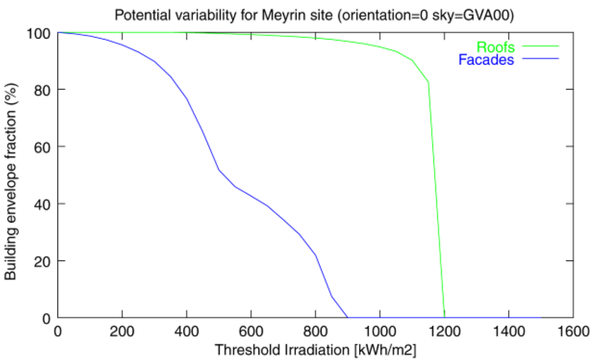
Statistical distribution of Winter illuminance on the building façades and roof.



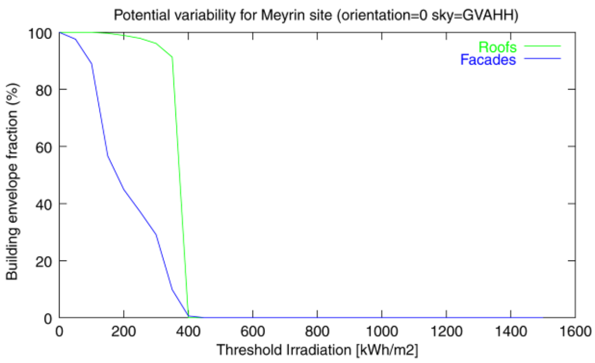
Statistical distribution of yearly irradiation on the building façades and roof.



Statistical distribution of winter irradiation on the building façades and roof. Heating season average sky model



Cumulative distributions characterising the façades' solar irradiation. Annual solar irradiation serves to assess the potential for building integrated photovoltaic systems and solar thermal collectors



Cumulative distributions characterising the façades' solar irradiation. Heating season irradiation serves to assess the potential for passive solar heating techniques

Figure 122: Meyrin site results.

Sensitivity of solar potential

The different potentials according to the threshold values are shown on the yearly and Winter statistical distribution of solar irradiation on the building façades and roof. The annual curve presents two initial rifts immediately before and after 500 kWh/m^2, another one at 800 kWh/m^2 and a fourth before 900 kWh/m^2. The Winter curve reveals a strong decrease after 300 kWh/m^2, which tends to confirm the presence of flat roofs in the 3D model. The same is also true for the annual roofs curve, which falls rapidly at 1,200 kWh/m^2 (see Figure 122).

Overall daylighting performance and solar potential

At this stage, the results (see Table 26) indicate that in a satellite town, developed in the spirit of the hygienist movement, only 46.5% of the façades are suitable for passive heating, 78.5% of the façades will receive a sound daylighting flux over the year and 45.5% in Winter. The façades receive a considerable amount of solar irradiation, so that 76.7% of the façades are suitable for domestic hot water production and 45.5% for the photovoltaic installations (BiPV); this figures increases up to 99.2% and 94.9% for the roofs. The latter value is skewed by the simplification of the buildings roofs, which considerably raises the two last figures.

Table 26: Summary of results for Meyrin

Geneva	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Meyrin site	78.5%	45.5%	46.5%	99.2%	76.7%	78.5%	45.5%

Implementation of solar energy technologies

The analysis of the thresholded images was focused in particular on one part of the Meyrin Estate to ensure that the implantation of the various apartment blocks conforms in terms of solar potential and daylighting to the hygienist spirit of that particular era (see Figure 123 to Figure 126). Although at that period, these various solar theories were only concerned with the daylighting performance and the passive solar gains in Winter.

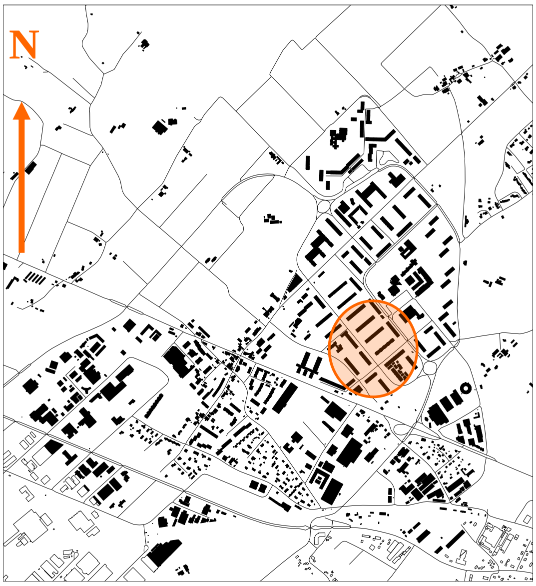
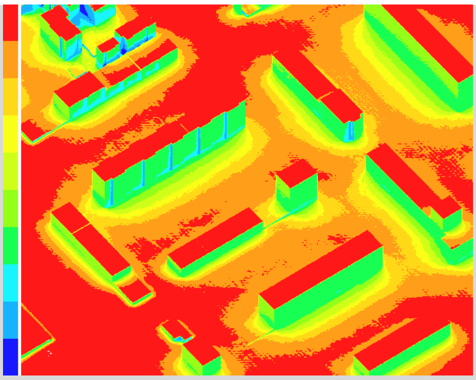
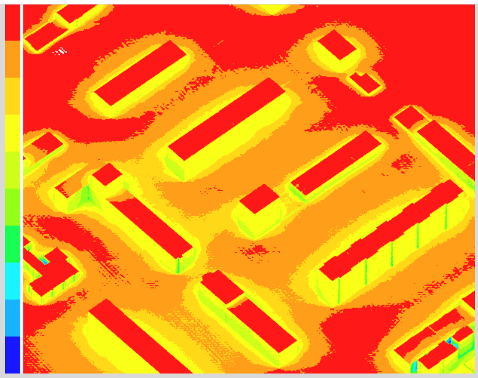


Figure 123: Studied sector in Meyrin Estate.

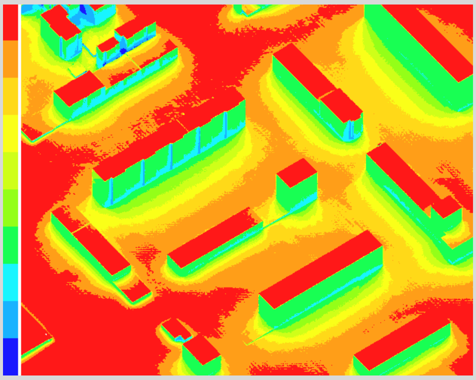
On the whole, the parallel blocks development layouts, showing a South-West/North-West orientation, have a larger potential than the other configurations. In this case, the North-West façades are the least effective for daylighting, although they are fairly efficient, except at the bottom of the apartment blocks: this is mostly due to the neighbouring building which projects shadows onto the building in front. Those buildings with a South-East/North-West orientation should be a little further from each other for optimal performance.



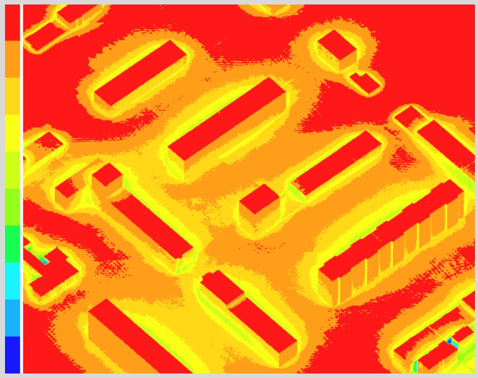
Discretised North false-colour image
(with 100 kWh/m^2 subdivisions) relating to the annual irradiation



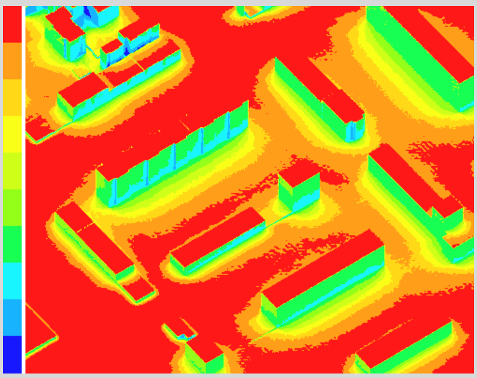
Discretised South false-colour image
(with 100 kWh/m^2 subdivisions) relating to the annual irradiation



Discretised North false-colour image
(with 100 kWh/m^2 subdivisions) relating to the Winter irradiation



Discretised South false-colour image
(with 100 kWh/m^2 subdivisions) relating to the Winter irradiation

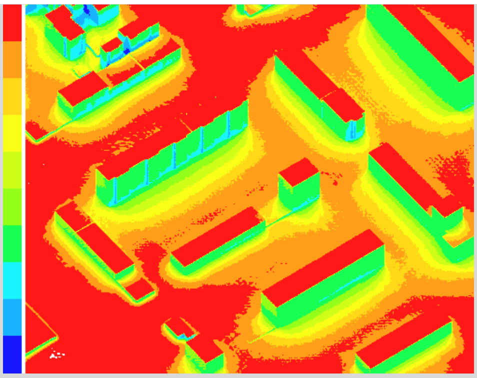


Discretised North false-colour image
(with 2 kLux subdivisions) relating to the annual illuminance

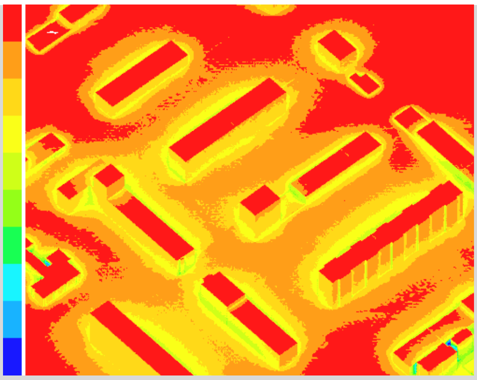
Discretised South false-colour image
(with 2 kLux subdivisions) relating to the annual illuminance

Figure 124: Meyrin Estate. False-colour images.

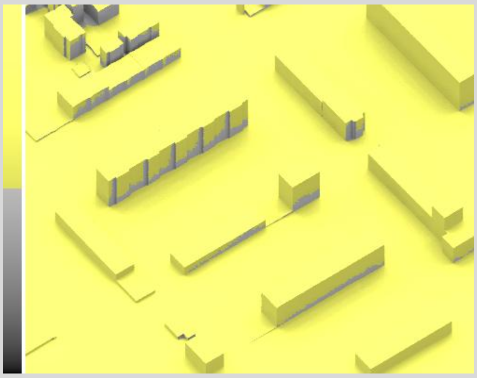
In Winter, the passive solar gains concentrate predominantly on the South-East and South-West façades; on the other hand, the North-East and North-West façades are entirely unsuitable. Most of the North-East, South-East and South-West façades are suitable for solar thermal applications in contrast to the North-West façade. A small fraction of the South-East and South-West façades is appropriate for BiPV. The North-East and North-West façades are inappropriate for this solar technology. Finally, flat roofs are optimal both for solar thermal and for BiPV.



Discretised North false-colour image
(with 2 kLux subdivisions) relating to the Winter illuminance

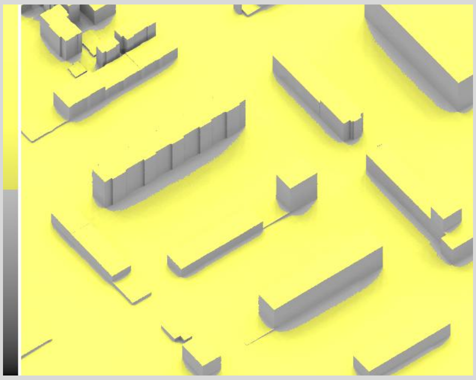


Discretised South false-colour image
(with 2 kLux subdivisions) relating to the Winter illuminance



Thresholded North view relating to daylighting (10 kLux)

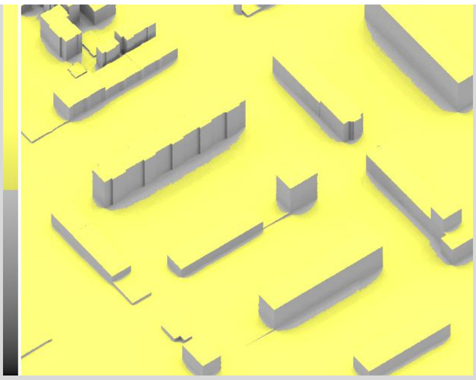
Thresholded South view relating to daylighting (10 kLux)



Thresholded North view relating to passive solar gain
(187 kWh/m^2.year)

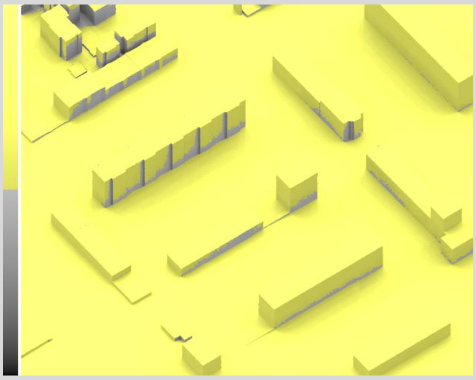
Thresholded South view relating to passive solar gain
(187 kWh/m^2.year)

Figure 125: Meyrin Estate. False-colour images and thresholded images using a Boolean filter.

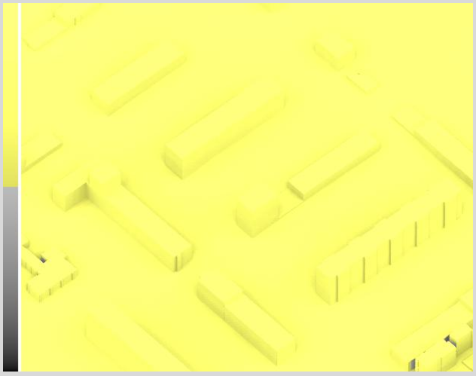


Thresholded North view relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)

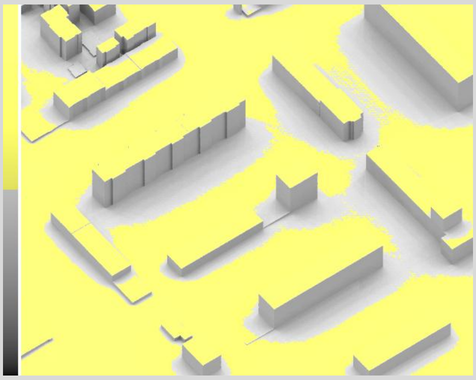
Thresholded South view relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)



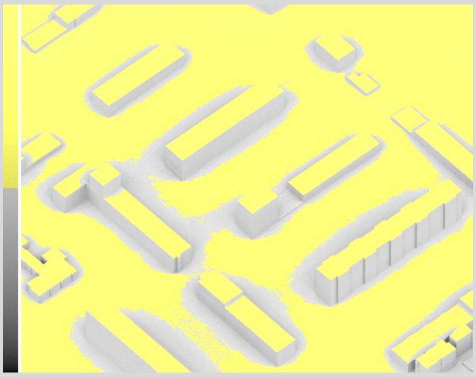
Thresholded North view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



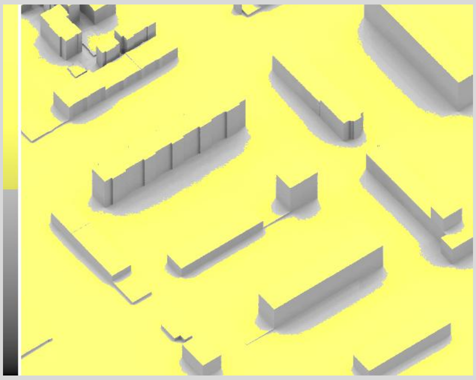
Thresholded South view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



Thresholded North view relating to roof-integrated BiPV (1000 kWh/m^2.year)



Thresholded South view relating to roof-integrated BiPV (1000 kWh/m^2.year)



Thresholded North view relating to façade-integrated BiPV (800 kWh/m^2.year)

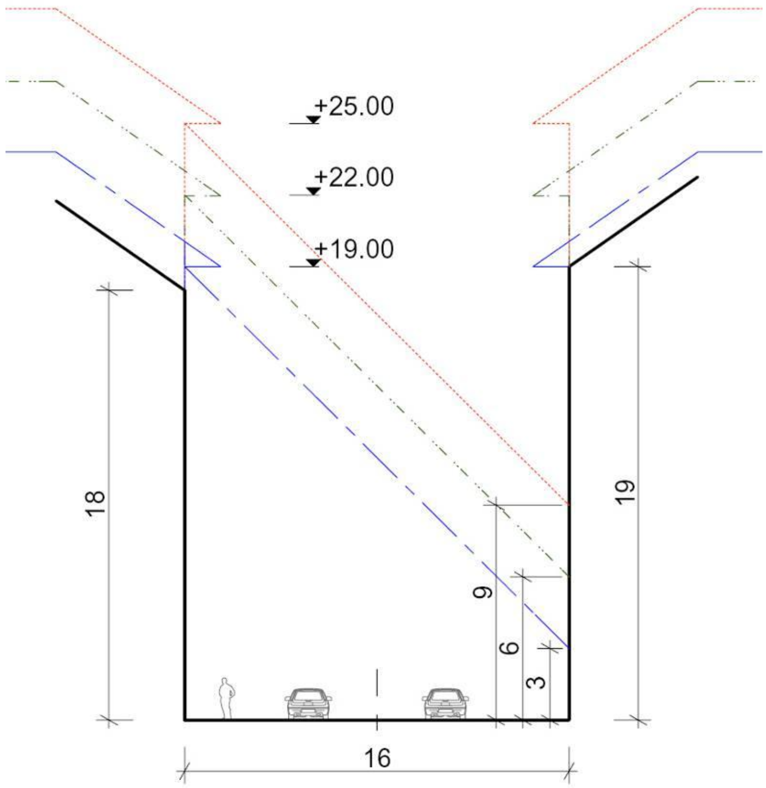
Thresholded South view relating to façade-integrated BiPV (800 kWh/m^2.year)

Figure 126: Meyrin Estate. Thresholded images using a Boolean filter.

4.5 Les Pâquis 1&2 district, Geneva, 46.20 latitude (Switzerland)

To tackle the housing shortage that plagues the lives of many of Geneva's inhabitants, densification becomes inevitable. As a consequence, the issue of urban density in Geneva has become a crucial one. Moreover, according to acknowledged statistics, the Geneva area is expected to accommodate 200,000 more inhabitants by 2030.

Urban areas that can be densified by adding a supplementary storey to an already existing building make them worthy of investigation. To serve that purpose, in the context of the study *Les enjeux qualitatifs de la densification par surélévation* (Marchand, Montavon et al. 2008), two street blocks were selected to evaluate the possibility of densification within the legal constraints of July 26, 2007[57] (see Figure 127 and Figure 128). These projects to heighten buildings would take place in built areas. The objective was to examine the consequences of these modifications in terms of daylighting and solar potential.



Zone 2	Loi actuelle	Loi 9529	Proposition
Gabarit rue	15m. (12 + 3)	21m. (12 + 9)	18m. (12 + 6)

Ech: 1/250

Tiret point gabarit actuel selon Art.23

Trait tillé gabarit selon PL 9529

Tiret court point gabarit selon nouvelle proposition

Figure 127: Les Pâquis district. The legal possibility to heighten buildings is related to the street width: the maximum authorized building outline cannot exceed this width adding up to 6 metres, within the limit of 30 metres in total. Dashed line: building outline according to PL 9529 (top). Dash-point line: building outline according to new proposal (middle). Long dash-short dash line: current building outline according to Art. 23 (bottom).

Source: [online] URL: www.ge.ch/grandconseil/data/texte/PL10088.pdf (Consulted on April 4, 2008).

[57] PL 10088 of July 26, 2007: bill amending the Law on constructions and various installations (L5 05).

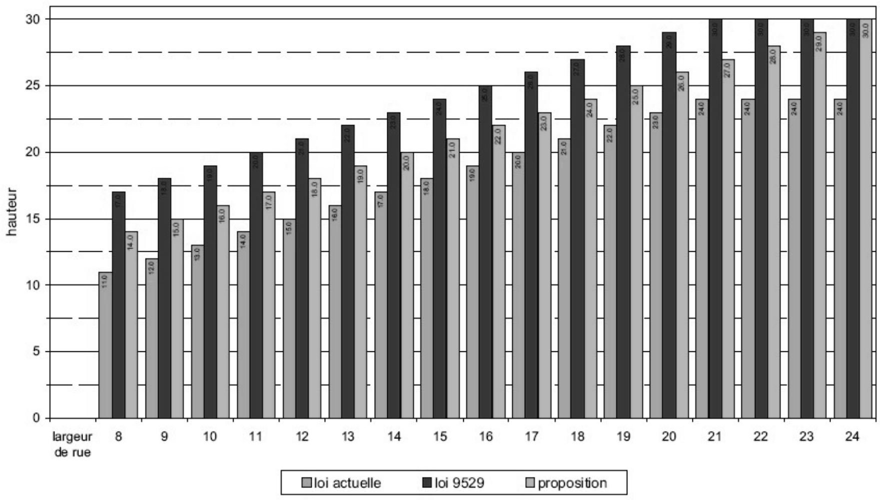


Figure 128: Height of the building outline as a function of the street width in zone 2.

Source: [online] URL: www.ge.ch/grandconseil/data/texte/PL10088.pdf (Consulted on April 4, 2008).

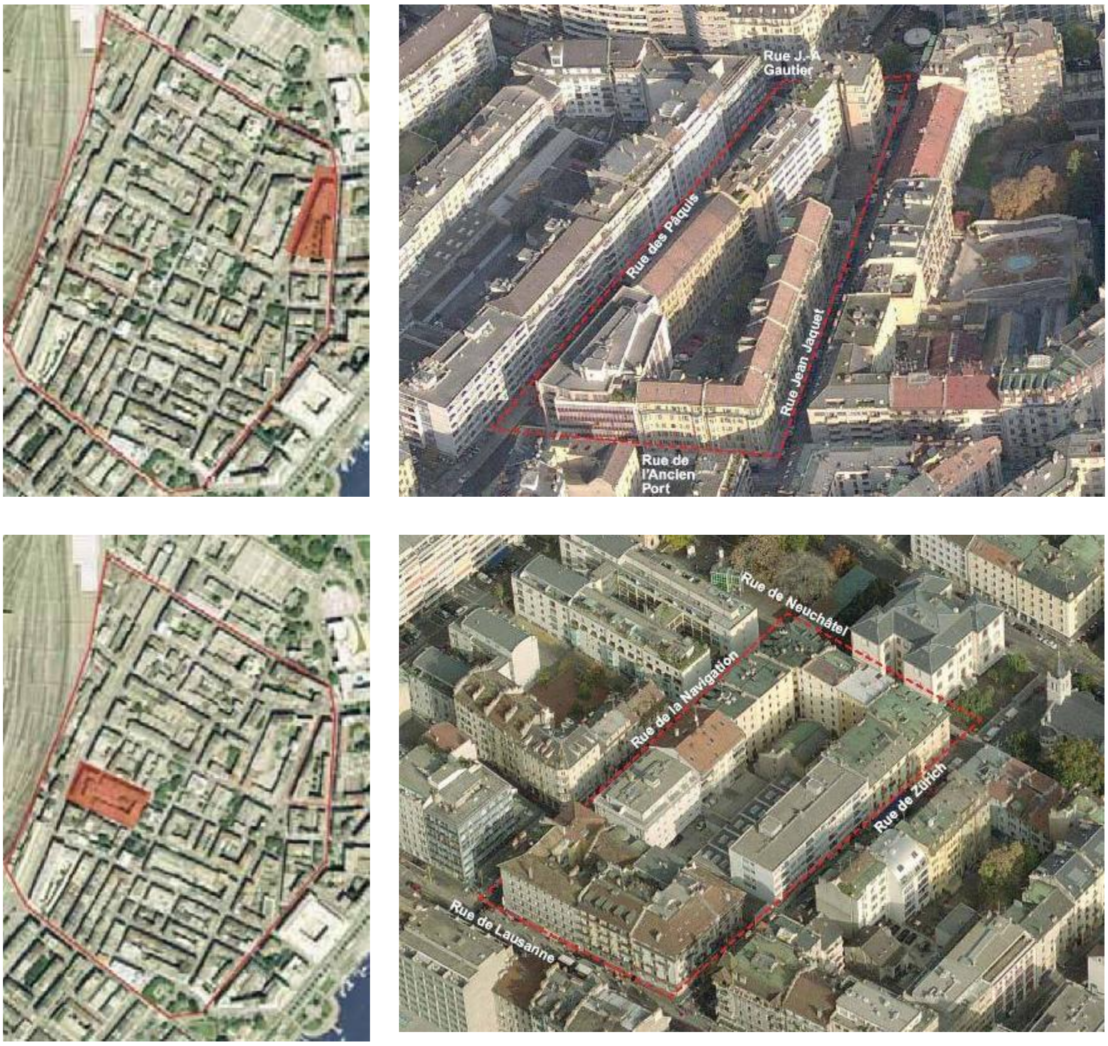


Figure 129: Les Pâquis district. “Les Pâquis street block 1” layout plan (top left) and view (top right), “Les Pâquis street block 2” layout plan (bottom left) and view (bottom right).

Source: Marchand, B., Montavon, M., Bossy, K. (2008). Ville de Genève. Les enjeux qualitatifs de la densification par surélévation. Geneva, DeLaMa Urbanisme et aménagement du territoire - Service d'urbanisme, ville de Genève.

4.5.1 Description of case study

The district of Les Pâquis is located on the west bank of Lake Geneva at the front lake (the so called *Rade de Genève*): its structure was basically created in the late 19th Century and was extended intensively in the 20th century. Very lively, multifunctional and attractive, it suffers from heavy road traffic, the lack of pedestrian areas, and also from the lack of schools and socio-cultural facilities (see Figure 129).

In earlier times, Les Pâquis were pasturelands, located outside the fortifications of Geneva, that went down to the Lake of Geneva and which now belong to the town of Le Petit-Saconnex. Beautiful residences surrounded by gardens occupied the former pasturelands. Geneva's ramparts were demolished after 1850; several new districts – Les Eaux-Vives, Plainpalais, La Jonction and Les Pâquis – were established at that time beyond the limit of the fortifications (where the former suburbs were located).

The modern district of Les Pâquis with its orthogonal streets was built from 1855 onwards. The heart of this popular district is extended by luxury buildings. Since the early 20th century, the north of Les Pâquis, which borders small shops and leisure areas, has witnessed a multiplication of bars, cabarets, dancing and music-halls – facing first-class hotels as well as dilapidated hotels frequented by prostitutes. Although it is Geneva's red-light district, Les Pâquis is also the most cosmopolitan district of the town: many nationalities, races, customs and types of cuisine flourish there.

More than 10,000 inhabitants live in the district (6% of Geneva's population) in approximately 6,500 accommodations. From a morphological point of view, the district's structure is made up of building blocks lined up on a high-density network of corridor-like streets. With an area of 30.6 ha (75.6 acres) the district of Les Pâquis covers a built-up area of 162,112 m2 (1,744,959 sq ft). The site coverage ratio is equal to 0.52 and shows for "Les Pâquis street block 1" a plot ratio of 3.1 and 3.7 for "Les Pâquis street block 2". These relatively high values indicate that the investigation for densification potential will take place in built areas. Consequently, it must take an existing social and architectural urban fabric into account.

4.5.2 Description of 3D digital model

The *Service d'Information du Territoire Genevois* (SITG) of the Canton of Geneva provided - as in the case of Meyrin – a GRID-Digital Terrain Model (GRID–DTM) and a GRID – Digital Height Model (GRID–DOM), which were acquired using airborne laser scans. The DTM and the DOM include the elevation of each square meter of the Canton of Geneva and allow a 3D visual display of the latter by means of the relevant software (MapInfo, ArcView, etc.). These digital data, which do not consider sloped roofs, were unfortunately not suitable for blocks 1&2 of Les Pâquis, which are nestled in a dense traditional urban fabric. Moreover, the district contains a few buildings characterized by complex roofs.

It was therefore necessary to create building volumes manually (façades and roofs) in order to build-up the appropriate 3D digital model of the considered district: architectural plans recorded on microfilms for building permit applications were used for that purpose. A 1:500 scale model of the City of Geneva, as well as a rules base stemming from the city legislation and buildings code for "potential raising" of the buildings' roofs, were also used to improve the 3D digital model. The scale model of the City of Geneva, as well as the associated database, can be consulted at the Urban Planning Service. It encompasses the entire territory of the City of Geneva (5 km × 6 km), 78% of the territory being currently modelled (see Figure 130).

A 2D cadastral data (2D digital data) of the Canton of Geneva, which includes height layers, was also used in the course of this study. During the handling of these 2D digital data, a certain number of open polylines (open in the case of contiguous objects) had to be closed "manually". The number of points (and therefore of faces) on each curve was reduced as much as possible. This preliminary process led to a 3D digital model, which was easily usable in other formats. The 2D cadastral plan had also to be “cleared out” by removing all useless layers.

An inventory of facets of the digital model was undertaken using 3D Studio Max software: 43,000 facets were identified in this way. Hand modelling of the entire sector was considered to be too tedious. As a consequence, 3D Studio Max was employed to model the site directly.

Figure 130: Model-puzzle of the City of Geneva (top and bottom).

Source: [online] URL: http://www.ville-ge.ch/geneve/amenagement/site_maquette/ (Consulted on April 4, 2008).

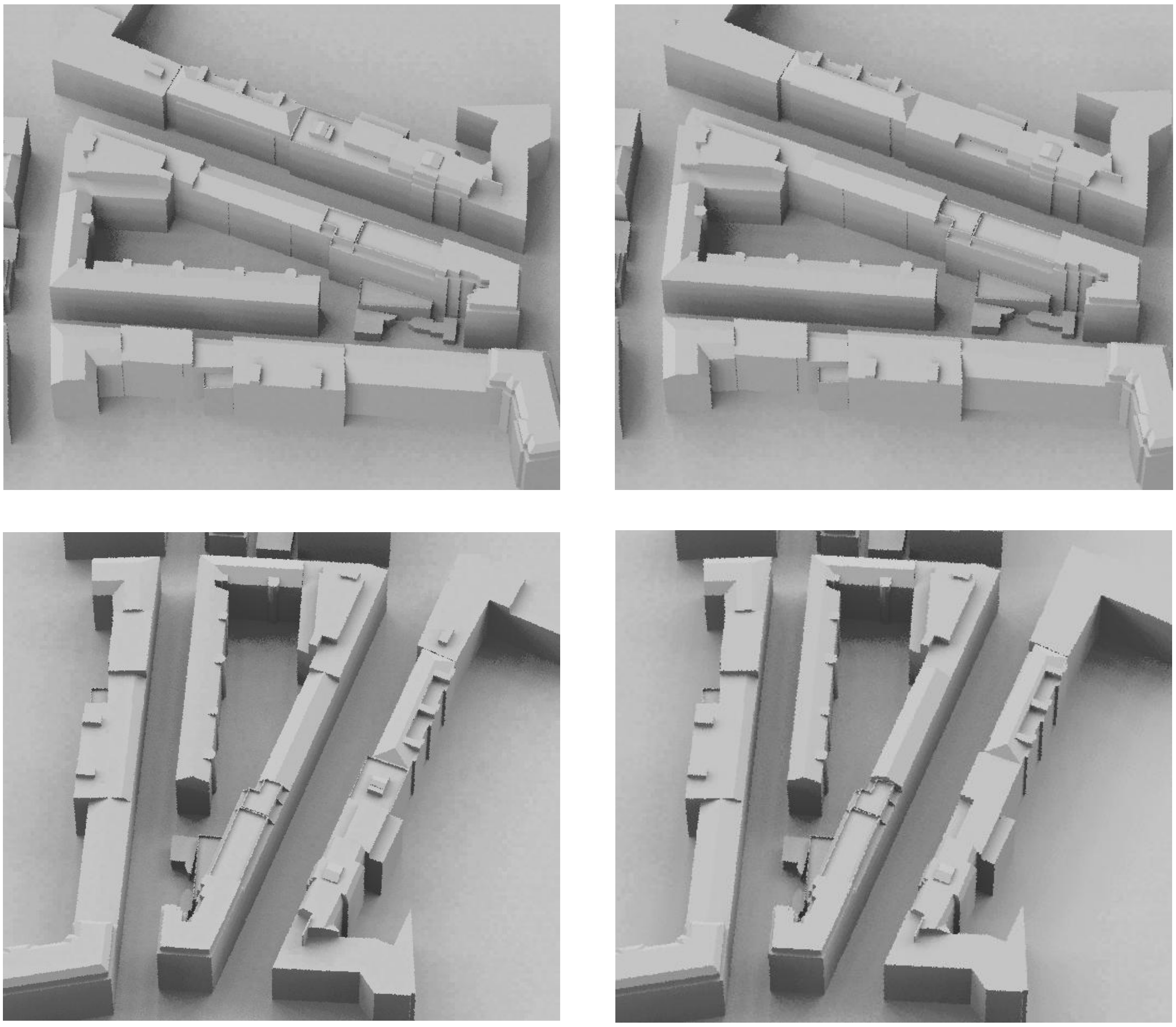


Figure 131: “Les Pâquis street block 1” of the existing site. East view (top left), North view (bottom left). East view of the site after heightening of buildings (top right) and North view of the site after heightening of buildings (bottom right) (RADIANCE renderings).

The achievement of this operation and the subsequent importation of the model into 3D Studio Max could not be fully tested beforehand: it was hoped that the experience already gained from this software would provide sufficient guarantee. The main task was the conversion of the whole 3D digital model into *poly*: it enabled the differentiation of façades and roofs, and made it possible to store them directly in the proper layers of 3D Studio Max. The following operations were carried out for that purpose:

- Polygons were selected;
- Detach command was applied;
- Attach command was applied between identical objects;
- Classification of the relevant layers.

The PPF software required no specific modifications to recognize 3DFACE objects and layers in order to build a 3D model (terrain, façades and roofs). A good organisation was important, together with the arrangement of the 3DFACE directly in the appropriate AutoCAD layer (3DF_DTM, 3DF_FASSADEN and 3DF_DACH) to avoid confusion. 3DFACE objects were imported using the *get3df* translator. The various tests made using PPF were quickly conclusive. The corresponding 3D digital model of the site is extremely accurate (up to 1–cm accuracy). All flat or sloped roofs were modelled, including some specific details (overhang flagstones) and superstructures (dormer windows, elevator shafts, blower rooms). Figure 131 and Figure 132 illustrate a Radiance rendering of the model.

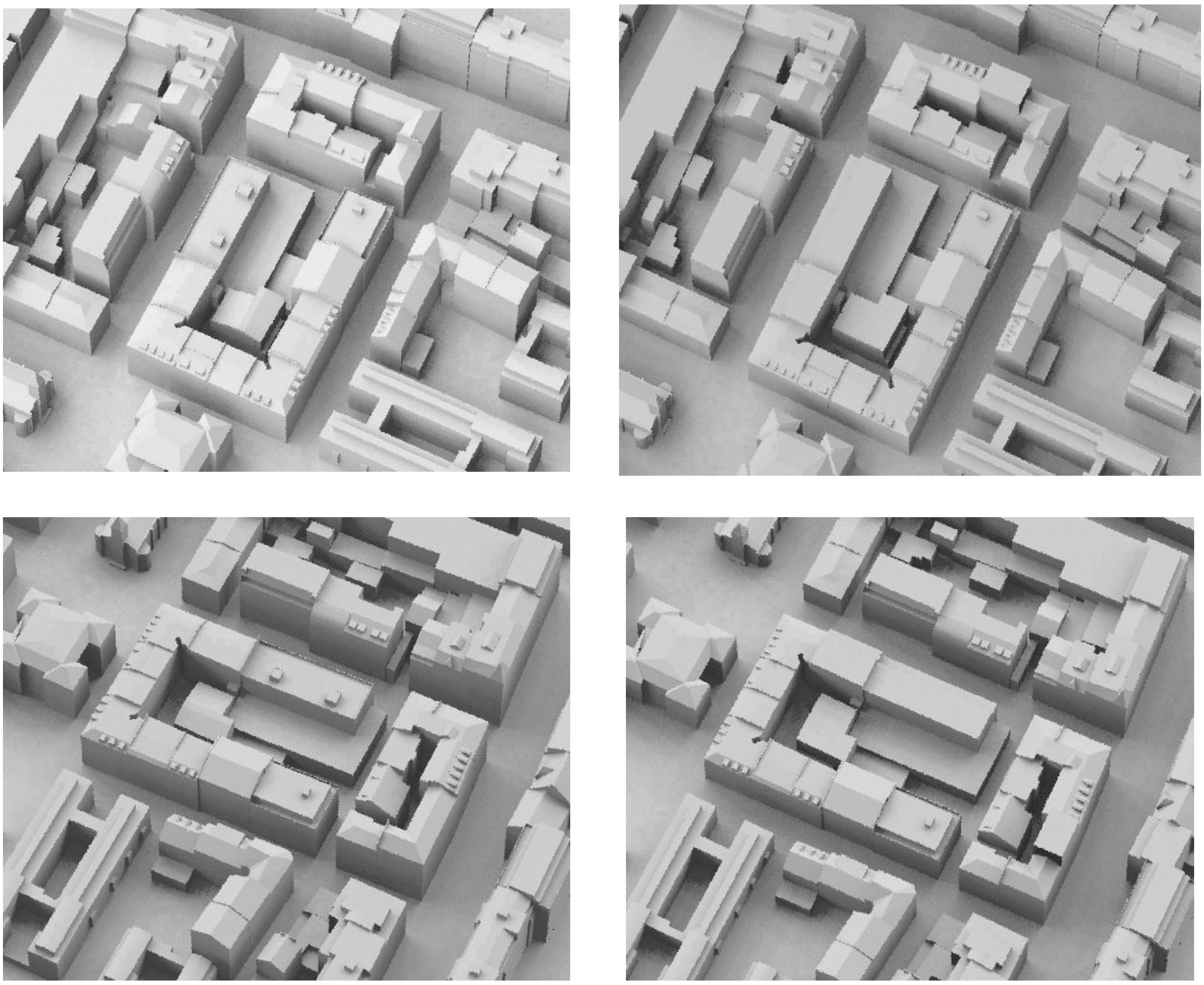
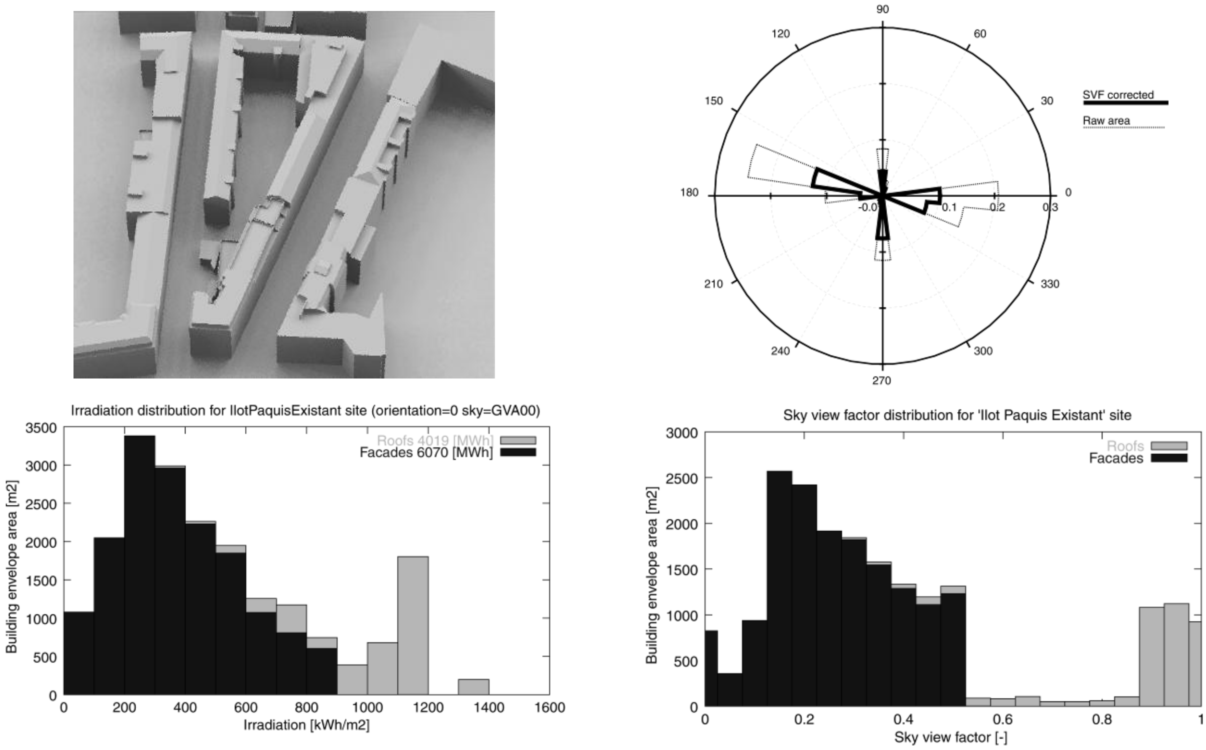
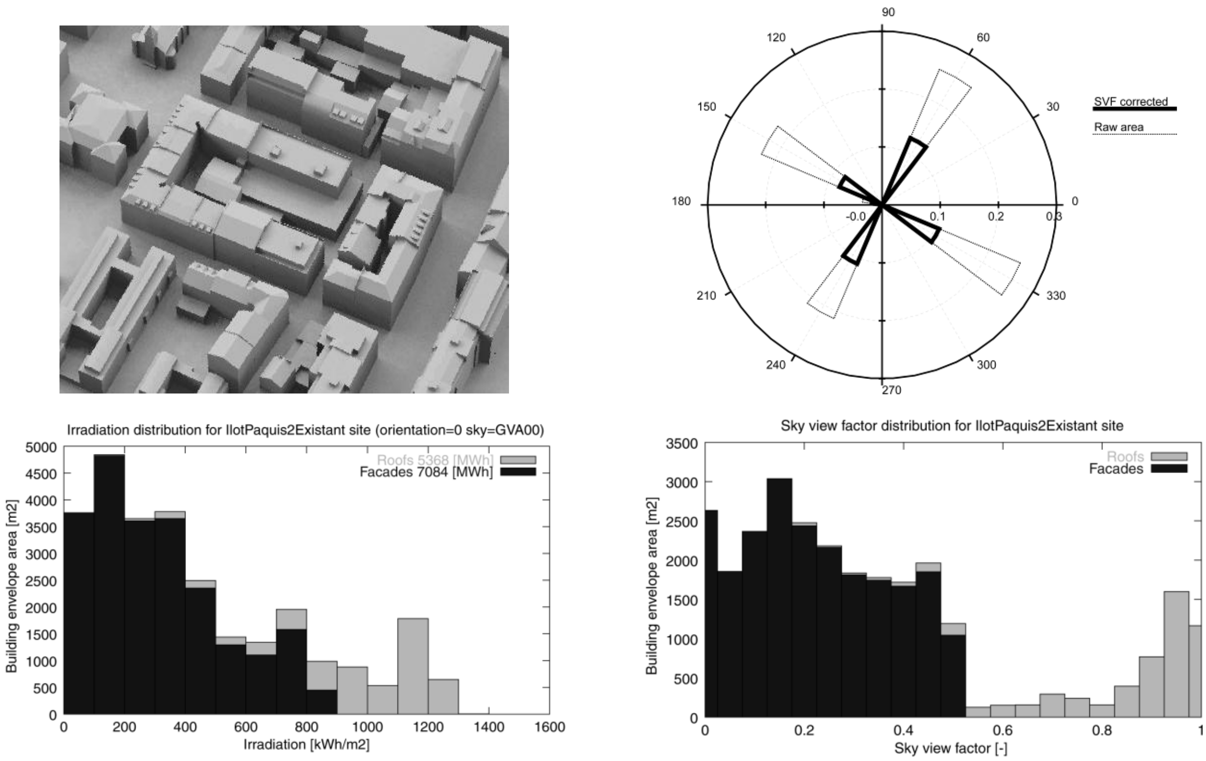


Figure 132: “Les Pâquis street block 2” of the existing site. East view (top left), North view (bottom left). East view of the site after heightening of buildings (top right) and North view of the site after heightening of buildings (bottom right) (RADIANCE renderings).



Visualisation of "Les Pâquis street block 1 –Existing site" (top left) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (top right). Statistical distribution of yearly irradiation on the building façades and roofs (bottom left) and sky view factor distribution (bottom right).



Visualisation of "Les Pâquis street block 2 –Existing site" (top left) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (top right). Statistical distribution of yearly irradiation on the building façades and roofs (bottom left) and sky view factor distribution (bottom right).

Figure 133: "Les Pâquis street blocks 1 and 2 –Existing sites". Visualisations of sites, cumulative irradiation (orientation rose), irradiation histogram and Sky View Factor (SVF).

4.5.3 Solar performance indicators

As noted earlier, a fundamental aim of *Les enjeux qualitatifs de la densification par surélévation* (Marchand, Montavon et al. 2008) was not to distort the original conditions of Les Pâquis district or even – had it been possible – to improve them. Different performance indicators were used to assess the daylight and solar potential of the corresponding project for Les Pâquis.

Passive solar gains and daylight viability are the major performance indicators of this study. Using heating season degree-days (3,151 DD) for Les Pâquis, the corresponding threshold relating to passive solar gains (187 kWh/m^2.year) was determined. An indoor required illuminance of 500 lux and a daylighting utilisation coefficient of 0.05 (typical for a vertical opening) were assumed. Simulations were conducted using the typical Winter sky conditions of Geneva (Compagnon 2004).

Layout of the urban sites

The orientation rose (see Figure 133) of the current “Les Pâquis street block 1” site shows a east-west dominant façade orientation. On the other hand, the current “Les Pâquis street block 2 ” site, shows an almost equal distribution of façades in the NE, SE and NW sectors, with a slight disadvantage for the south-west sector. From the Sky View Factor (SVF) corrected surfaces, one can observe that façades are in both cases heavily obstructed at the rate of 48% for “Street block 1” and 56% for “Street block 2”.

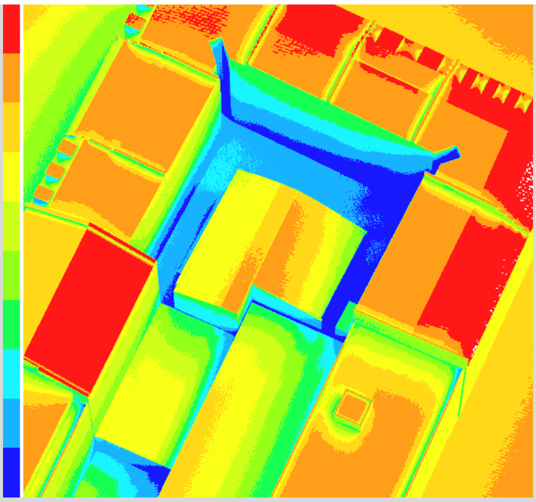
Sky view factor and irradiation distributions

The Sky View Factor distribution has an important peak between 0.16 and 0.2 for “Street block 1”; for “Street block 2” the peak is located at 0 and between 0.12 and 0.2 (i.e. the fraction of the sky vault viewed by the façade divided by 0.5, the value corresponding to an unobstructed façade). Façade irradiation for “Street block 1” has a pyramidal shape centered at 300 kWh/m^2.an. At the opposite end, the roofs are relatively unobstructed and have a peak in the ranges of 1,200 kWh/m^2.year. For “Street block 2”, the peak of the façades is situated in the ranges of 100 kWh/m^2.year; moreover, the distribution has a long tail towards the end of the irradiation scale, suggesting that some low façades and roofs are heavily obstructed. The roofs are fairly normally distributed between 900 - 1,300 kWh/m^2.year. In both cases the annual global solar irradiation on the horizontal plane exceeds 1,200 kWh/m^2.year (see Figure 133).

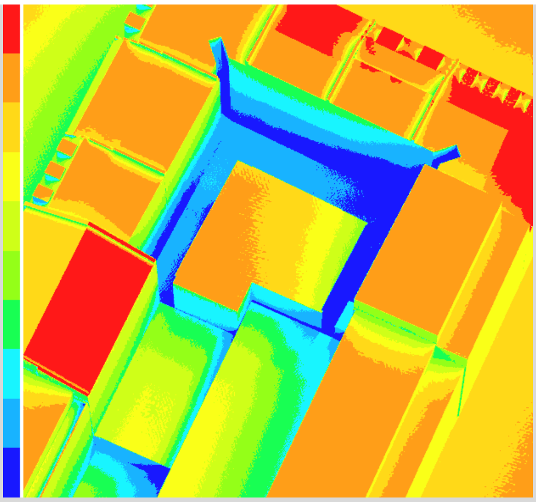
Overall daylighting performance and solar potential

Table 27 shows that in a district which has developed under multiple legal constraints without taking the access to solar radiation into account, only 21.3% of the façades of “Street block 1” and 17.5% of “Street block 2” are suitable for passive heating. This value rises up to 44.8% and 32.8% respectively for daylighting on an annual basis and to 19.9% and 16.4% respectively for Winter daylighting. This means that solar gains during wintertime are rather low. In view of these results, more than half of the openings are consequently incapable of generating the required indoor illuminance.

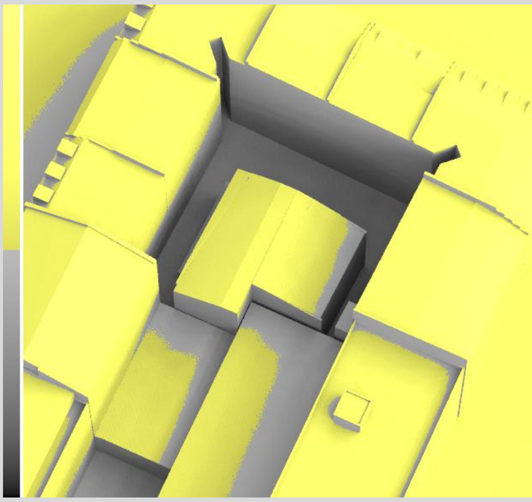
As far as BIPV is concerned, these façades do not benefit from sufficient sunshine because of cast shadows: as a consequence only 3.8% for “Street block 1” facades and 2% for “Street block 2” benefit from a solar irradiation higher than 800 kWh/m^2.an. However, this figure increases up to 68.2% and 54.2% for the roofs and corresponding roof fraction, which benefit from an annual irradiation larger than 1,000 kWh/m^2.an. More than half of the roofs can be utilized to generate solar electricity in spite of their orientation or inclination. These values reflect the uniformity of building heights and the high density of the site. For solar thermal collectors, the corresponding values reach 41% and 31% resp. for the façades and 95.6% and 91.2% for the roofs.



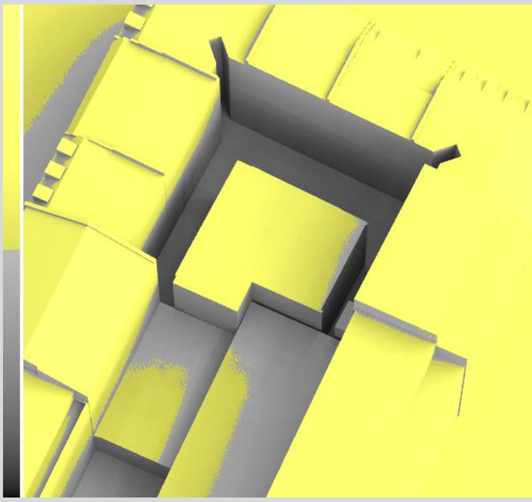
Discretised false-colour image of
“Les Pâquis street block 2 -Existing site”
(Annual irradiation 1250 kWh/m^2.year (red): West view)



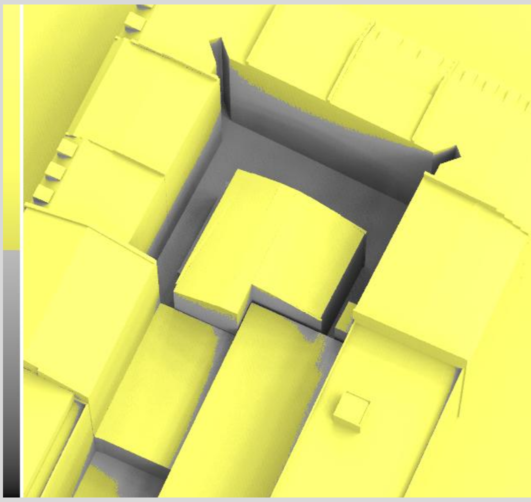
Discretised false-colour image of
“Les Pâquis street block 2 –Potential site”
(Annual irradiation 1250 kWh/m^2.year (red): West view)



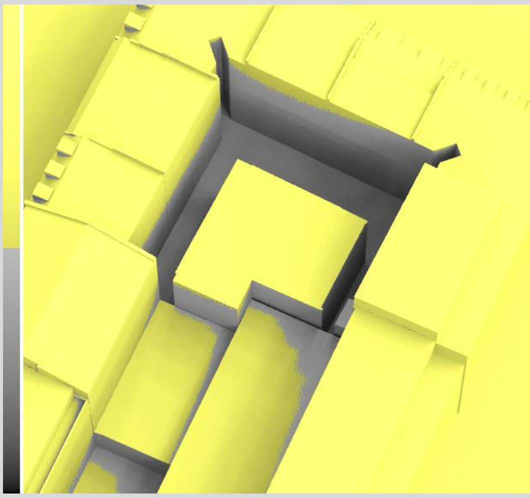
Thresholded image relating to passive solar gain
West view of “Les Pâquis street block 2 -Existing site”
(187 kWh/m^2.year)



Thresholded image relating to passive solar gain
West view of “Les Pâquis street block 2 –Potential site”
(187 kWh/m^2.year)



Thresholded image relating to daylighting
West view of “Les Pâquis street block 2 -Existing site”
(10 kLux)



Thresholded image relating to daylighting
West view of “Les Pâquis street block 2 –Potential site”
(10 kLux)

Figure 134: “Les Pâquis street block 2” of courtyard inside. False-colour images and thresholded images using a Boolean filter.

Table 27: Summary of results for “Les Pâquis street block 1”and “Les Pâquis street block 2”

Les Pâquis	Daylighting viability		Passive solar viability	Solar thermal viability		BiPV viability	
	Façades (annual)	Façades (Winter)	Façades (Winter)	Roofs (annual)	Façades (annual)	Roofs (annual)	Façades (annual)
Street block 1 Potential site	44.8%	19.9%	21.2%	95.4%	40.2%	67.5%	3%
Street block 1 Existing site	46.1%	19.6%	21.3%	95.6%	41%	68.2%	3.8%
∆ Potential - Existing	**-1.3%**	**0.3%**	**-0.1%**	**-0.2%**	**-0.8%**	**-0.7%**	**-0.8%**
Street block 2 Potential site	32.8%	16.4%	17.1%	90.4%	29.4%	59.1%	2.4%
Street block 2 Existing site	34%	16.8%	17.5%	91.2%	30%	54.2%	2%
∆ Potential - Existing	**-1.2%**	**-0.4%**	**-0.4%**	**-0.8%**	**-0.6%**	**4.9%**	**0.4%**

Table 27 also shows the results corresponding to the two existing and potential sites, the latter involving raising the buildings’ height. In the case of street blocks, the increased elevation of the buildings permitted by law had a minimal effect on the solar performance indicators of the buildings, the latter being not significantly affected. At the very most, there was a slight deterioration of solar utilisation potential inside and at the bottom of the courtyards and on the ground floors of buildings. On the other hand, these increased elevations, especially in the case of highly dense street blocks, can emphasize the feeling of density and thereby contribute to lowering the sense of spaciousness – particularly for low constructions located in the courtyards (see Figure 134).

Balance of the Les Pâquis 1&2 district analyses

Table 28 shows that the potential of urban densification provided by raising the existing buildings is relatively limited. It indicates that in reality for “Street block 1-Potential site” and “Street block 2 – Potential site” the raw floor area will be increased by 28.2 m^2 and 467.3 m^2 respectively, which would be the equivalent of one studio and 4 apartments of 116 m^2. At the opposite end, the façades bring a significant increase, in contrast to the roofs area. This indicates a simplification of the roofs; as for the plot ratio, their area remains unchanged in both cases.

In conclusion, the 2007 governmental bill strongly limits the development potential of the area through a raising of the buildings’ height. Few apartment blocks would be concerned by these transformations and would find it difficult to remain economically viable without them.

Table 28: Summary of surface area for “Les Pâquis street block 1”and “Les Pâquis street block 2”

Les Pâquis	Façades area	Roofs area	Raw floor area	Plot ratio
Street block 1 Potential site	16,364.9	3,875.8	26,408.5	3.1
Street block 1 Existing site	16,020.9	3,930.1	26,380.3	3.1
∆ Potential - Existing	**+344 m2**	**-54.3 m2**	**+28.2 m2**	**0**
Street block 2 Potential site	23,703.2	5,306.2	32,164.7	3.7
Street block 2 Existing site	22,612.4	5,482.7	31,697.4	3.7
∆ Potential - Existing	**+1,090.8 m2**	**-176.5 m2**	**+467.3 m2**	**0**

4.6 Tower Works' site, Leeds, 53.79 latitude (England)

Tower Works is a development in Holbeck Urban Village in Leeds (West Yorkshire), which was designed to create a sustainable life/work environment. The real estate company Yorkshire Forward, owner of the site, invited competitors in 2006 for the design of a new urban "Eco-village". Six consortia were invited – including Carey Jones Architects – to submit schemes for a new media-based creative quarter, which preserved the "rich architectural legacy" of the site (Wilson 2006). The flagship 10,117 m^2 (2.5 acres) site of Tower Works should set a new standard for sustainable urban development in the town of Leeds. The project was considered in this study from the point of view of its daylighting and solar energy utilisation potential in order to assess the design proposal (see Figure 135).

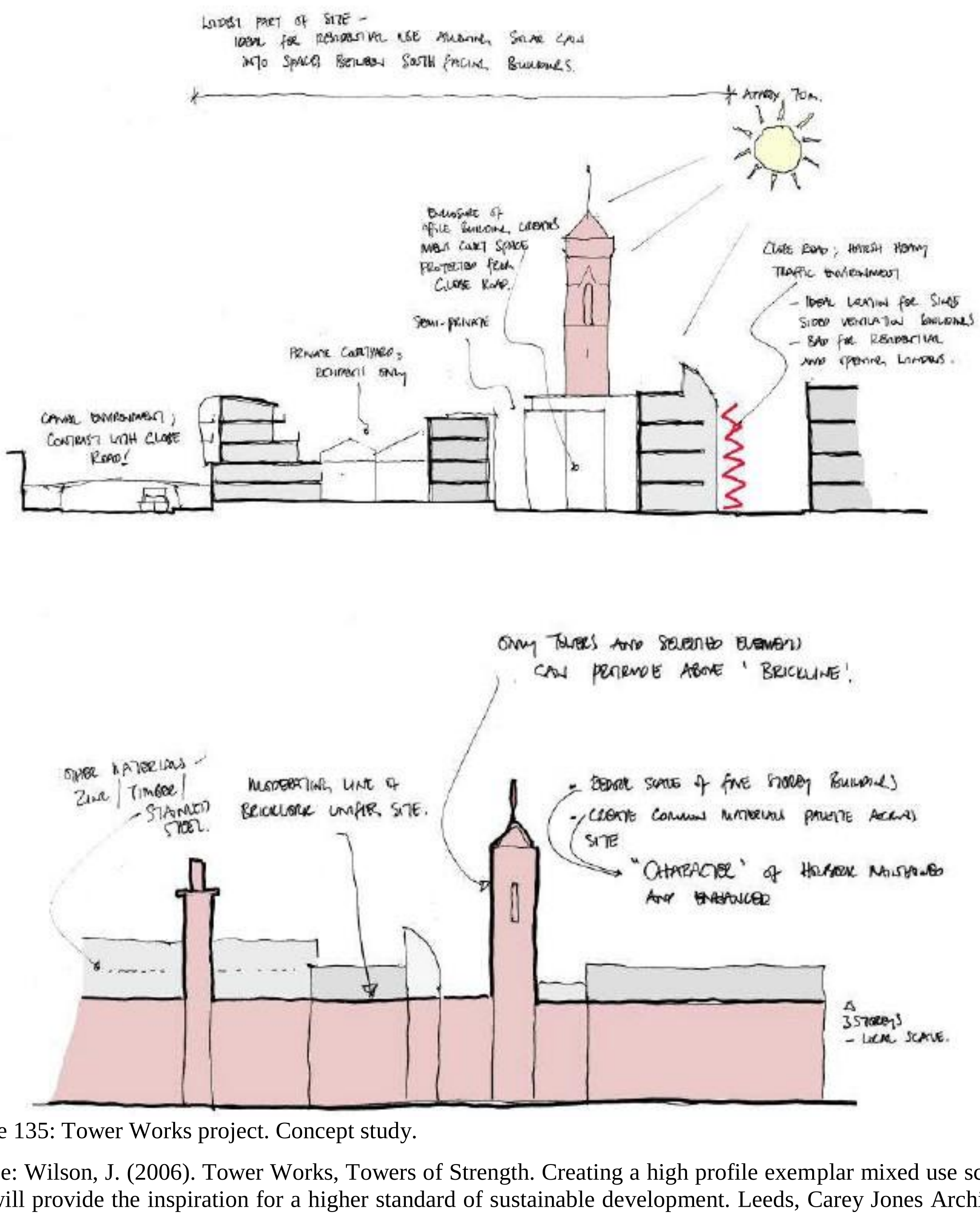


Figure 135: Tower Works project. Concept study.

Source: Wilson, J. (2006). Tower Works, Towers of Strength. Creating a high profile exemplar mixed use scheme that will provide the inspiration for a higher standard of sustainable development. Leeds, Carey Jones Architects: 85.

4.6.1 Description of case study

The Tower Works' site, illustrated on Figure 136, was a former pin factory made of three listed towers situated next to the Leeds and Liverpool Canal. The factory, built by Colonel Thomas Harding, opened in 1864: its design was influenced by Harding's love for Italian art and architecture. The towers of the factory in their Italian style are a distinctive landmark on the Leeds skyline.
During World War II the factory, the neighbouring buildings and Leeds Railway Station suffered severe air raid damage. The factory has never been repaired and was closed in 1981 after 117 years of operation; today, the site is empty, many of its buildings are in ruins.

Tower Works was acquired by Yorkshire Forward in 2005 to undergo a thorough transformation. It was expected to become a modern Leeds district combining modern city offices and businesses that respected the heritage of the Industrial Revolution. Tower Works is a major catalyst for the regeneration of Holbeck Urban Quarter in the city and makes up a gateway to Holbeck Urban Village.

The project developed by Carey Jones Architects involved the creation of two new public squares around buildings listed on the site: the Giotto Tower and the Verona Tower. These are emblematic buildings modelled according to their Italian equivalents. The project consisted of 4,500 m^2 (50,000 sq ft) of A3 / retail (A3 = Restaurants & cafés) over 12,000 m^2 (3 acres) (with a density of 2 m^2 of living area per square meter of terrain, 4, 500 m^2 (50,000 sq ft) of offices, 250 residential units and 350 car parking spaces: a vast outdoor plan containing a canal towpath and a surrounding road network were included in the project as shown in Figure 137.

Figure 136 left and right: Canal side views of Tower Works.

Figure 137: Tower Works project. Ground plane (left) and Main Square views (right).

Source: Wilson, J. (2006). Tower Works, Towers of Strength. Creating a high profile exemplar mixed use scheme that will provide the inspiration for a higher standard of sustainable development. Leeds, Carey Jones Architects: 85.

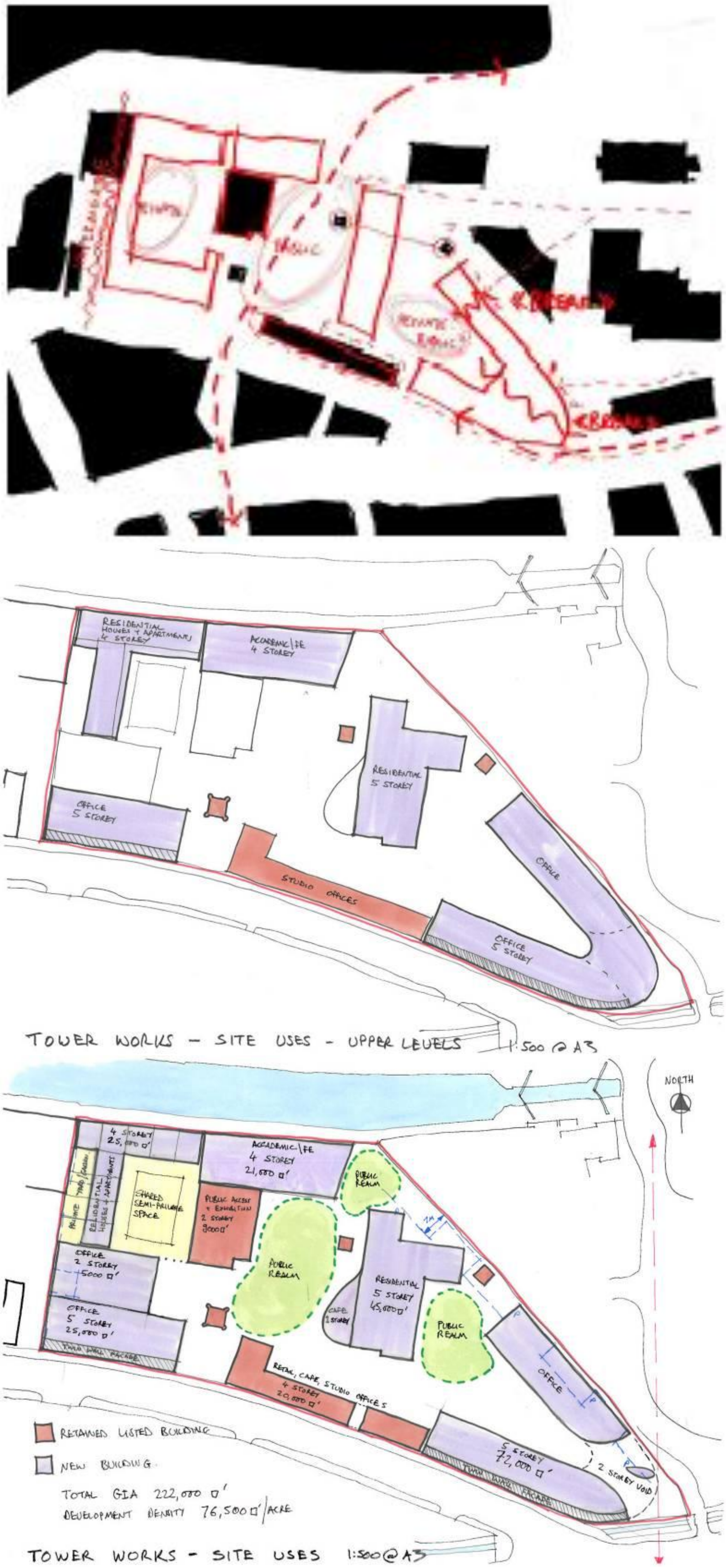


Figure 138: Schemes of Tower Works project © Carey Jones Architects.

The project will achieve the following environmental performance (see Figure 139) (Wilson 2006):
- 70% reduction in carbon emissions below that required from current Building Regulations in UK;
- 30% carbon emissions offset by on site renewable energy sources;
- 100 m^2 area of photovoltaic panels used to load electric vehicles;
- daylight optimisation through 5:1 maximum depth versus height of floorplate;
- no waste removal from the site;
- BREEAM[58] rating that will be achieved for commercial buildings;
- Eco-Homes rating that will be achieved for the residential buildings;
- communication of the buildings' performance to all site visitors.

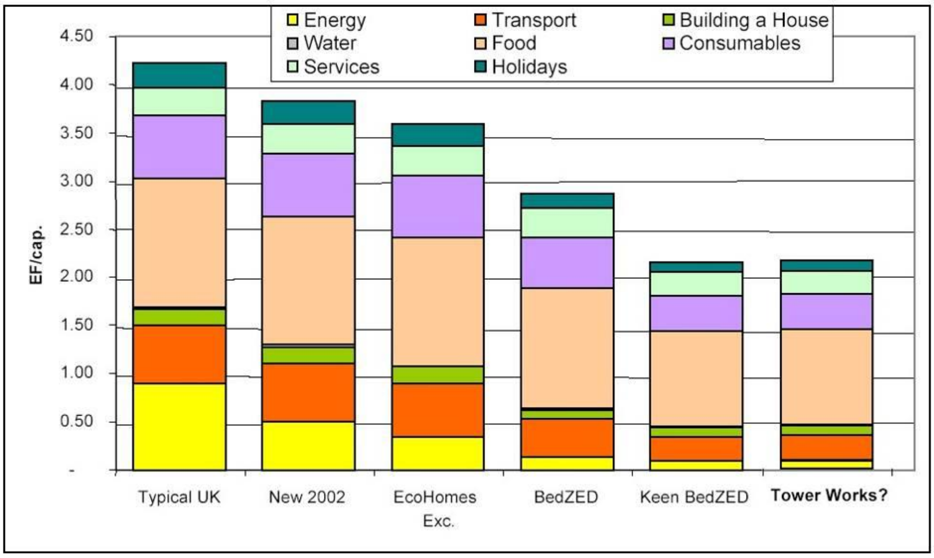


Figure 139: Sustainable living of Tower Works project.

Source: Wilson, J. (2006). Tower Works, Towers of Strength. Creating a high profile exemplar mixed use scheme that will provide the inspiration for a higher standard of sustainable development. Leeds, Carey Jones Architects: 85.

The Holbeck Urban Village development will improve the connectivity between Leeds City Centre and Beeston and Holbeck communities. The zone is already renowned as the creative quarter of the city. The overall goals are to attract new private companies and to enhance Leeds' reputation as the regional capetown. The final project should offer 150 dwellings, 13,500 m^2 (3.35 acres) of shopping area and up to 500 new job positions.

Unfortunately, Carey Jones Architects did not win the architectural competition with the Leeds Eco-village project.

4.6.2 Description of 3D digital model

The 3D digital model of the preliminary architectural design of Tower Works' Site was made available by the Martin Centre for Architectural and Urban Studies at the University of Cambridge (Prof. K. Steemers). Figure 138 illustrates the latter.

Original PDF images of the project, stored in JPG format, were used and keyed into AutoCAD, as a first step of the digital model set-up (one uses the *Insert* menu and *Raster Image* command to import the images). The latter were used to trace the project buildings outlines and generate polylines and

[58] BREEAM is the world's longest standing and most widely used environmental assessment method for buildings.

3DFACE objects by the way of AutoCAD. A first rendering of these images was carried out in order to check if the buildings frames were correctly outlined (using the IMAGEFRAME command).

Once these operations were carried out, transparency was assigned to the raster image to prevent the latter from hiding the polylines drawn above the original scheme. Non-image objects were filtered by means of a series of functions: the PALETTEOPAQUE variable states if frames can be made transparent.

The urban district scheme was used as a background in order to build conceptual building volumes. The façade outlines were created using the building footprints thanks to the POLYLINE/thickness command. A thickness corresponding to each building's height was defined in the POLYLINE tool. This semi-automated operation permitted the erection of all the building outlines in one stage for each building. The latter was used as a base model for the implementation of 3DFACE. The corresponding digital objects were simply laid on the original buildings volumes like a skin. By assigning a thickness to a polyline, a face was defined (as opposed to a 3DFACE). The hand drawing of 3DFACES facets on these volumes required a constant, anticlockwise rotation on each surface in order to define the orientation of the corresponding external façade and roof element (by defining a surface normal vector): this allows PPF to "recognize" them easily and orientate the surfaces properly. The preliminary digital model is shown on Figure 140.

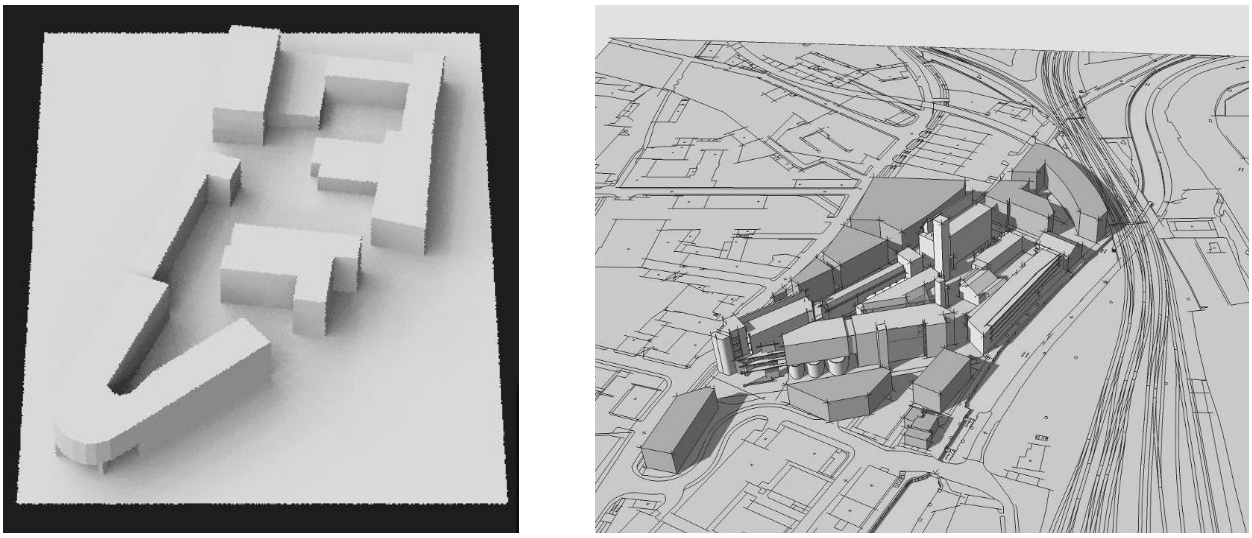


Figure 140 East view of Tower Works draft project (RADIANCE rendering) (left) and Tower Works final project (SketchUp rendering) © Carey Jones Architects (right).

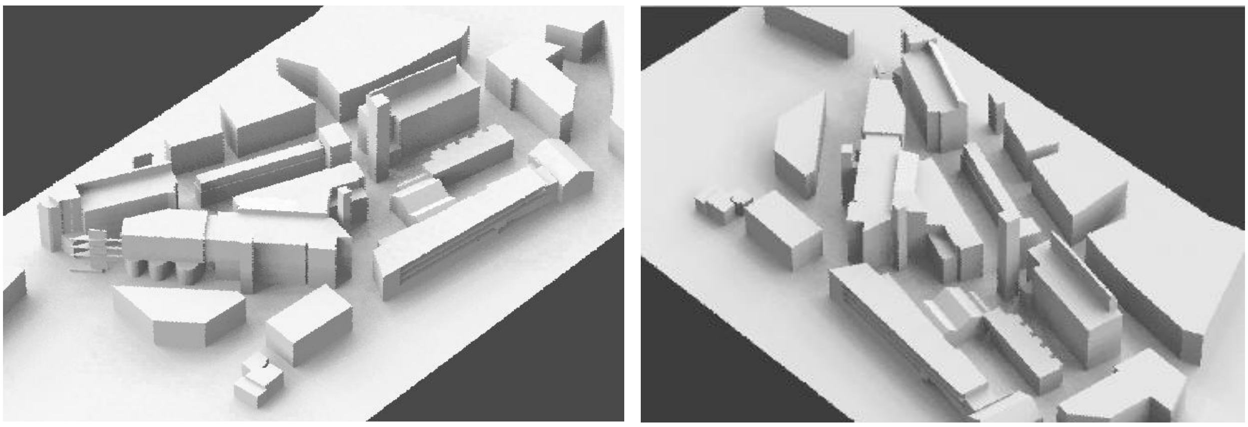


Figure 141: Tower Works final project. North East view (left) and North West view (right) (RADIANCE renderings).

When the 3D buildings model was ready, the SCALE function was applied to set it in the adequate scale and dimensions. The scaling problems arise only upon paper printing (and subsequent reductions) prior to the PPF import of the 3D urban digital model. Some objects, having unknown external dimensions, were drawn according to the original drawing and scaled up.

No other specific routines for the recognition of 3DFACE model types and layers by PPF had to be written (this problem was overcome for the Matthaeus district in Basel). The import of 3DFACE objects was carried out using the Radiance *get3df* function; a series of conclusive tests was made beforehand with PPF.

As the model was based on a conceptual drawing, it was not as accurate as some other urban digital models considered in this study. The heights of the buildings storeys were estimated to be equal to 3m; the buildings' volumes were simplified and roofs were considered to be flat. This was judged to be sound and representative enough to draw conclusions on the overall solar performance of the preliminary design project.

The 3D digital model of a more advanced project of the Tower Works site was elaborated later on: it is based on two architectural schemes, which were made available by the Martin Centre (Prof. Koen Steemers). Carey Jones Architects Company, operating in London, Leeds and New York, drew the original plan using SketchUp. SketchUp is an architecture-oriented 3D modelling software tool, edited by @Last Software: it is characterized by straightforward functionalities (rotation, extrusion, shift, etc.), yet actually very different from conventional 3D software modelling tools. As this digital plan was not usable "as is", it had to be exported first in DXF format (or DWG). Some extensive modifications to the original plan had to be made via AutoCAD in order to be able to use these data as input files for PPF (see Figure 140).

A certain amount of 3DFACE facets had to be manually corrected during the preparation of the 3D digital model (some of the 3DFACE facets were incorrectly exported). The terrain, the façades and the roofs had to be dissociated and stored in the proper AutoCAD layers (3DF_DTM, 3DF_FASSADEN and 3DF_DACH). Finally, once the model was satisfactory, the *SCALE* function had to be applied to match the scale of the model with those of the drawings. 3DFACE objects were imported using the *get3df* function. The various tests made using PPF were quickly conclusive.

As this was the last 3D digital model of the final project, it is very accurate (1 cm accuracy). All flat or sloped roofs were properly modelled, including the overhang parts. The RADIANCE renderings and results showed a level of accuracy unmatched thus far (e.g. the presence of openings, supporting pillars, balconies, overhangs, etc.): Figure 141and Figure 142 illustrate this.

The elaboration of 3D digital models relying on the available data, as well as the efforts devoted to its implementation, are important in a practical case. The experience gained within the framework of this thesis was crucial.

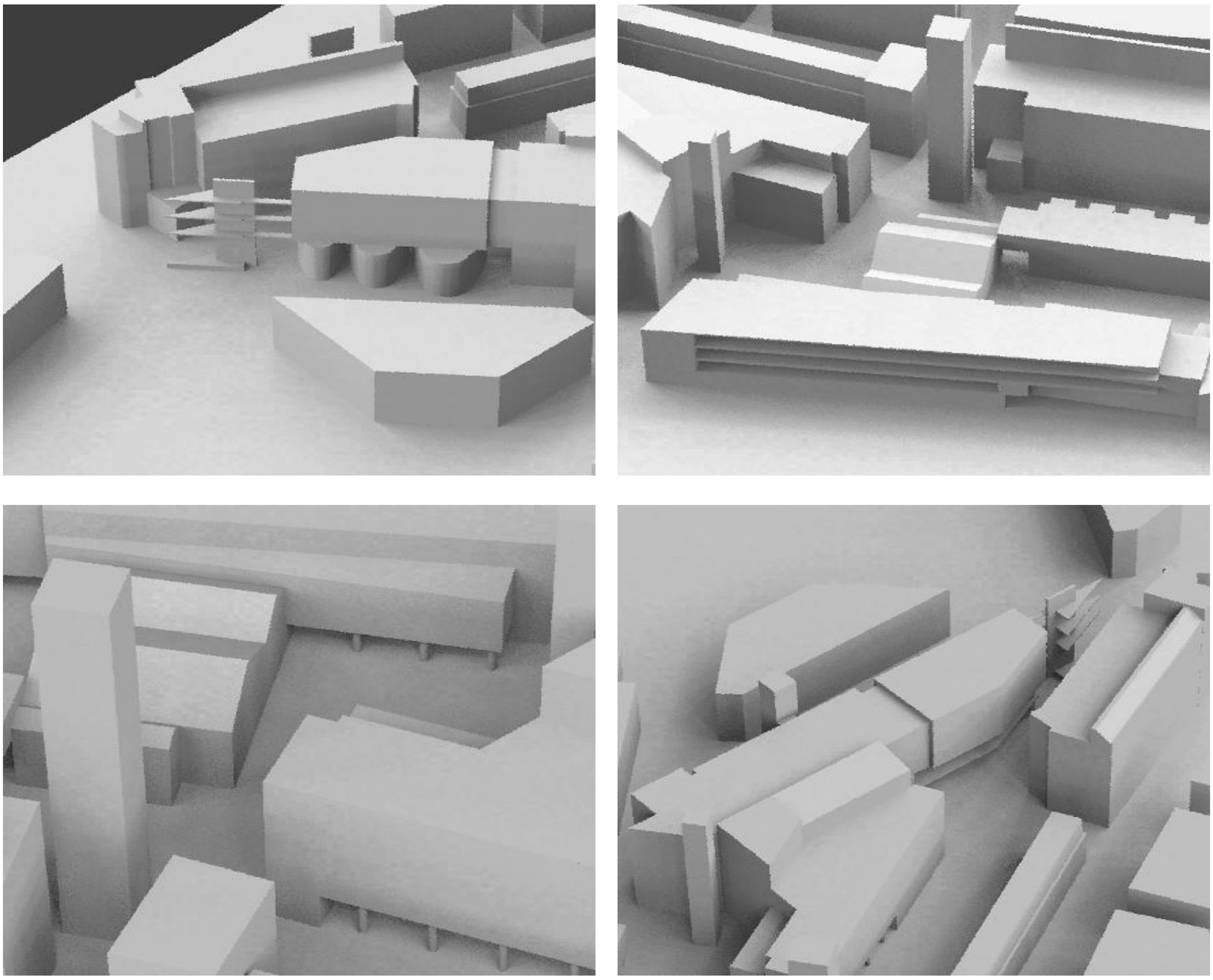


Figure 142: Tower Works final project. Various zooms (RADIANCE renderings).

4.6.3 Solar performance indicators

The evaluation of the available solar radiation in the “Tower Works -Draft project” as well as that of the “Tower Works -Final project” were carried out. These made it possible to test the method in a real urban case study.

Using heating degree-days of 2,414 DD, the threshold for passive solar gain reaches 192 kWh/m^2.year. Assuming an indoor required illuminance of 500 lux and a utilisation coefficient of 0.05 – typical of a vertical opening – it corresponds to the fraction of façade area which receives on average annually, 10,000 lux or more. For solar thermal collectors the lower figures of 400 and 600 kWh/m^2.year were used for façades and roofs respectively. Thresholds of 800 and 1,000 kWh/m^2.year were used respectively for photovoltaics. The simulation has been carried out using the typical winter sky conditions of Leeds (Compagnon 2004).

Layout of the urban sites

Surprisingly, the two orientation roses show resemblances as well as a similar overall appearance (see Figure 143), despite the fact that the “Tower Works -Draft project” is rather rough and the “Tower Works -Final project” very accurate. In both cases, the façades take up the four quadrants of the orientation rose in an irregular pattern. 34% of the façades are located in the South-West sector for the “Draft project”, this value falls to 28% for the “Final project”. For this latter, the North-East sector includes the biggest part of façades area with 36%. The South-East sector is only sparsely used for both with an area of only 15% and 16% of raw façades respectively (Compagnon 2004).

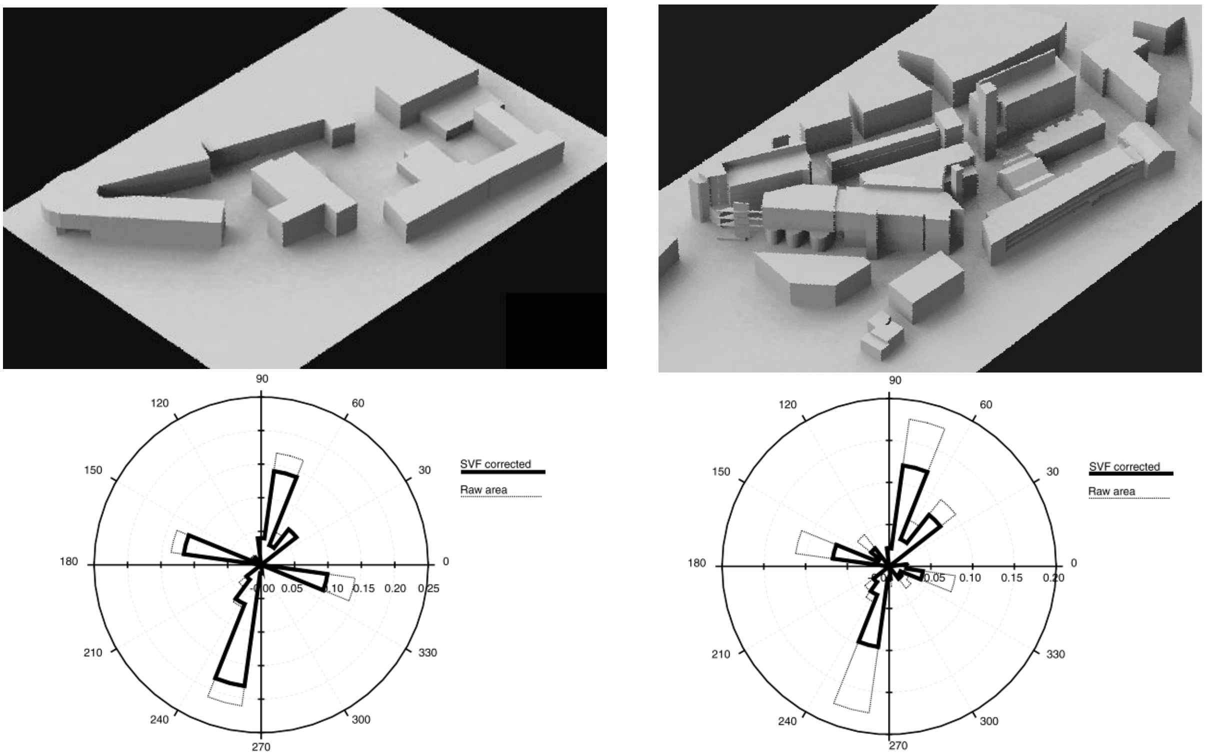


Figure 143: Visualisation of "Tower Works -Draft project" and "Tower Works -Final project" (top left and right) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (bottom left and right).

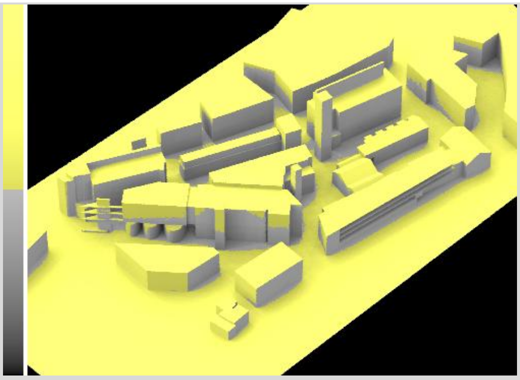
Overall daylighting performance and solar potential

The assessment of the "Final project" indicates that only 30.1% of the façades are suitable for passive heating; this value reaches 38.4% for annual daylighting and to 27.3% for Winter daylighting. 3.1% (539 m^2 of panels – without taking into account openings that decrease this surface) and 6% (459 m^2) of the façade and roof surfaces respectively are viable for the integration of photovoltaics. However, this increases to 33.2% (5,770 m^2 of panels – without taking into account openings that decrease this surface) and 88.2% (6,745 m^2) of the corresponding surfaces for solar thermal collectors (see Table 29).

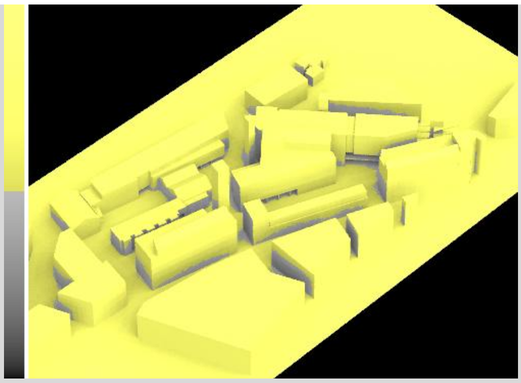
Table 29: Summary of results for "Tower Works –Draft project"and "Tower Works –Final project"

Tower Works	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Tower Works Draft project	65.5%	51.4%	58.7%	96.3%	62.7%	0%	18.7
Tower Works Final project	38.4%	27.3%	30.1%	88.2%	33.2%	6%	3.1%
∆ Draft - Final	**27%**	**24.1%**	**28.6%**	**8.1%**	**29.5%**	**-6%**	**15.6%**

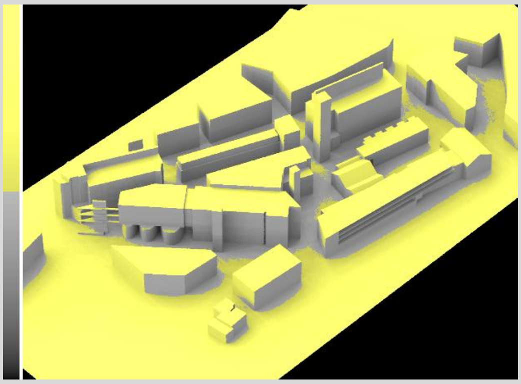
These rather unsatisfactory results can be explained by the insufficient amount of sunlight at the site, the presence of cast shadows (obstructions), the inappropriate orientations of the façades and above all by the impact of the open courtyards of the project. In fact, the "Draft project" offered more inside open space, whereas the "Final project" led to the filling of these spaces by buildings. As a consequence in Winter 70% of the façades do not allow for an optimal passive heating. Furthermore, the placement, the shape and the dimensions of more than 60% of the openings are restricted and consequently do not



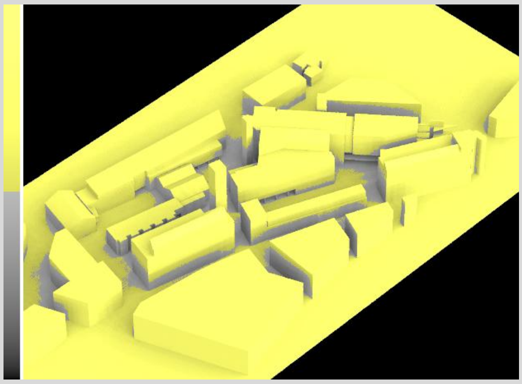
Thresholded North-East view relating to daylighting (10 kLux)



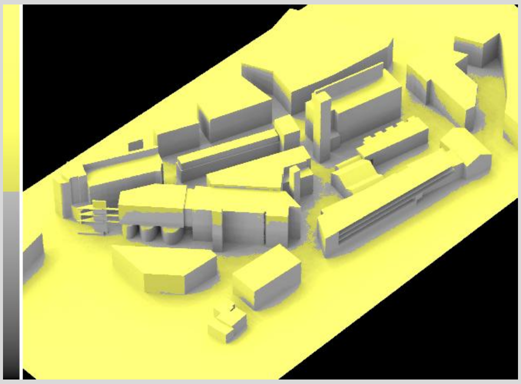
Thresholded South-West view relating to daylighting (10 kLux)



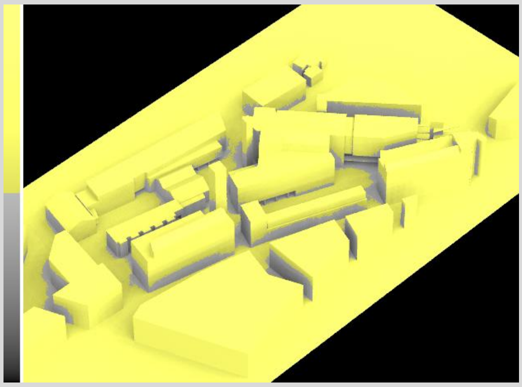
Thresholded North-East view relating to passive solar gain (192 kWh/m^2.year)



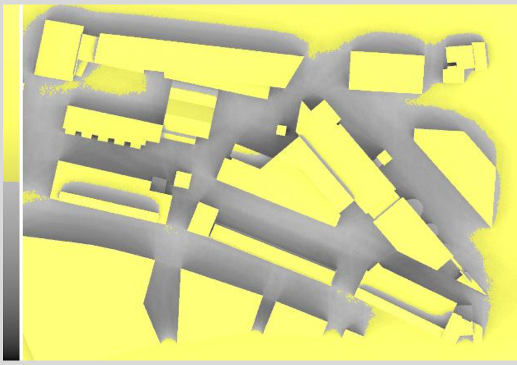
Thresholded North-East view relating to passive solar gain (192 kWh/m^2.year)



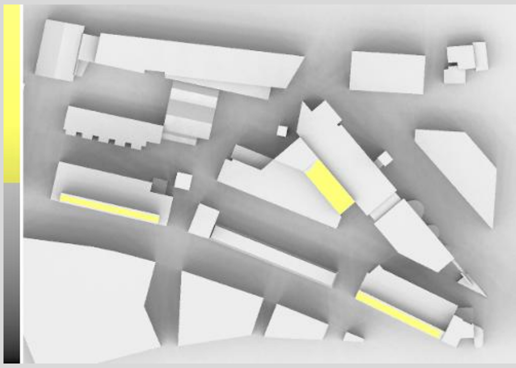
Thresholded North-East view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



Thresholded North-East view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



Thresholded layout plan relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)



Thresholded layout plan relating to roof-integrated BiPV (1000 kWh/m^2.year)

Figure 144: “Tower Works -Draft project” and “Tower Works -Final project”. Thresholded images using a Boolean filter.

make it possible to obtain a minimal 10 kLux of outdoor illuminance. Finally the +6% improvement of the BiPV available areas in comparison to the “Draft project” – for which all the roofs are flat – raises the question of the adequate amount of flat roofs for this project. Indeed, one can conclude from certain images that some appropriate sloped roofs considerably improve the values of the photovoltaic installations (BiPV) (see Figure 144).

Implementation of solar energy technologies

The images corresponding to daylighting and passive solar gains (see Figure 144) show that most of the North-East oriented façades are not appropriate for these two solar technologies. On the other hand, the corresponding South-West façades are optimal for these two technologies, except for some courtyards, the bottom of the courtyards and on the ground floors of the buildings. The same conclusions can be drawn regarding the North-East oriented façades for the solar thermal collectors and photovoltaic plants. The majority of the South-West façades are appropriate to solar thermal and not for BiPV. The two remaining directions, namely the South-East and the North-West represent 17% and 19% of the total façades: in the first case all solar technologies are suitable and on the other hand BiPV is deficient. The North-West direction provides no advantage for solar nor for daylighting.

Balance of the Tower Works’ site analyses

These results show that neither this construction project nor its integration into its urban context are convincing from the point of view of solar utilisation potential. Architectural considerations took precedence over environmental aspects.

The urban morphology of the “Final project” was considerably modified compared to the first draft, but not necessarily in regards to the solar and daylighting potential. In both cases the orientation roses reveal the same patterns, meaning that a large proportion of the façades have similar orientations. They have not evolved significantly, even if the flat roofs deserved to be exploited.

Finally, the modelling of the “Draft project” and its use without obstructions have distorted the analyses and have certainly produced errors affecting the continuation of the project. In conclusion, these premature and overoptimistic results had a negative impact on the “Final project”.

4.7 Eastern Quarry development, London, 51.49 latitude (England)

Kent Thameside it is one of the principal regeneration areas identified in the British Government's strategy for the Thames Gateway, which over the next 25 years will deliver up to 30,000 new homes: approximately 20% of this target has already been achieved. Land Securities owns, or has the development rights to, over approx. 566 ha (1,400 acres) in Kent Thameside, the principle sites being:

- Crossways;
- Waterstone Park;
- Swanscombe Peninsula;
- Eastern Quarry, Ebbsfleet and Springhead.

The research project *Testing the masterplan, An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley* funded by Land Securities offered a valuable opportunity to link academic research to practice, and achieve two primary aims (Steemers, Montavon et al. 2007):

- the development and testing of innovative analysis techniques;
- the application of these techniques to test the current Eastern Quarry masterplan (see Figure 145).

The aim of this study was to test the daylighting and solar utilisation potential of the development proposal for Eastern Quarry in Ebbsfleet Valley in order to improve the Masterplanning (Steemers, Montavon et al. 2007).

Figure 145: Diagram of the outline masterplan for East Village (Eastern Quarry).

Source: Steemers, K., Montavon, M. et al. (2007). Testing the masterplan. An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge: 35.

4.7.1 Description of case study

Ebbsfleet Valley is the name given to a new town and redevelopment area in Kent, South East England: it includes Eastern Quarry (opposite Bluewater), the site of the new Ebbsfleet International Station and Springhead Park. Eastern Quarry offers the largest development potential of the Thames Gateway region. Land Securities own the site in conjunction with Lafarge Cement UK. Dartford Borough Council is the planning authority, although Gravesham Borough Council is responsible for managing the development of the south- eastern part of the site. The British Government has identified this site as a key opportunity to respond to the drastic economic development of the region: it will be split up into ten development zones, to be set in 157 ha (390 acres) of parks, lakes and woodland areas (see Figure 146 and Figure 147).

The British Government is aiming to promote in particular on this site:
- a Smart Development by encouraging the provision of Broadband Technology;
- Green Growth that fosters sustainability through a greater use of public transport;
- innovation in urban and architectural design;
- the reduction of material waste and increase of recycling;
- a range of housing types and tenures;
- a provision of open green spaces and corridors.

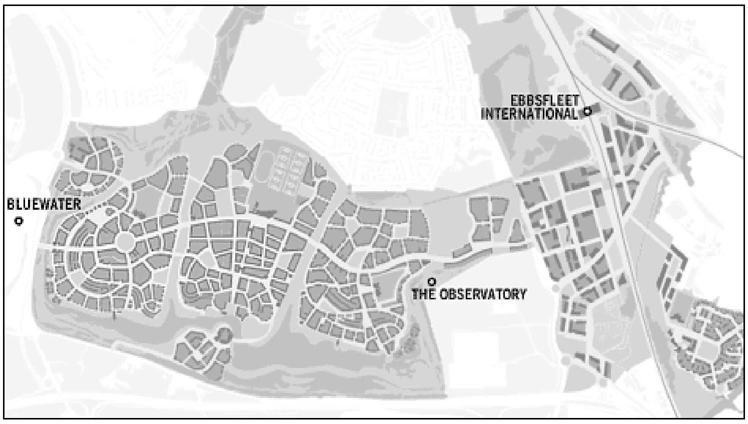


Figure 146: Ebbsfleet Valley map.

Source: [online] URL: http://www.ebbsfleetvalley.com/ (Consulted on April 30, 2008).

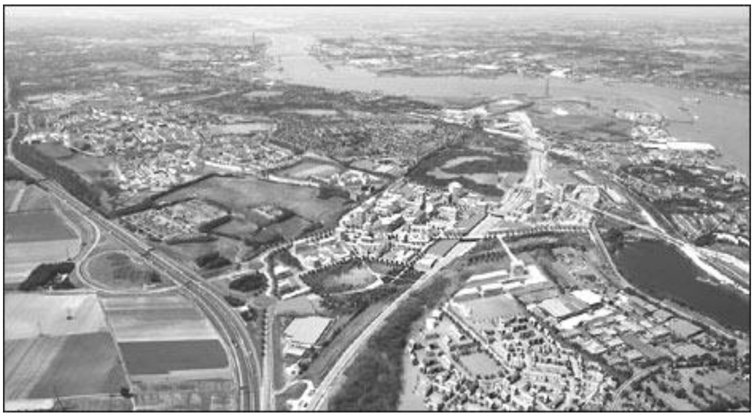


Figure 147: A CGI plan of the Ebbsfleet Valley site.

Source: [online] URL: http://www.ebbsfleetvalley.com/ (Consulted on April 30, 2008).

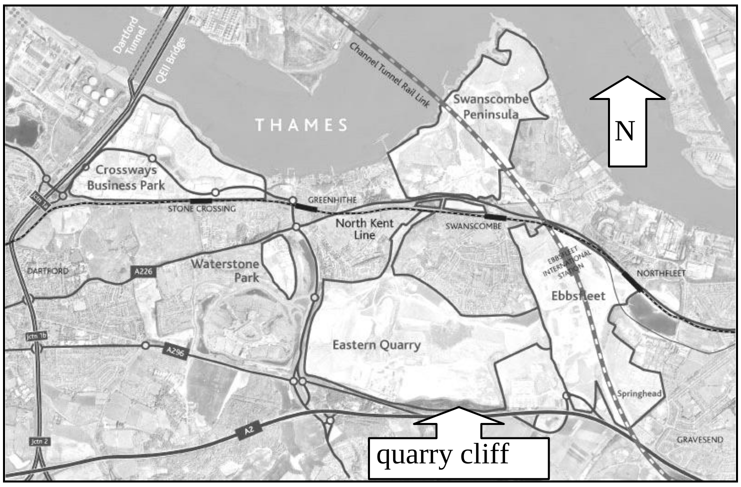


Figure 148: Location of the proposed development site, highlighting the location of the quarry cliff.

Source: Steemers, K., Montavon, M. et al. (2007). Testing the masterplan. An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge: 35.

Figure 149: A bird's-eye view of the Eastern Quarry site in 2006. Image: Kent Thameside.

Source: [online] URL: http://www.ebbsfleetvalley.com/ (Consulted on April 30, 2008).

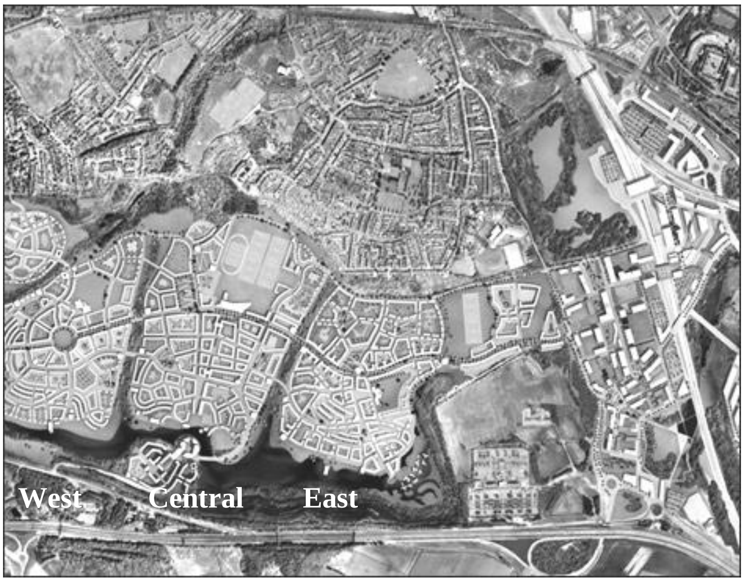


Figure 150: A CGI impression of the Ebbsfleet Valley site, showing the A2 at the bottom and the new Ebbsfleet International Station on the right.

Source: [online] URL: http://www.ebbsfleetvalley.com/ (Consulted on April 30, 2008).

A large fraction of the site of Eastern Quarry was initially renowned for its clay and chalk extraction (see Figure 148). Clay was first extracted by hand at the beginning of the 20th century; chalk excavation began in the 1930's and was transported by railway to the nearby Swanscombe cement works via tunnels: both the Queen Elizabeth II Bridge and parts of the Channel Tunnel were built using cement from Eastern Quarry. Some of the site's parts were subsequently devoted to agriculture; at this point, the quarry has been exhausted of resources.

An important characteristic of this study is the site topography. East Village is located in a unique environment where the water and the variety of landscape create a spectacular panorama (see Figure 149). The quarries, that have produced an uncommon landscape to the south and to the west of the site, offer an interesting settlement for the future buildings. Nevertheless, the considerable variations in the terrain elevation restrict access to the site, and produce significant shadows on certain buildings in the southern part. This limits the development potential of the area, as well as the creation of leisure and ecological zones. An alternative would be to have a smoother topography and slope from the south cliff up to the north of East Village. This would improve the solar and natural ventilation potentials of the site and positively influence its microclimatic conditions and increase the building energy performances.

The further development of East Village is based on five basic principles which should create a vibrant sustainable community:

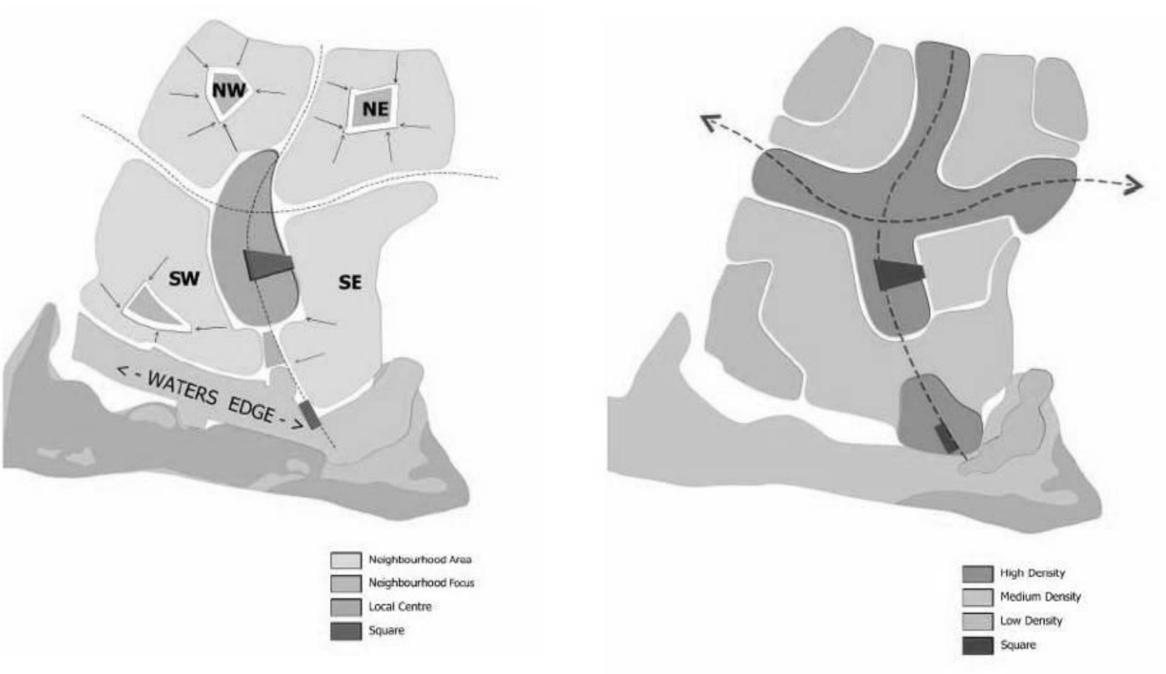
- an innovative transportation system will be implemented across Kent Thameside offering a regular and efficient public transport by the way of Fastrack (less than five minutes walk from a bus stop);
- the transportation system is designed to favour the development of Fastrack (internal lanes will serve the various quarters by forming a loop on which all bus stops will be accessible with a two minute walk);
- compaction is the key concept of East Village to encourage inhabitants to walk to the various community facilities and schools;
- local services, such as public transportation and retail services, and a whole range of varying-density accommodations types, will be supported;
- East Village's landscape will provide viewpoints and ecological links on site.

Three main neighbourhoods will be created in Eastern Quarry (East, West and Central Villages) around a primary layout made of north/south and east/west routes. A series of urban design principles will be applied to offer differing characteristics for each neighbourhood (see Figure 150).

Each neighbourhood is made up of a cluster of building blocks, called "superblocks", with distinctive character areas and 2 minute walk catchments (see Figure 151). The smallest blocks are characterized by dimensions of 60 m by 80 m, offering a safe and secure environment. Two blocks located on the north of the plateau are residential in use; both neighbourhoods have green areas. The south-east block incorporates a school set in a residential area with stepped residential units, which lead south to the wharf at the lake edge. The south-western block has a rather similar structure. The central neighbourhood surrounds a civic square with a variety of uses. The lake edge has a unique character: its landscape provides a pleasant environment for leisure time and walking, with the opportunity to enjoy local wildlife and views of the Eco Zone' (Barton 2006).

The urban density range consists of between 20 and 105 dwellings per hectare (the plot ratio of the Eastern Quarry development is equal to 1), creating a variety in both physical and market terms. The provision of different housing types also contributes to legibility and orientation. Two wide ranging density bands have been used to fit in with these constraints: one within 400 m of a Fastrack stop with at least 60 dwellings per hectare and the other with at least 30 dwellings per hectare.

Figure 152 illustrates the large range of densities planned for the urban site. Low densities are placed around the edge of the neighbourhoods; higher densities are found around the village centre, wharf areas and key routes such as Fastrack. Mixed use blocks are located in the East Village centre and next to the water front (Barton 2006).



DENSITY BANDS

Density	Density Bands (dwellings per hectare)
High	75 d/ha - 105 d/ha
Medium	45 d/ha – 74 d/ha
Low	20 d/ha – 44 d/ha

Figure 151: Eastern Quarry. Superblocks – Neighbourhoods for East Village (left) and density bands for East Village (right).

Source: Barton, W. (2006). Eastern Quarry, East Village and Gateway, Initial Master Plan Proposals and Strategy for Delivery. Reading, Town Planning and Masterplanning Consultancy: 94.

Headlines include:		
Total developable area (PPG 3)	:	30 ha
Total residential floorspace	:	130,000 sqm - 210,000 sqm
Total dwelling numbers	:	Up to 2,001
Highest density	:	105 d/ha
Lowest density	:	20 d/ha
Range of floor areas	:	75 sqm - 150 sqm
Storey heights	:	2-5

Figure 152: Areas plan and budget for East Village (Eastern Quarry)

Source: Barton, W. (2006). Eastern Quarry, East Village and Gateway, Initial Master Plan Proposals and Strategy for Delivery. Reading, Town Planning and Masterplanning Consultancy: 94.

Ebbsfleet Valley offers one of the highest opportunities for urban regeneration that the UK has experienced in decades. Thousands of new dwellings, transport links, schools, medical centres, office buildings, shops, leisure and community facilities will be created from scratch; 400 ha (988 acres) will be devoted to open spaces and parkland (40% of the urban site). The creation of 16, 000 new jobs is foreseen. Personnel for the new office jobs and for the development will be primarily recruited in that region.

4.7.2 Description of 3D digital model

The original 2D architectural plan was conceived by Barton Willmore Company – one of the partners of the Eastern Quarry projects organised by Land Securities– using AutoCAD. The data file was made up of several layers, some of them being linked to the height of buildings; the storey heights were estimated to 3 m. Assumptions were also made on roof slopes; the latter were based on the sketches published in the Master Plan Proposal, the information contained in the 2D architectural plan being insufficient (Barton 2006). However, the sketches published in the Master Plan Proposal were detailed enough for that purpose (see Figure 153). Prior to the 3D computer modelling, this plan had to be cleared up by suppressing all the superfluous layers: only those of the terrain, façades and roofs, necessary for the solar utilization potential assessment, were preserved.

The method used to implement the 3D digital model via AutoCAD (3DFACE command) is described in detail in Chapter 3. The model construction was laborious, as was its translation into Radiance compatible data. As no other digital terrain model was available, the terrain had to be reprocessed so that new buildings could fit into it. East Village's sloped topography was modelled, as a consequence, from a few contour lines and elevations (see Figure 154). Its implementation required the following operations:

- opening the layer entitled Proposed East village contours in another file;
- locking the Proposed East village contours layer to avoid accidental erasures;
- redrawing polylines on the saved contour lines for the same block property;
- raising the contour lines (polylines) by assigning the altitude corresponding to the suggested contours file to each of them (using POLYLINE/thickness command);
- linking together the polylines by triangulation (using 3DFACE);
- storing this data in the proper 3DF_DTM layer;
- suppressing the superfluous Proposed East village contours layers;
- validating the 3D digital model through the rendering of 3DFACE data (using PPF).

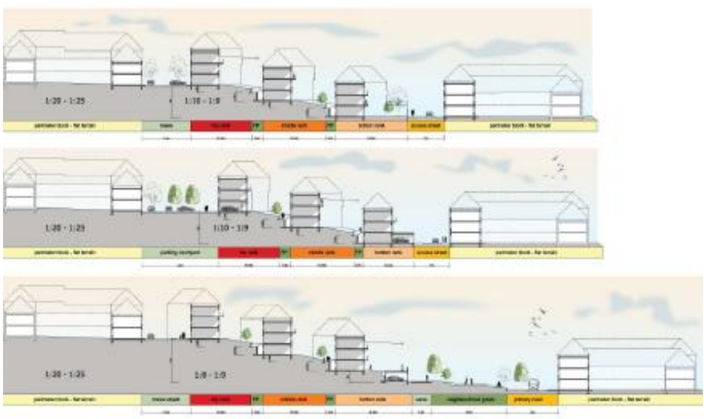


Figure 153 left and right: Axonometry and cross-sections of the "possible" urban development of Eastern Quarry.

Source: Barton, W. (2006). Eastern Quarry, East Village and Gateway, Initial Master Plan Proposals and Strategy for Delivery. Reading, Town Planning and Masterplanning Consultancy: 94.

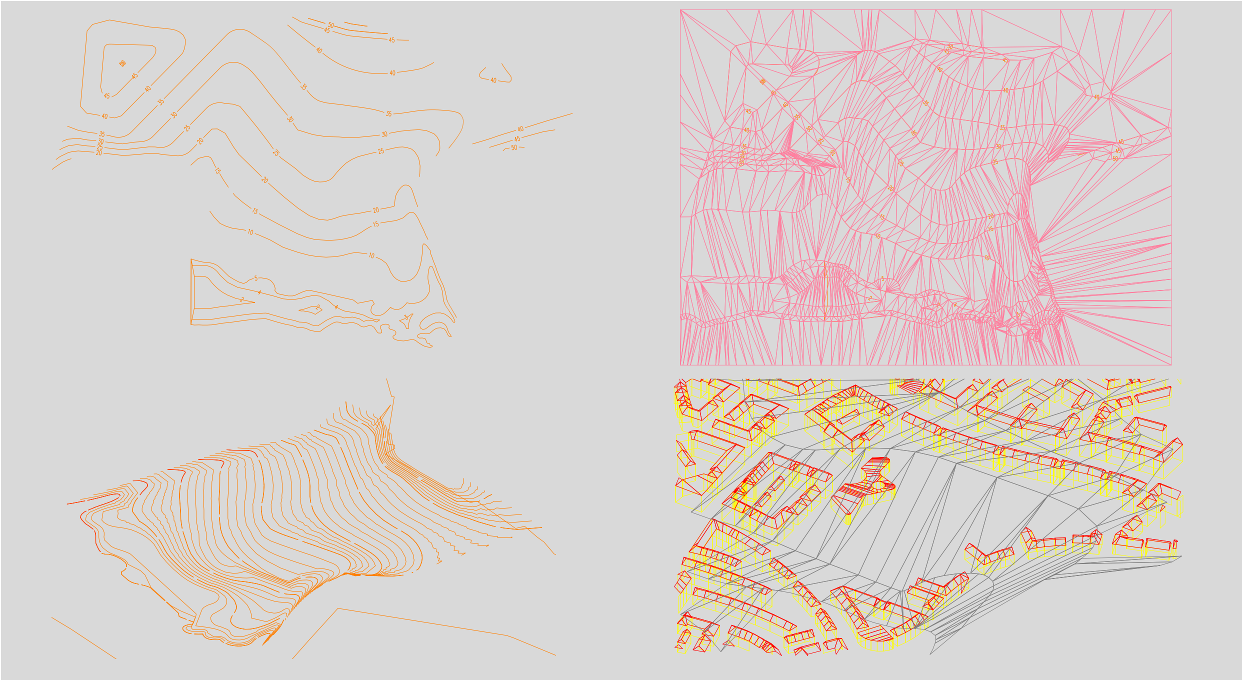


Figure 154: Eastern Quarry topography. Sketch of the terrain with received altitudes (top left), axonometric sketch of the natural terrain (bottom left), 3DFACE of the natural sloped modelled terrain (top right) and 3DFACE perspective of the natural terrain after insertion of the buildings into the natural terrain (bottom right).

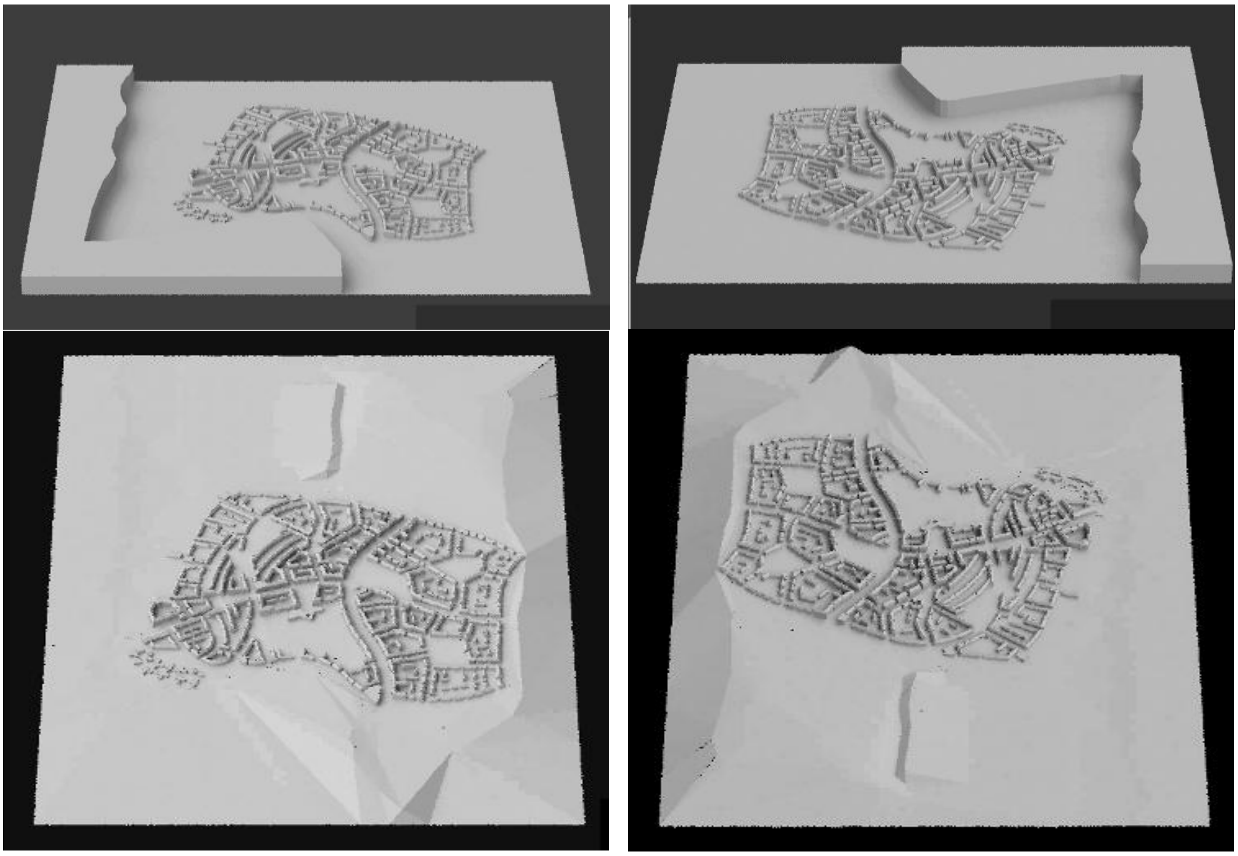


Figure 155: Eastern Quarry with flat topography (with cliff): East view (top left) and West view (top right), Eastern Quarry with sloping topography: East view (bottom left) and West view (bottom right) (RADIANCE renderings).

One of the main difficulties encountered during the modelling operations of Eastern Quarry was the input of the buildings in a sloped topography. In order to facilitate this, buildings were modelled on a flat terrain and raised back manually to an altitude corresponding to the lowest cutting across the terrain. Figure 156 shows 3DFACE modelling stages of the terrain and insertion of the buildings.

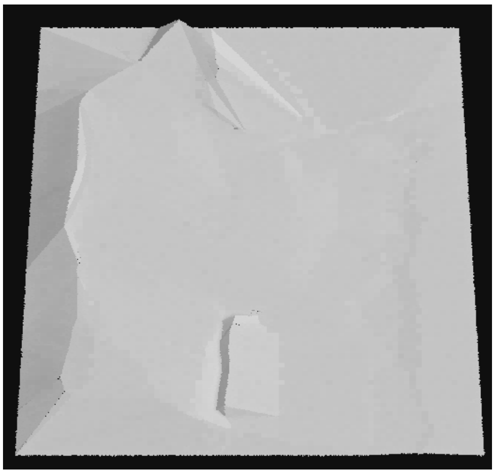


Figure 156: East view of Eastern Quarry topography (RADIANCE rendering).

The PPF software tool required no specific modifications to recognize 3DFACE and layers in building the 3D model (terrain, façades and roofs). This problem had already been solved when the 3D model of Matthaeus, Basel was constructed. Good organisation was important, together with the arrangement of the 3DFACE directly in the appropriate AutoCAD layer (3DF_DTM, 3DF_FASSADEN and 3DF_DACH) to avoid any confusion. 3DFACE objects could be imported using the *get3df* translator. The various tests made using PPF were quickly conclusive.

As Eastern Quarry project was based on a conceptual architectural scheme, its modelling was not very precise: other digital models elaborated in the course of this thesis, such as the projects of Tower Works' site in Leeds, Bellevaux in Lausanne, Les Pâquis 1+2 blocks in Geneva and even Matthaeus in Basel, were definitely more accurate. As the objective of this study was to obtain a reasonable evaluation of the solar utilization potential of this district, the model was deemed to be adequate. Figure 155 and Figure 155Figure 157 illustrate the latter.

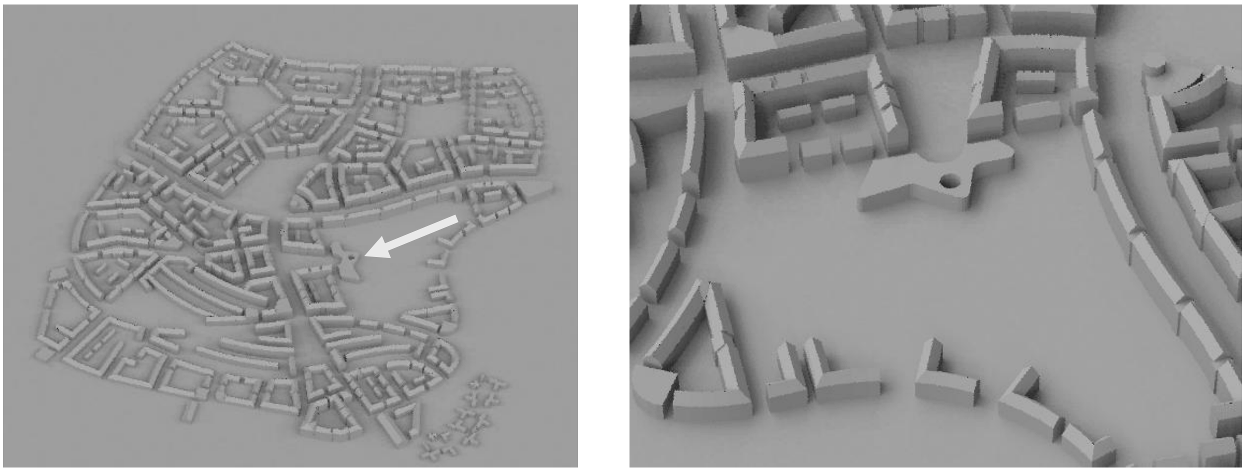


Figure 157 left and right: South view of Eastern Quarry project (top) and zoom of East views (bottom) (RADIANCE renderings).

4.7.3 Solar performance indicators

The general approach adopted within the framework of this study has been to evaluate the gross and useful solar radiation and daylight flux in the Eastern Quarry development. One of the goals was to compare “Eastern Quarry - Flat topography with cliff” with “Eastern Quarry - Flat topography without cliff” to see if the site would have any implications for the availability of solar radiation. Solar potential and daylighting can be interpreted in a number of ways related directly to building energy strategies. The next subsection presents the systems assessed in this study and the minimum threshold values for effectiveness (and economic viability) which were identified and applied in the subsequent analysis.

Using 2,276 heating season degree days for Eastern Quarry, a threshold for passive solar gain of 192 kWh/m^2.year was determined (it is based on the Winter irradiation at which solar gains exceed heat losses through the glazing). It corresponds to the potential of direct solar gain to enter the interior and offset the need for space heating (on average 13% of the space heating demand in the UK housing stock). Assuming an internal required illuminance of 500 lux and a utilisation coefficient of 0.05, typically a vertical opening, an illuminance of 10,000 lux on the façade is taken as the minimum threshold level required to achieve useful indoor illuminance levels. Achieving “useful illuminance levels inside” means gaining sufficient daylighting to offset the need for electric light.

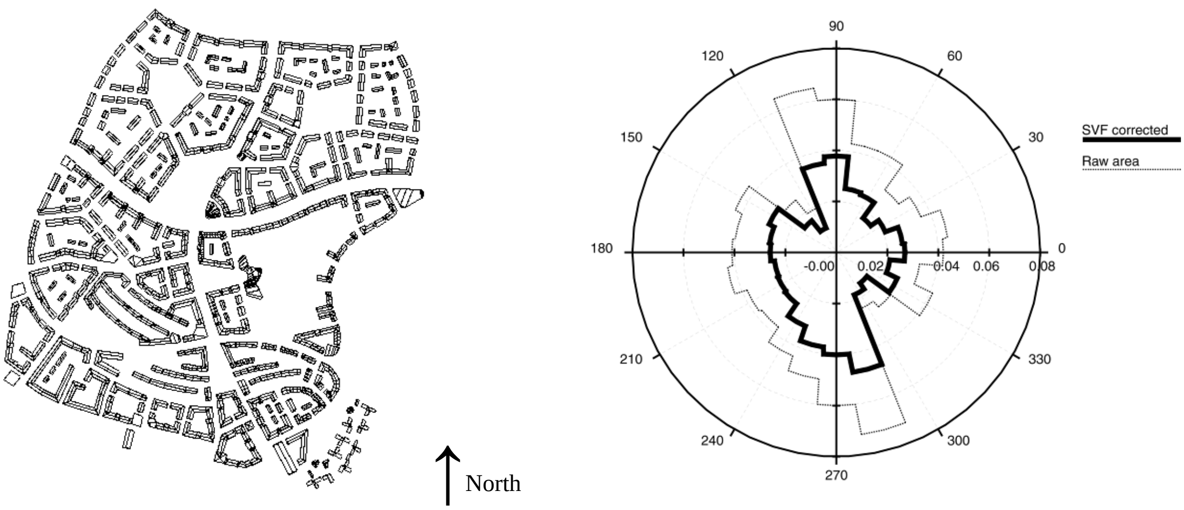


Figure 158: Layout plan of the Eastern Quarry development (left) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (right).

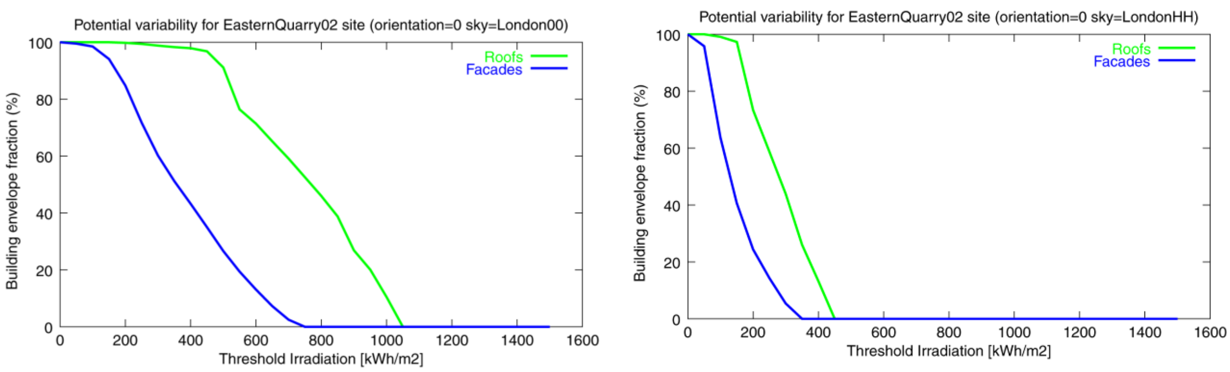


Figure 159: Cumulative distributions characterising the façades’ solar irradiation of the Eastern Quarry development. Annual solar irradiation serves to assess the potential for building integrated photovoltaic systems and solar thermal collectors (left); heating season irradiation serves to assess the potential for passive solar heating techniques (right).

For solar thermal collectors the lower figures of 400 and 600 kWh/m^2.an were applied for façades and roofs respectively, owing to the generally reduced costs for these types of collectors. Regarding photovoltaics (BiPV), thresholds of 800 and 1,000 kWh/m^2.an were applied for vertical façades and roofs respectively (i.e. to generate electricity locally to offset lighting and small power demands). The simulation was conducted using the typical annual sky conditions of London in Winter (Steemers, Montavon et al. 2007).

Layout of the urban site

The orientation rose does not reveal any predominant direction for Eastern Quarry (see Figure 158). This means that the façades occupy the four quadrants regularly with a slight predominance of 1% for the direction South-West: the North-East sector contains 26% of the façades, the North-West sector 23%; the South-West sector 27% and the South-East sector 24%. The Sky View Factor (SVF) corrected surface show that the façades are obstructed at the rate of 37%, which is a considerable amount for new construction. The most obstructed façades are located in the North-East sector (28%) and the least obstructed in the South-East sector (23%). As for the South-West and North-West sectors, they are obstructed at the rate of 24% and 25% respectively. The squares that enhance the area of the four neighbourhoods reduce the percentage of obstruction, which without them would certainly be higher.

Sensitivity of solar potential

The variation of the different potentials according to the threshold values is shown on the cumulative distributions in Figure 159. As already explained in Section 3.3.1, current technical limitations as well as economic factors have been taken into account in establishing the threshold. Roofs are generally located at a height that does not vary greatly between neighbouring buildings. This means they have a good view of the sky vault and shadowing effects are limited. Consequently, the potential for solar energy collection on roof areas remains less affected by the urban texture. On the other hand, neighbouring buildings largely affect façades (Compagnon 2004). In the existing situation, however, the Winter curve reveals fairly rapidly a strong decrease, which tends to confirm that certain roofs are shaded during the wintertime: an initial rift is located immediately after 400 kWh/m^2, another one at 500 kWh/m^2 and a third just before 600 kWh/m^2. At this stage, 71.4% of the roofs would benefit from a solar thermal collector, which is significant but still far from the optimum. The Winter curve decreases abruptly starting from 150 kWh/m^2; at 600 kWh/m^2 no more roof area is able to benefit from solar energy. So, the potential for solar energy collection on roof areas remains less affected by the actual urban texture. On the contrary, neighbouring buildings mostly affect the façades. In both cases, the curves decrease rapidly starting from 200 kWh/m^2 annually and starting from 50 kWh/m^2 in Winter.

Overall daylighting performance and solar potential

The calculations (see Table 30) indicate that 35.2% of the façades can potentially exploit passive solar gains in Winter, 49% of the façades will receive a good level of daylighting throughout the year and only 24.7% in Winter. As far as solar thermal collectors are concerned, 71.4% of the roof area and 43.2% of the façades are suitable for solar hot water production. Solar photovoltaic panels show less potential, with only 10.5% of the roofs' surfaces and zero for the façades.

Studies of two different configurations

Apart from the effect of the solar potential of the proposed topography, a comparative analysis was also carried out on two differing configurations:
- "Eastern Quarry -Flat topography with cliff";
- "Eastern Quarry -Flat topography without cliff".

Table 30: Summary of results for “Eastern Quarry -Flat topography with cliff”and “Eastern Quarry -Flat topography without cliff”

Eastern Quarry	**Daylighting viability**		**Passive solar viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Façades (Winter)**	**Façades (Winter)**	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Proposed topography	49%	24.7%	35.2%	71.4%	43.2%	10.5%	0%
Flat topography with cliff	43.1%	17.9%	27.7%	71%	36.6%	3.1%	0%
Δ Sloped - Flat with cliff	**5.9%**	**6.8%**	**7.5%**	**0.4%**	**6.6%**	**7.4%**	0%
Proposed topography	49%	24.7%	35.2%	71.4%	43.2%	10.5%	0%
Flat topography without cliff	43.5%	18.7%	4.5%	71.4%	37.4%	7.6%	0%
Δ Proposed - Flat without cliff	**5.5%**	**6%**	**30.7%**	**0%**	**5.8%**	**2.9%**	**0%**

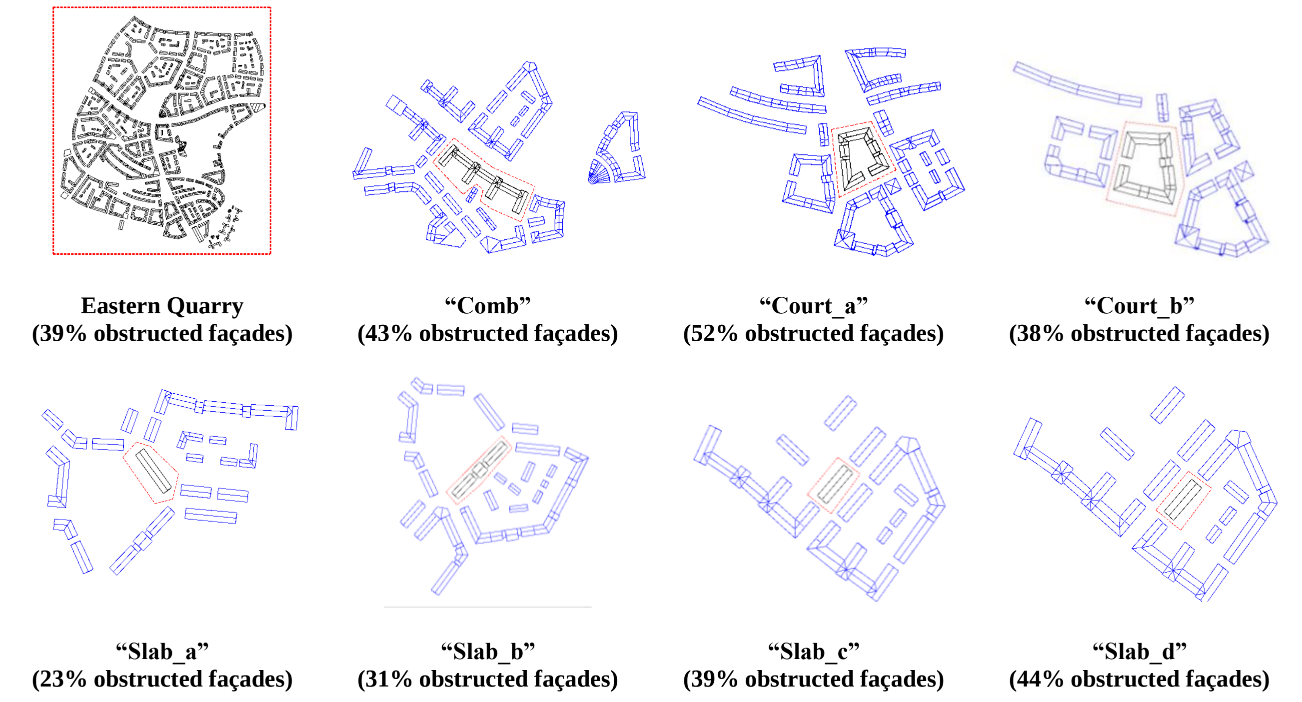


Figure 160: Sample of seven built forms selected for comparative studies. From top left: “Comb”, “Court_a”, “Court_b”, “Slab_a”, “Slab_b”, “Slab_c” and “Slab_d”.

Source: Steemers, K., Montavon, M. et al. (2007). Testing the masterplan. An environmental assessment of the Eastern Quarry development proposal in Ebbsfleet Valley. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge: 35.

The latter include the same buildings in order to see if the cliff would have any influence on the availability of solar radiation. "Eastern Quarry - Flat topography with cliff" consists of a flat site with quarry cliffs, "Eastern Quarry - Flat topography without cliff" is modelled entirely on a flat site (see Figure 155).

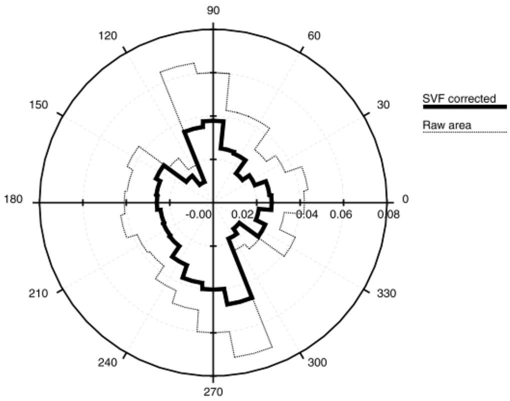
The results of "Eastern Quarry -Flat topography with cliff" show that the proposed graduation of the site up to the north has a positive effect. This is more significant for Winter solar availability on south-facing façades, increasing the passive solar potential from 27.7% to 35.2% of the façades. Over the year the slope increases the daylighting potential from 43.1 to 49 % and from 17.9 to 24.7% in Winter. Active solar roof area remains largely unaffected by the changes in slope, in contrast to the façades which move from 36.6% to 43.2%. The solar photovoltaic panels show more potential with the proposed topography (+7.4% increase).

The potential of "Eastern Quarry -Flat topography without cliff" is almost invariably lower than the one of "Eastern Quarry -Flat topography with cliff". This means that the slope of the site has a positive influence on the various solar strategies excepting passive solar gains in Winter. In conclusion, the buildings that are erected on a sloping site remain less affected by the urban texture, which means they have a better view of the sky vault and that shadowing effects are limited: the sloping site significantly favours the solar potential and daylighting of the buildings.

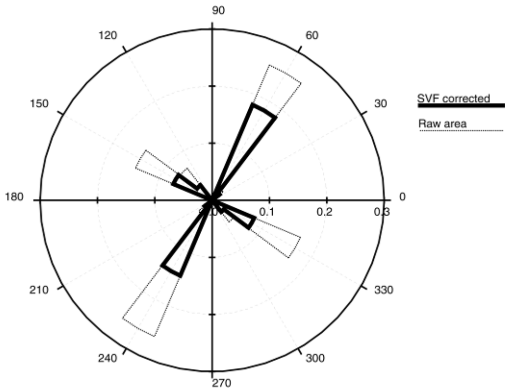
Built form potential

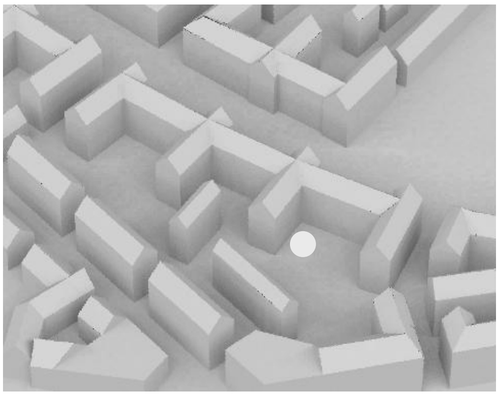
For closer analysis, seven typical building blocks – such as a comb configuration, courtyard or linear block – were selected for comparative investigations. The purpose was to explore the role of built form parameters – in terms of shape, compactness index, orientation and level of surrounding obstructions, etc. – regarding their solar potential. The seven urban forms are shown in Figure 160 to Figure 163. Table 31 and Table 32 show the corresponding detailed simulation results ("Comb", "Court_a", "Court_b", "Slab_a", "Slab_b", "Slab_c" and "Slab_d").

Figure 161: Location of the seven built forms selected for detailed study.

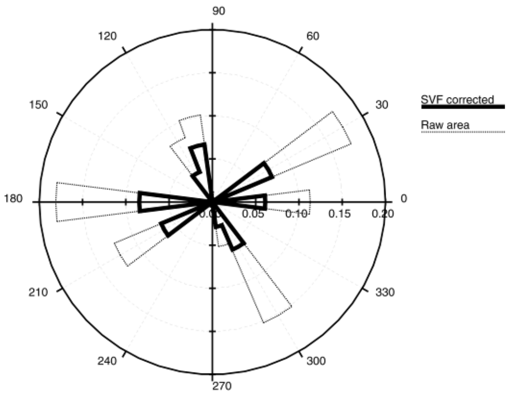


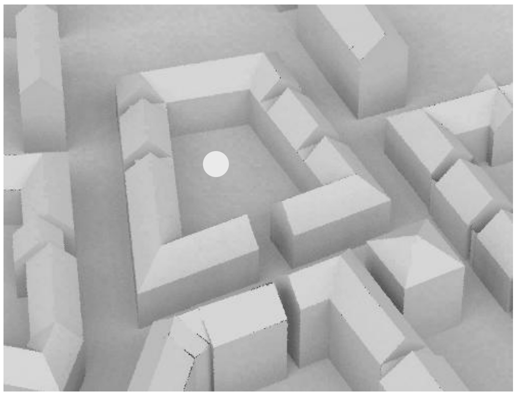
Eastern Quarry development



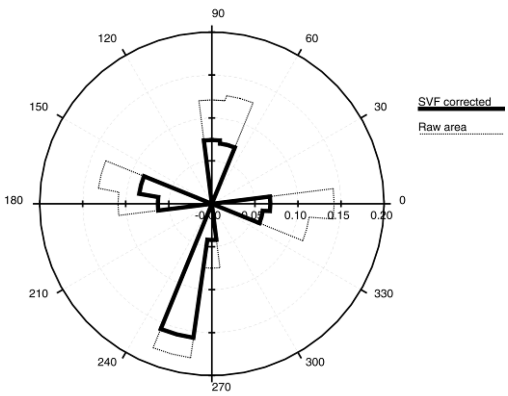


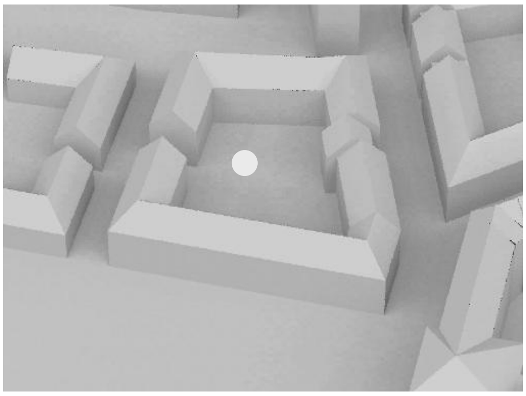
“Comb”





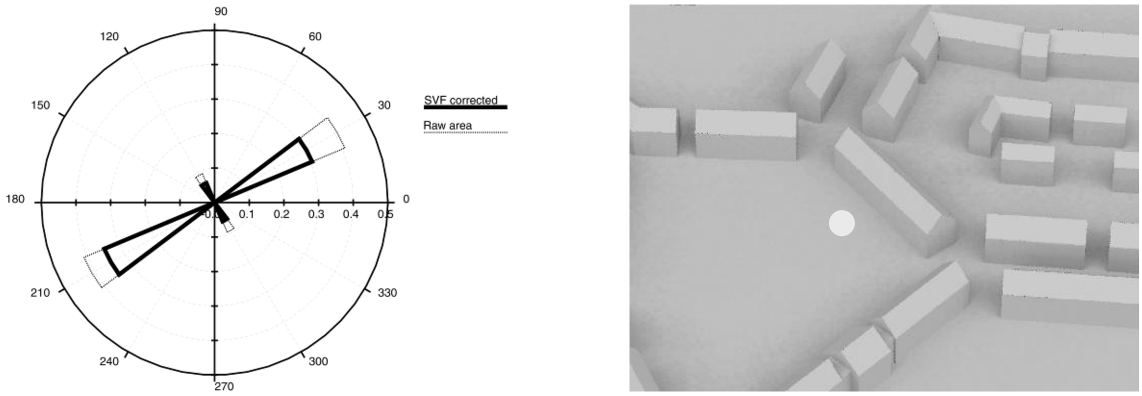
“Court_a”



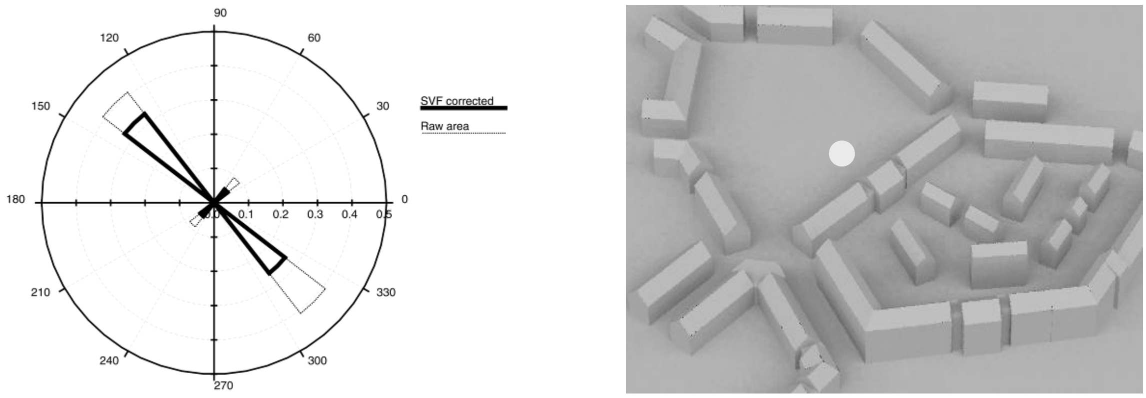


“Court_b”

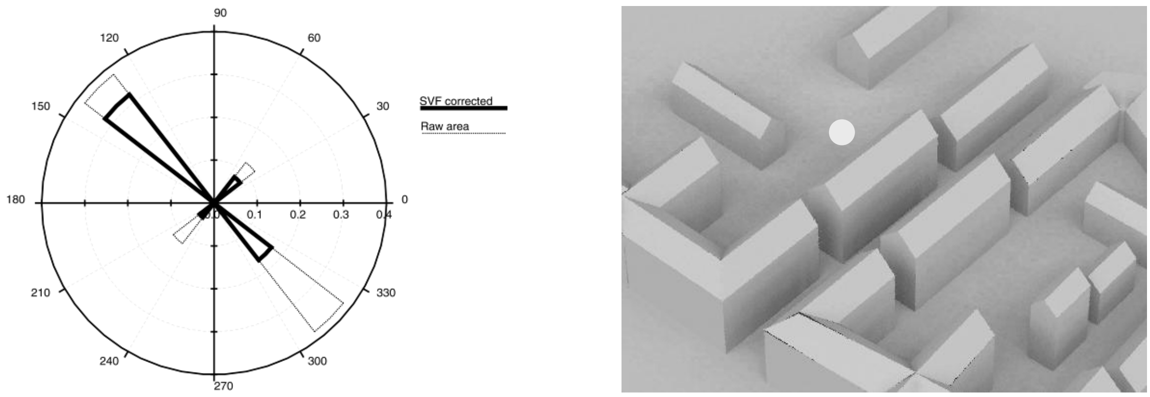
Figure 162: Illustration of the orientation roses of the seven analysed built forms (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (left) and visualisations of built forms (right) (RADIANCE renderings).



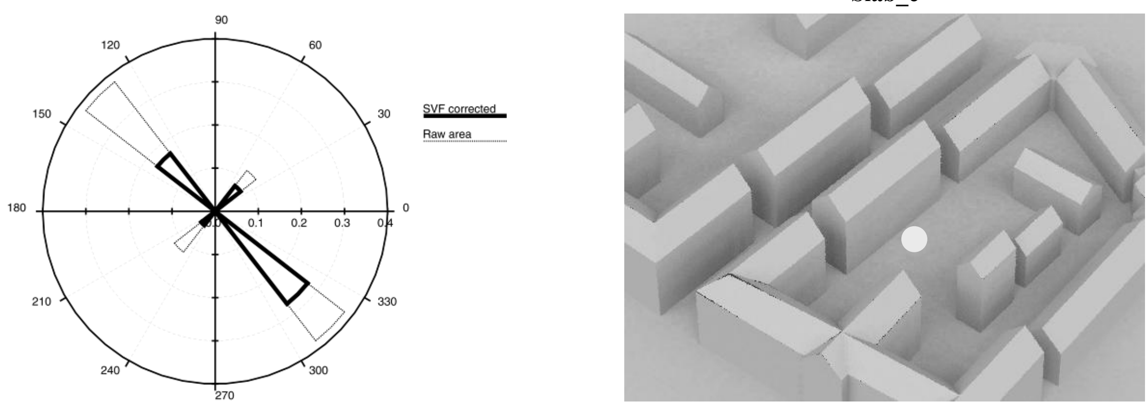
“Slab_a”



“Slab_b”



“Slab_c”



“Slab_d”

Figure 163: Illustration of the orientation roses of the seven analysed built forms (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (left) and visualisations of built forms (right) (RADIANCE renderings).

Table 31: Comparison of percentage of surfaces available for energy exploitation for a range of selected built forms in the proposed development

Eastern Quarry	Daylighting viability		Passive solar viability	Solar thermal viability		BiPV viability	
	Façades (annual)	Façades (Winter)	Façades (Winter)	Roofs (annual)	Façades (annual)	Roofs (annual)	Façades (annual)
Eastern Quarry	49%	24.7%	35.2%	71.4%	43.2%	10.5%	0%
“Comb”	35.9%	14.2%	23.7%	71.1%	27.4%	0%	0%
“Court_a”	27.8%	4.4%	8.7%	71.5%	17.3%	0.9%	0%
“Court_b”	41%	20.5%	26.3%	74.9%	35.7%	13.3%	0%
“Slab_a”	53.6%	45.3%	49%	92.9%	50.2%	0%	0%
“Slab_b”	47.8%	21.1%	35.6%	84.5%	43.2%	0%	0%
“Slab_c”	18.2%	1.6%	7.4%	89.6%	12.4%	0%	0%
“Slab_d”	40.2%	17.4%	28.1%	73%	37.6%	0%	0%

On the whole, the terraced block “Slab_a” has the greatest potential of the seven configurations studied: its irradiation per external surface is the largest compared to the other buildings, as well as its irradiation per floor area. Its orientation rose shows that the façades are mainly oriented South-West/North-East with a slight predominance for the South-West, and that they are only obstructed by height at 23%. In addition, “Slab_a” has the best compactness index. It is customary in England to build multifamily housing but on one or two levels, so that the compactness of a building is the essential element in controlling energy consumption. The rarity of surrounding obstructions partly explains its good performance, in spite of a main rear façade with a North-East orientation (and by definition an equivalent set of South-West façades). This is followed by a South-East/North-East facing terrace “Slab_b” despite of some obstructions (31%).

The terraced block “Slab_c” has the worst potential, in spite of its medium compactness (4th position). Its orientation rose shows that the façades are fairly divided between the North-West and the South-East and that they are obstructed at a height of 39% (i.e. the same value that the Eastern Quarry development). The courtyard configuration “Court_a” has façades obstructed up to 52% (13% more than “Slab_C”) and in spite of that, its results are superior to “Slab_C”; this is also true for the façades of “Court_b” which are obstructed to a height of 39%. On the other hand, the orientation rose of “Court_a” has six points, which means that the façades occupy the four quadrants with a strong predominance for the South-East and North-West directions. As a result, some living areas have a very good solar potential and others less so; this tends to “even out” the results.

The courtyard configuration “Court_b” (38% obstructed façades) with a southern façade overlooking the lake (and facing the quarry cliff) also performs quite well: this is due to the fact that it has a fairly large and unobstructed façade facing nearly due south. The southeast facing terrace “slab_d” follows it, despite some obstructions to the South-East and North-West. The terraced block “Slab_b” (31% obstructed façades) is approximately representative of the site’s overall solar potential in terms of area available for passive and active solar technologies.

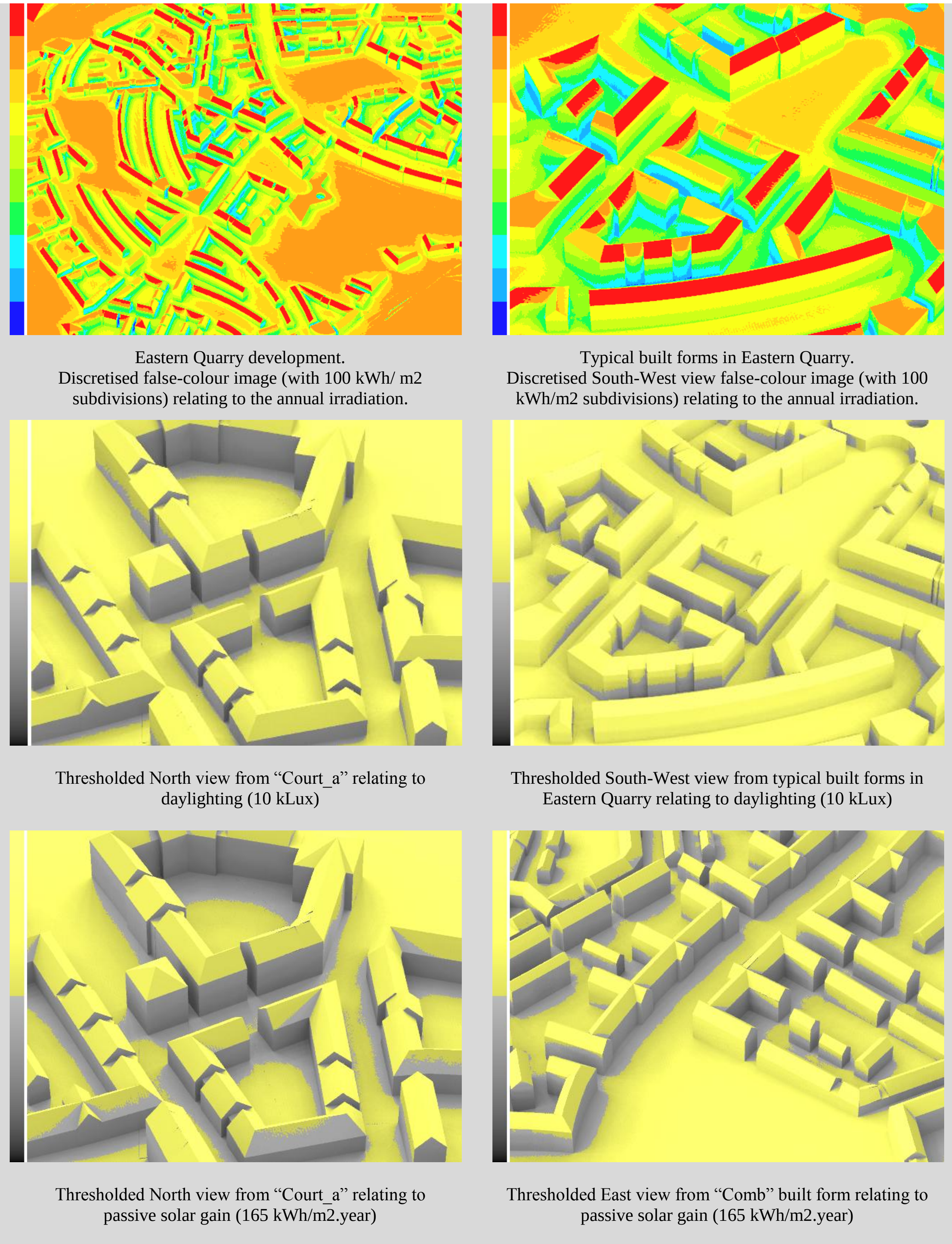
Table 32: Comparison for a range of selected built forms in the proposed development

Eastern Quarry development	Eastern Quarry	Comb	Court_a	Court_b	Slab_a	Slab_b	Slab_c	Slab_d
Obstructed façades (%)	39	43	52	38	23	31	39	44
Compactness index (Envelope area/Volume)	0.314	0.288	0.335	0.323	0.359	0.345	0.344	0.333
Annual irradiation (MWh)	205494	3639	2029	2533	854	1336	638	661
Envelope area (m^2)	400759	7973	4530	4932	1488	2565	1535	1515
Volume (m^3)	1272705	27633	13492	15262	4140	7419	4457	4457
Raw floor area (m^2)	385048	8556	4014	4505	1225	2245	1380	1380
Covered ground area (m^2)	100930	1588	1213	1350	367	668	258	258
Irradiation per external surface (kWh/m^2)	512	456	447	513	573	520	415	436
Irradiation per floor area (kWh/m^2)	533	425	505	562	697	595	462	479

Balance of Eastern Quarry analyses

Overall, the total useable solar irradiation that falls on the façades and roofs equates to 533 kWh/m^2 of raw floor area (15 kWh/m^2.year is the maximum consumption for heating per square metre per year for a passive house). This theoretically meets the demands of an energy efficient house. It can be seen from the thresholded images relating to photovoltaics that the southern sloping roofs offer a certain potential for BiPV (10.5%) (see Figure 164 and Figure 165). However, the technical viability (not to mention the economic viability) of the photovoltaic systems is weak.

Of the overall illuminance, more than twice the intensity falls on average on the roofs compared to the façades. Solar domestic hot water has a weak potential over the year because the North and East façades receive a low amount of solar radiation and because their potential is nil during the Winter. On the other hand, the slopes of the roofs with a South, West and East orientation perform annually much better than the façades (71.4%). Passive solar is viable up to 35.2% for all blocks in Winter; the best performance are for those buildings showing unobstructed façades facing South-East or South-West.



Eastern Quarry development.
Discretised false-colour image (with 100 kWh/ m2 subdivisions) relating to the annual irradiation.

Typical built forms in Eastern Quarry.
Discretised South-West view false-colour image (with 100 kWh/m2 subdivisions) relating to the annual irradiation.

Thresholded North view from “Court_a” relating to daylighting (10 kLux)

Thresholded South-West view from typical built forms in Eastern Quarry relating to daylighting (10 kLux)

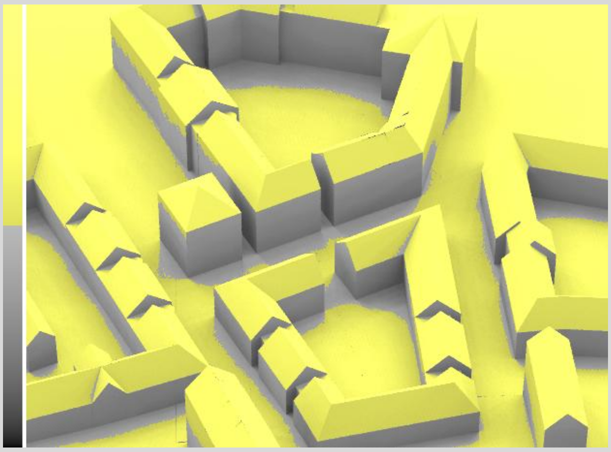
Thresholded North view from “Court_a” relating to passive solar gain (165 kWh/m2.year)

Thresholded East view from “Comb” built form relating to passive solar gain (165 kWh/m2.year)

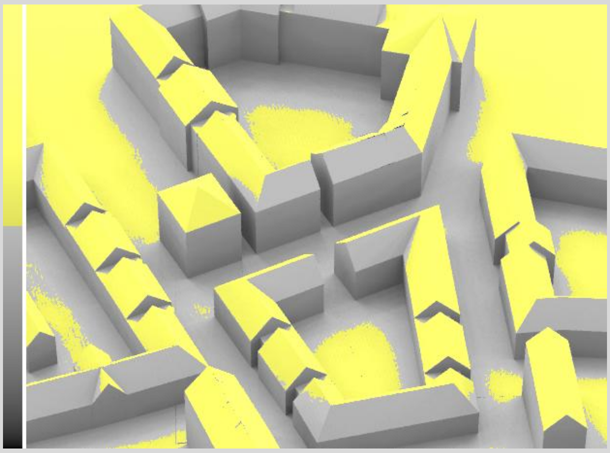
Figure 164: Eastern Quarry. False-colour images and thresholded images using a Boolean filter.

Thresholded South-West view relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)

Thresholded South-West view relating to roof-integrated solar thermal collectors (600 kWh/m^2.year)

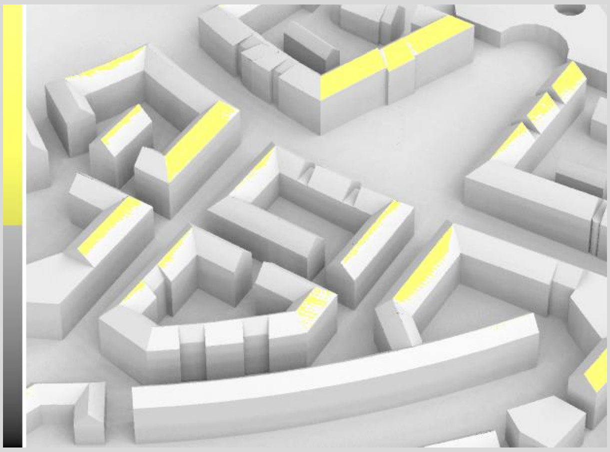


Thresholded North view from “Court_a” relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)



Thresholded North view from “Court_a” relating to façade-integrated solar thermal collectors (400 kWh/m^2.year)

Thresholded South-East view relating to roof-integrated BiPV (1000 kWh/m^2.year)



Thresholded South-West view relating to roof-integrated BiPV (1000 kWh/m^2.year)

Figure 165: Eastern Quarry. Thresholded images using a Boolean filter.

4.8 Barra Funda and Luz districts, São Paulo, -23.53 latitude (Brazil)

One of the main goals of the research project *Sustainable Urban Spaces. A Case Study in São Paulo, Brazil*, was to assess the daylighting and solar potential of Barra Funda and Luz (see Figure 166 and Figure 167). Barra Funda and Luz are two districts in the centre of São Paulo in Brazil; they will undergo extensive transformation in the foreseeable future (Cheng, Steemers et al. 2006; Cheng, Steemers et al. 2006). Rapid urbanization in recent years has exerted tremendous pressure on the urban development of São Paulo.

São Paulo is now one of the biggest metropolitan areas in the world with a population of about 18 million. Its polluted, tropical-like climate is subject to a wide range of urban microclimates, depending on the occupation patterns and topography of the site: these microclimates are topics of interest for wide research programmes. Sprawling over a high rise and high density urban development, São Paulo is characterized by unbridled town planning, interspersed with housing for poor people (*favelas)*. To cater to the expanding urban population, densification seems to be an inevitable outcome. In this respect, Barra Funda and Luz have an advantageous potential.

Figure 166: Barra Funda district.

Source: Steemers, K. et al. (2005). *Sustainable Urban Spaces: a case study in São Paulo, Brazil*. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

Figure 167: Luz district.

Source: Steemers, K. et al. (2005). *Sustainable Urban Spaces: a case study in São Paulo, Brazil*. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

4.8.1 Description of case studies

Barra Funda and Luz districts are two sites of different morphological layout located near the city centre of São Paulo. They are situated along the railway, where the urban centre regeneration is a socioeconomic and environmental objective (see Figure 168). Barra Funda's urban planning project aims at the creation of a new community within an obsolete industrial area; as a consequence, the project comprises interventions at certain points in a consolidated urban fabric. Urban infrastructures that to a certain extent have mixed uses were already settled there.

Barra Funda's obsolete industrial zone (see Figure 169) is located in an area classified by the local government as one of the sites for the *Operações Urbanas*: a process whereby parts of the city are selected for substantial interventions and modifications of its urban configuration in order to achieve economic and social objectives through public and private partnerships (PPP). The same area was chosen for a national design competition, held in 2004 and promoted by the Municipal Administration of São Paulo and the Brazilian Institute of Architects/ (BIA) in order to create the *Bairro Novo* (New Neighbourhood). The goal of the competition was to build up a new urban fabric with more public amenities and facilities, including an improved landscape (Duarte and Gonçalves 2006).

Figure 168: Aerial photo of São Paulo. Barra Funda (left) and Luz (right) districts.

Source: Steemers, K. et al. (2005). *Sustainable Urban Spaces: a case study in São Paulo, Brazil*. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

Figure 169: Aerial photo of Barra Funda.

Source: Steemers, K. et al. (2005). *Sustainable Urban Spaces: a case study in São Paulo, Brazil*. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

The area of Barra Funda is located within the Água Branca district on the western side of São Paulo, 5 km (4.34 miles) from the city centre. It is crossed by a main railway line and stretches to the edge of the Tietê River, encompassing 107 ha (264.4 acres). Barra Funda Station is the second largest public transport station in the city and is located in the centre of the site. Public access from other locations of the city, as well as from the metropolitan area, is facilitated by different means of transportation. Places and buildings assigned to culture and leisure activities are major points of interest: SESC Pompéia; Casa das Caldeiras; Memorial da América Latina and Água Funda Park. In 1991 the population of Barra Funda was close to 16,000 people, but fell to a figure closer to 13, 000 in the year 2004, resulting in an annual negative growth rate (-1.7% per year) and an urban density of 21 persons/ha (1 hectare = 2.5 acres). This extremely low density for such an urban site can be explained by the past history of this area since 1960.

The urbanisation process of the northwest region of Brazil started with the introduction of the railway and the development of industrial activities. The immediate effect on the urban configuration was the formation of relatively large sites in order to accommodate industrial buildings and warehouses. In the sixties, a national economic “boom” had a large impact on the decline of the area. The demand for larger industrial sites led to the building of factories at the outskirts of the city: this trend was supported by a shift in the key transportation network from railways to roads. Following the relocation of these industries, many old warehouses and industrial buildings were demolished; others were simply deserted, turning the area into a brown field, where pedestrians’ mobility and comfort were compromised. However, 34% of the local income is still associated with industrial activities, 64% with commerce and services and 2% with the construction industry.

A range of different urban occupation patterns, crossed by busy major roads, is shaping the urban environment: blocks of old warehouses, isolated tall buildings, a central three-storey transport interchange station, clusters of low density residential blocks, big car parks, open spaces by the side of the railway lines, hard landscaped public spaces and the Àgua Funda Park (the only significant green area in the neighbourhood).

However, the site does offer possibilities for environmental regeneration: it could be a showcase for other typical brown field sites in the city. The Latin American Square, designed by Niemeyer in the 1990’s, is the second largest public space in Barra Funda. It is located close to the railway station, in the middle of the area and is characterized by a lack of greenery and by shading, hard surface pavement and barriers all around. However, due to the existing relationship between the use of public space and environmental conditions, the occupation of the Latin American Square is compromised by its harsh environment (Duarte and Gonçalves 2006).

The Luz district (see Figure 170) is located on the north side of the city centre, close to the Estação da Luz railway station. The latter was built in the 19th century as the headquarters of the newly founded São Paulo Railway. In the first decades of the 20th century, it was the main entranceway to the city. This gave it a major economic relevance, because most of the coffee from Santos was delivered to the station, together with imported goods. In 2004, the population of Luz was close to 26,000 people with an urban density of 61 persons/ha. This is an extremely high density compared to Barra Funda (+40 persons/ha).

The district of Luz became attractive when the Mayor’s Office announced that this area ought to be primarily devoted to public use. The official master plan included the demolition of buildings, which cover an area of 105,000 m^2 (25.94 acres) and new open public areas insuring a better access to solar energy, daylight and natural ventilation for existing buildings in case of refurbishment. One of the objectives of the official master plan was to improve the environmental quality for people living in the area and to achieve a better social mix; it had to provide more sustainable solutions in an urban context by promoting mixed-usage development.

Figure 170: Aerial photo of Luz.

Source: Steemers, K. et al. (2005). *Sustainable Urban Spaces: a case study in São Paulo, Brazil*. Cambridge, The Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

The *Nova Luz* urban operation, which was started in 2005, involved approximately 225 hectares (556 acres) in the area. Tax incentives in line with specific regulations favoured the settling of technology companies and other services.

Nova Luz urban planning was criticized by urban planners, such as Nada Somekh, the Polis Institute[59] and others, for the reason that by granting tax incentive subsidies to companies that did not really need them, they were depriving the inhabitants of this central district who would eventually be expelled.

4.8.2 Description of 3D digital models

The 3DFACE digital models of Barra Funda and Luz districts are based on a computer SOLID 3D format representation of the urban site set-up using AutoCAD by students of the Faculty of Architecture and Urbanism at the University of São Paulo (FAUUSP): the latter was a partner of the *Sustainable Urban Spaces: a case study in the São Paulo* project.

These SOLID 3D format models include redundant information layers which were not really useful for the solar potential assessment. Moreover, the digital model was not directly usable as the PPF software was unable to read the SOLID 3D format. Creating a new 3D model of the site was easier than writing an appropriate translator for PPF or modifying the SOLID 3D formatted files in order to make them readable as text files (readable in text mode). In this format, a solid represents the volume of an object; this is an easier 3D model type to handle thanks to the information provided with it. Solid (or volumetric) objects are closed which means that inside and outside domains can be clearly distinguished. Solid objects can undergo addition, subtraction and intersection operations to form more complex solid objects. The latter are far easier to build and to handle than wireframe or mesh models (see Figure 171 and Figure 172).

[59] "*Polis – Social Policies Studies, Training and Advisory Institute is a Non-Governmental Organization active throughout Brazil, incorporated as a non-profit, non-partisan, pluralistic civil society organization, recognized as being of public utility at the local government, state and federal levels. Founded in 1987, it has been closely identified with issues related to cities and activities in the field of public policies and local development. Exercise of citizen's rights, as a democratic achievement, is the central theme linking its different activities aimed at constructing cities that are just, sustainable and democratic*".
Source: [online] URL: http://www.polis.org.br/default_en.asp (Consulted on April 4, 2008).

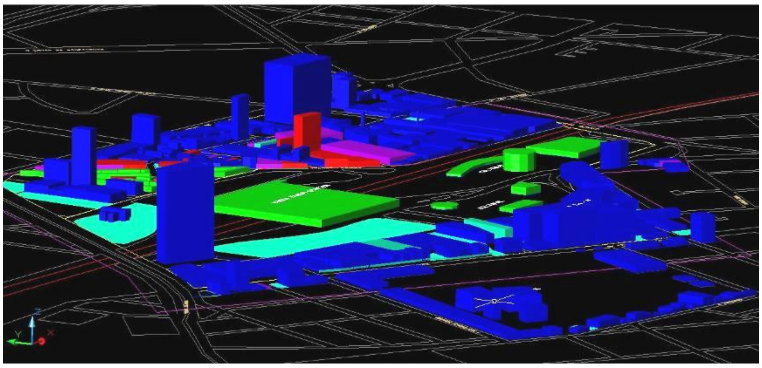


Figure 171: Barra Funda district modelled on AutoCAD in SOLID 3D (AutoCAD rendering) ©FAUUSP.

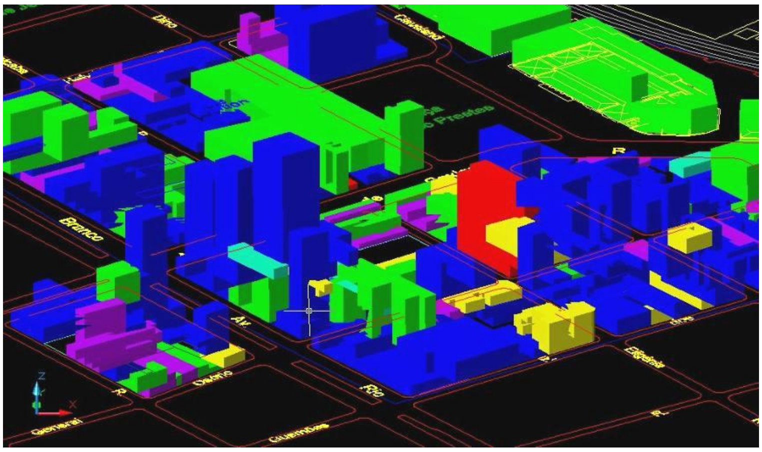


Figure 172: Luz district modelled on AutoCAD in SOLID 3D (AutoCAD rendering) ©FAUUSP.

However, it was still necessary to transform the considered SOLID 3D digital model into a corresponding 3DFACE formatted file (accounting for all façades and roofs): this was done by hand using AutoCAD. In order to achieve this objective the original file had to be “cleared” by suppressing all layers excepting those of the terrain, façades and roofs, which are necessary for the solar utilization potential assessment. The SOLID 3D outlined buildings served as a base model for the transformation into 3DFACE facets. The corresponding objects were simply laid over the original buildings’ volumes like a skin. The hand drawing of 3DFACES facets on these volumes required a constant anticlockwise turning in order to provide the appropriate external façade and roof orientations (surface normal vector) and to allow PPF software to recognize them. Such a model is shown on Figure 173.

The PPF software tool required no specific alterations to recognize 3DFACE and layers for the creation of the 3D model (terrain, façades and roofs). This problem was overcome when the 3D model of Matthaeus, Basel was launched. To avoid confusion, good organisation was important, together with the arrangement of the 3DFACE directly in the appropriate AutoCAD layer (3DF_DTM, 3DF_FASSADEN and 3DF_DACH); 3DFACE objects were imported using the *get3df* translator. The various tests made using PPF were quickly conclusive.

The two urban districts of Barra Funda and Luz are large: to achieve highly accurate modelling of the latter was difficult. The height of the buildings storeys was estimated by on- site visits and photography carried out by the FAUUSP students. However, volumes were simplified and roofs were considered as being flat. The process was similar to the other digital models created in the course of this thesis, such as the Tower Works project’s site in Leeds, Bellevaux in Lausanne, Pâquis 1+2 blocks in Geneva and Matthaeus in Basel. The objective was to obtain a first evaluation of the solar utilization potential of these Brazilian districts. As most of the buildings in the Barra Funda and Luz districts have flat roofs, the results achieved in this study can be considered to be sound and representative enough to draw a first set of conclusions regarding the overall solar performance of typical Brazilian districts.

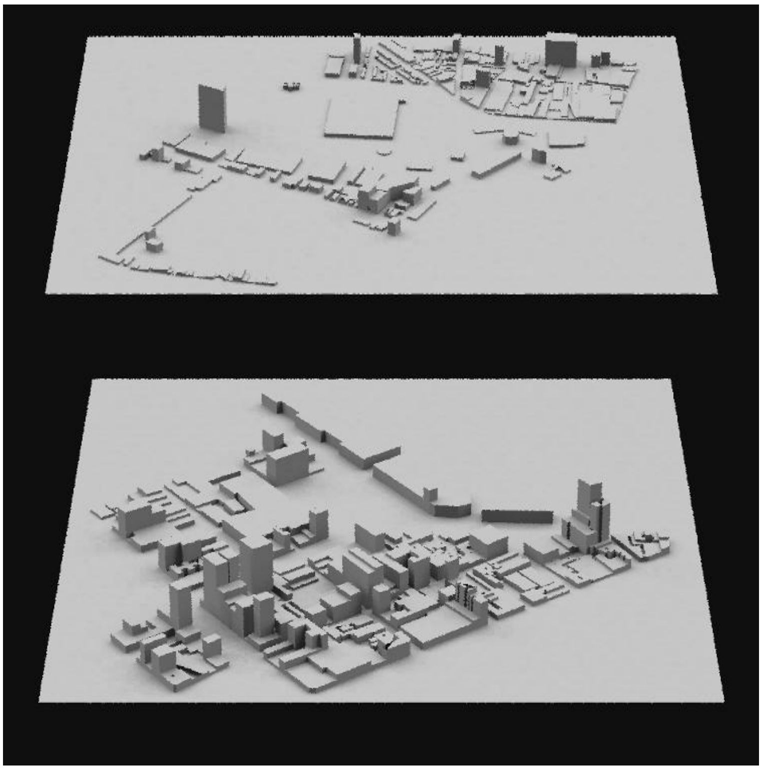


Figure 173: South view of Barra Funda district (top) and south view of Luz district (bottom) (RADIANCE renderings).

4.8.3 Solar performance indicators

Evaluations were made of the available solar radiation in the Barra Funda and Luz districts, as well as of the eleven existing urban blocks in Luz. They made it possible to compare the gross and useful solar radiation and daylight flux in these two districts. The diverse influences of built density on daylight access and the potential of two solar systems were also considered.

The daylight simulation was carried out under CIE Standard Overcast Sky conditions and solar potential under typical São Paulo sky conditions. Assuming an indoor required illuminance of 500 lux and an utilisation coefficient of 0.05 – typical of a vertical opening – it corresponds to the façade fraction which receives an average annual illuminance of 10,000 lux or more. For solar thermal collectors figures of 400 and 600 kWh/m^2.year were used for façades and roofs respectively. Thresholds of 800 and 1,000 kWh/m^2.year were used respectively for photovoltaics (Compagnon 2004).

Layout of the urban sites

Figure 174 shows the orientation roses of the Barra Funda and Luz districts. The two drawings are completely different, which is not surprising given that the urban morphology of these two districts is so distinctive. The appearance of the Barra Funda rose is difficult to characterize: all directions are represented with a strong predominance for the South-West direction where one branch that is veering slightly towards the South breaks away from the others. Globally, the South-East sector represents 27% of the raw area, the North-West 26%, the South-West 24% and the North-East 23%. The appearance of the Luz rose is much clearer and above all less "jagged" than the Barra Funda one. The four directions North-East (27%), North-West (22%), South-West (27%) and South East (24%) are represented. If the two sectors North-East and South-West occupy the same number of façades area, the obstructions for the South-West sector are more conspicuous than for the North-East sector. From the Sky View Factor (SVF) corrected surfaces, one can observe that façades are obstructed at the rate of 23.6% for the Barra Funda district and 36.4% for the Luz district. This is not surprising considering that the index of compactness of Luz is practically twice as high as the one for Barra Funda (see Figure 175).

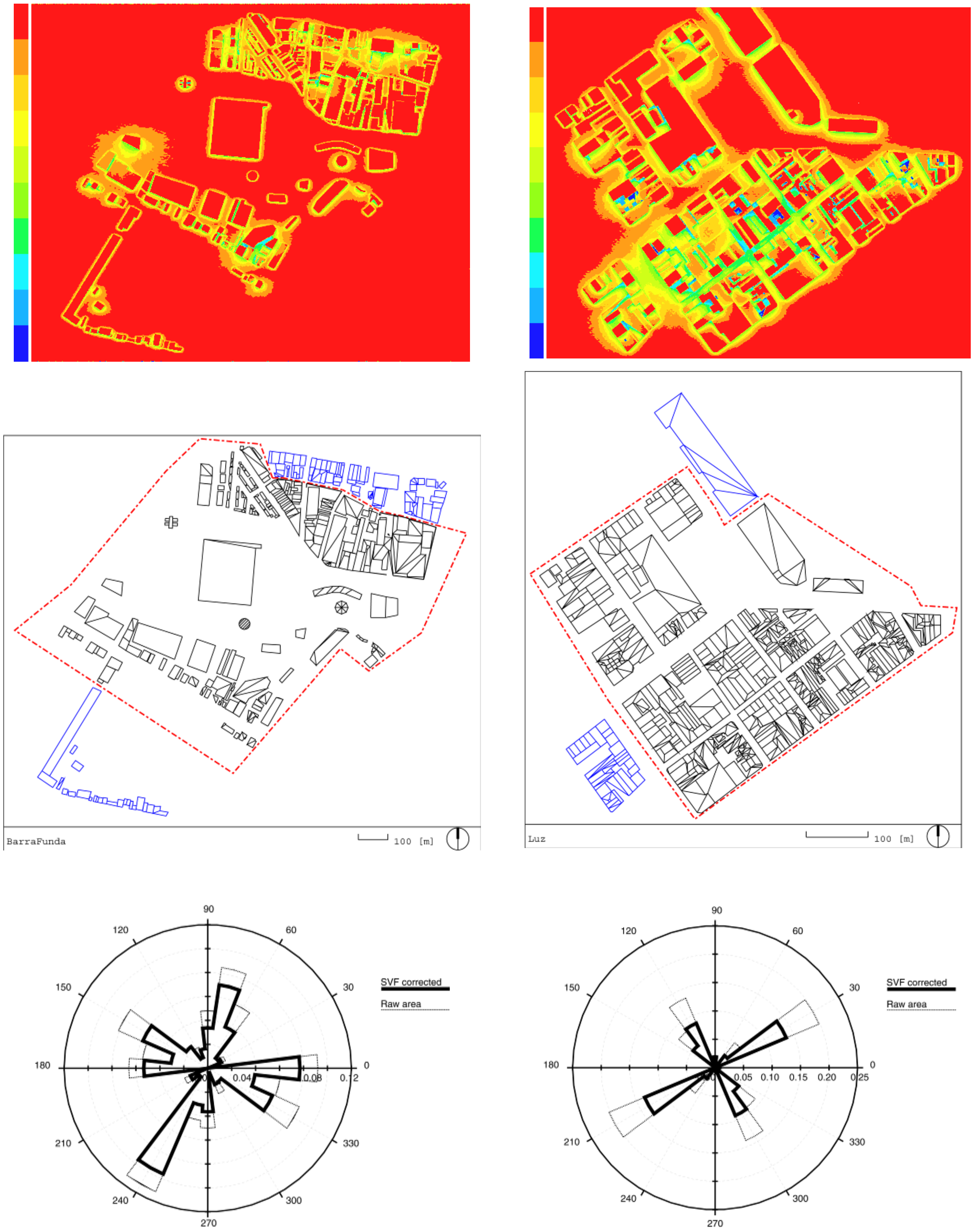


Figure 174: Discretised false-colour layout plan (with 100 kWh/m2 subdivisions) relating to the annual irradiation of Barra Funda and Luz districts (top left and right), corresponding layout plan (middle left and right) and illustration of the orientation rose of the overall building façades of the urban site (polar diagram) determined on the basis of the façade area, as well as through the weighting of these areas by their respective Sky View Factor (SVF) (bottom left and right).

Daylight and sky view factors

Figure 175 shows that the outdoor daylight factor and sky view factor from the Barra Funda and Luz districts on building envelope follow similar patterns with some peaks when the light breaks through or the SVF for those locations where the buildings rise above a generally horizontal and uniform skyline. The daylight factor of Barra Funda is rather uniform peaking between 42 and 56%. On the other hand, the Luz daylight factor is constantly growing and peaks at 42% only afterwards to descend again abruptly.

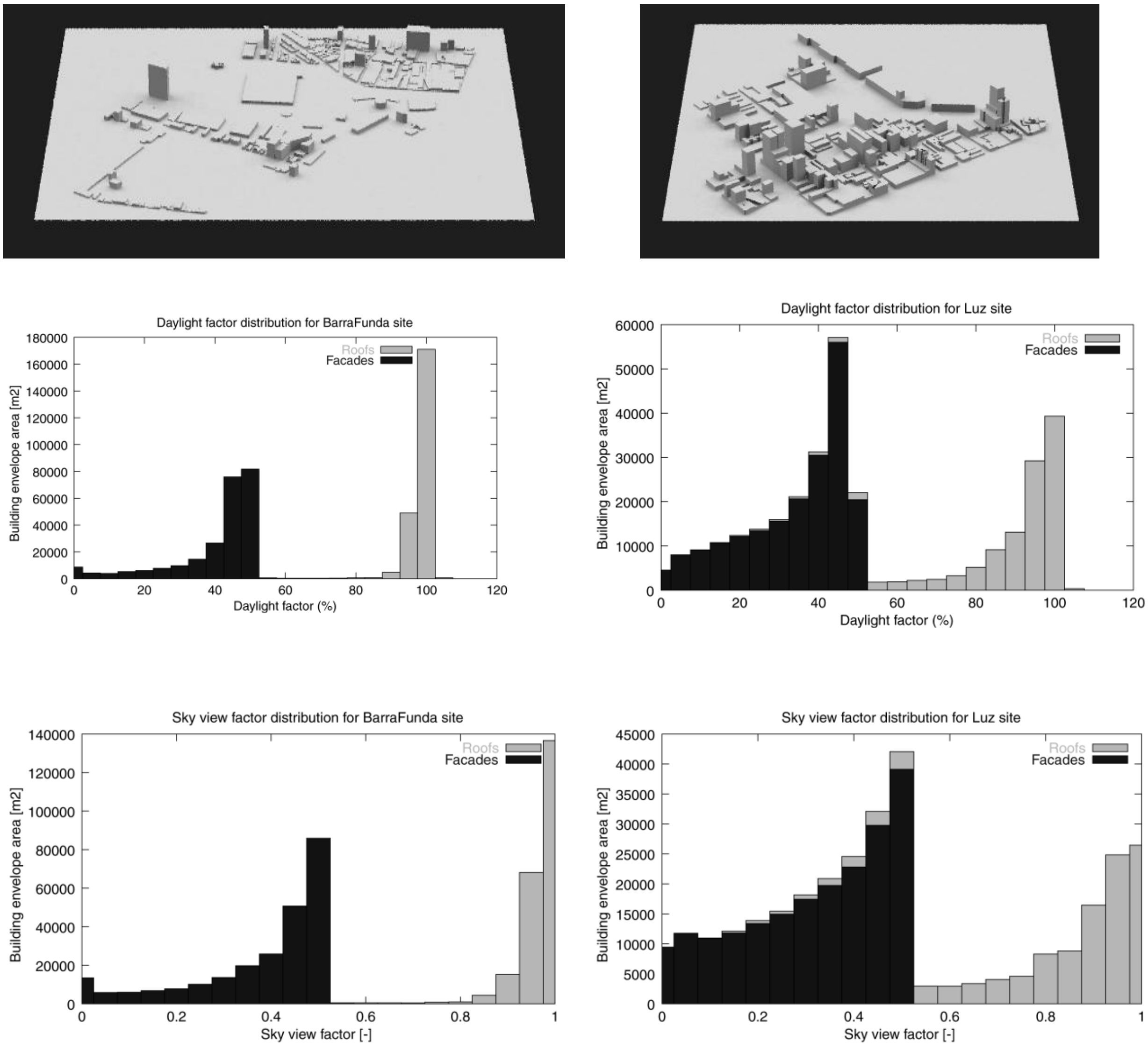


Figure 175: Visualisation of the Barra Funda and Luz districts (top left and right), corresponding outdoor daylight factor (middle left and right and sky view factor distributions (bottom left and right).

Overall daylighting performance and solar potential

The assessment of the Barra Funda and Luz districts in Table 33 indicates that respectively 83.2% and 70.1% of the façades are suitable for daylighting. On the other hand 17.2% and 12.4% of the façade are viable for the integration of photovoltaic technology; these values rise up to 97.6% and 81.9% respectively for roof areas. For solar thermal collectors, the corresponding values reach 79.3% and 64.9% for the façades and 99.7% and 96.2% for the roofs.

The majority of the roof areas can be utilized to generate solar electricity and solar hot water; these values reflect the uniformity of building heights (especially for the Barra Funda sector) and the presence of flat roofs for the majority of the buildings of the two urban 3D models. The present façades – without taking the deterioration of the existing buildings and the interior refiguring of the flats into account – also offer interesting potential for all solar technologies.

Table 33: Summary of results for Barra Funda and Luz districts

São Paulo	Daylighting viability	Solar thermal viability		BiPV viability	
	Façades (annual)	Roofs (annual)	Façades (annual)	Roofs (annual)	Façades (annual)
Barra Funda	83.2%	99.7%	79.3%	97.6	17.2%
Luz	70.1%	96.2%	64.9%	81.9%	12.4%
∆ Barra Funda - Luz	**13.1%**	**3.5%**	**14.4%**	**15.7%**	**4.8%**

It is also possible to see on Table 34 that the irradiation per unit of external surface of Barra Funda (937.5 kWh/m^2) is higher than that of Luz (739 kWh/m^2); this value undergoes a reversal respectively from 415.9 kWh/m^2 and from 466.2 kWh/m^2 for irradiation per floor area, which is hardly surprising. In fact, Barra Funda is made up of buildings with “flat cake[60]” shapes, which maximizes the collection of irradiation per external surface, but has the tendency to minimize the contribution of irradiation per floor area.

[60] *Galette* was used in French.

Table 34: Comparison for Barra Funda district, Luz district and Luz street blocks

São Paulo	Barra Funda	Luz	Luz Block A	Luz Block B	Luz Block C	Luz Block D	Luz Block E	Luz Block F	Luz Block G	Luz Block H	Luz Block I	Luz Block J	Luz Block K
Obstructed façades (%)	23.6	36.4	21	22.8	28.4	26.7	26.8	28.3	21.7	36.6	29.8	24.9	10.1
Plot ratio Raw floor area (m^2) / Site area (m^2)	1.1	2.4	2.8	3.3	5.0	5.8	2.5	2.8	3.6	1.7	3.8	2.2	4.7
Compactness index of built form (Envelope area/Volume)	0.13	0.20	0.21	0.17	0.20	0.19	0.27	0.24	0.23	0.38	0.27	0.32	0.20
Compactness index of built form related to site (Floor area/site area) / (Footprint/Site area)	3.70	4.40	3.46	3.76	6.26	6.23	3.32	3.29	3.84	2.18	4.50	2.51	4.72
Average building height (m)	-	12.09	10.4	11.3	18.8	18.7	10	10	11.8	6.6	13.6	7.6	14.2
Envelope area (m^2)	474436	314143	31660	30468	48028	31516	18466	24292	19939	17554	23705	4961	14652
Volume (m^3)	3459627	1501315	148437	179131	236446	168752	67608	100674	87451	46268	88244	15264	73004
Raw floor area (m^2)	1069510	497966	49175	59453	78606	56101	22426	33392	29027	15308	29308	5055	24251
Covered ground area or footprint (m^2)	288734	112966	14172	15782	12556	9002	6747	10137	7548	7011	6510	2007	5134
Non-built area (m^2)	620254	91720	3351	2257	3271	681	2140	1642	584	2197	1220	260	49
Site area (m^2)	908988	204686	17523	18039	15827	9683	8887	11779	8132	9208	7730	2267	5183
Annual irradiation (MWh)	444768	232148	27617	29196	32400	22823	14832	19601	15645	13907	15960	4219	12178
Annual illuminance (Mlm)	12351	6444	767	811	894	621	412	546	434	386	443	117	336
Irradiation per unit of external surface (kWh/m^2)	937.5	739	872.3	958.2	674.6	724.2	803.2	806.9	784.6	792.2	673.3	850.5	831.2
Illuminance per unit of external surface (kLux)	26.03	20.51	24.22	26.62	18.61	19.70	22.31	22.48	21.77	21.99	18.69	23.58	22.93
Irradiation per floor area (kWh/m^2)	415.9	466.2	561.6	491.1	412.2	406.8	661.4	587	539	908.5	544.6	834.6	502.2

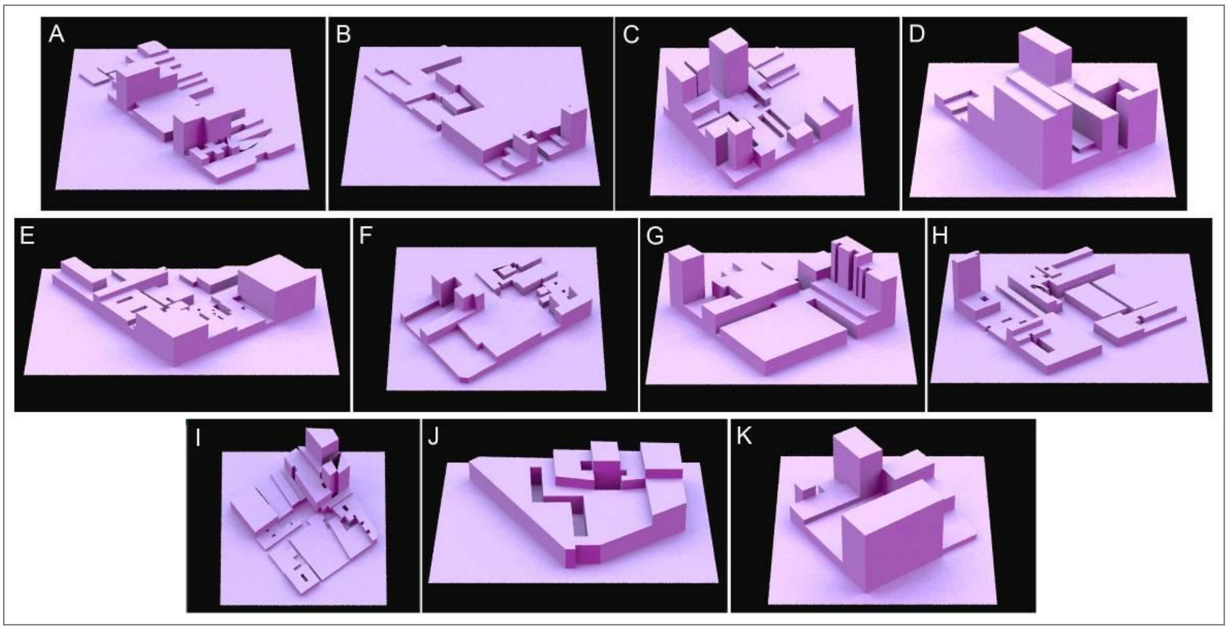
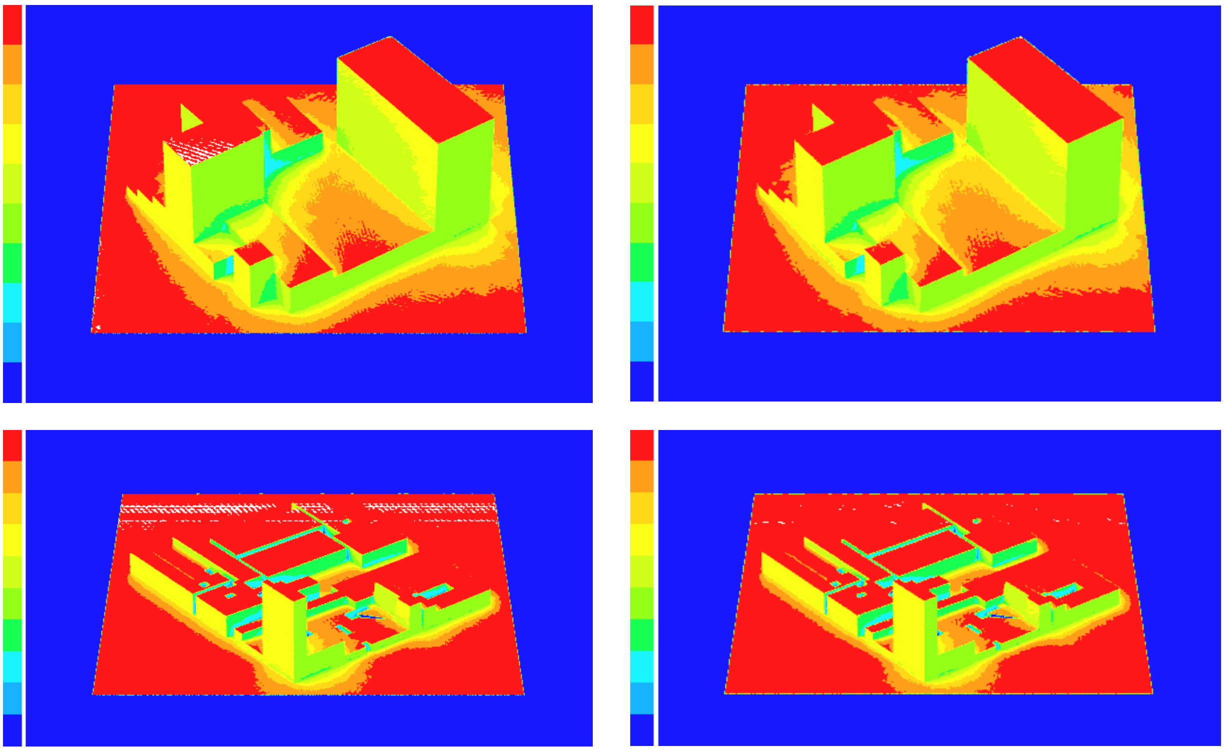


Figure 176: Luz district. Visualisation of existing urban blocks (RADIANCE rendering).

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.



West view of Block K (top) and West view of Block H (bottom). Discretised false-colour image (with 100 kWh/ m^2 subdivisions) relating to the annual irradiation.

West view of Block K (top) and West view of Block H (bottom). Discretised false-colour image (with 100 kWh/ m^2 subdivisions) relating to the annual illuminance.

Figure 177: Urban block in Luz. Discretised false-colour images (with 100 kWh/m2 subdivisions).

Studies of existing urban blocks

In order to examine the influence of built density, eleven existing urban blocks in Luz were examined. Figure 176 shows the urban blocks which provide a rich urban texture representing a range of different built forms from compact high-rise to a relatively flat and open layout.

Table 35 on top shows that Block H is the most compact in terms of built form: with 36.6% of obstructed façades, it also possessed the highest rate of obstruction in the district. Conversely, Block B possesses the smallest index of compactness. On the other hand, Block K with 10.1% comprises the weakest rate of obstruction. Blocks C and K with 0.20 % index of compactness conform to the average for the Luz district. The average rate of obstruction for the overall district is 36.4%, which corresponds approximately to Block H. In terms of effectiveness of compactness for the urban form relative to the site, Block C is the optimal with its plot of land, the opposite of Block H. This last result seems to be a paradox. In fact, Block H is the most compact built form yet at the same time, it is also the block which is least effective when considered with its plot of land – a mere 2.18 index of compactness related to site area. In conclusion, Block A with 3,351 m^2 (0.828 acres) comprises the largest non-built area, as opposed to Block K with only 49 m^2 (0.012 acres) of non-built area is the last one.

Table 35 provides a summary of the simulations results for the evaluation of solar potential and daylighting obtained for the urban blocks in the Luz district. On the whole, Block K has the greatest potential of the eleven configurations studied; Block H has the worst potential over all (see Figure 177).

Table 35: Summary of results for the urban blocks in Luz

São Paulo	**Daylighting viability**	**Solar thermal viability**		**BiPV viability**	
	Façades (annual)	**Roofs (annual)**	**Façades (annual)**	**Roofs (annual)**	**Façades (annual)**
Luz	**70.1%**	**96.2%**	**64.9%**	**81.9%**	**12.4%**
Block A	80.8%	98.9 %	78.4 %	90.4 %	30.3%
Block B	78.3%	98.8%	75.3%	93.1%	28.6%
Block C	76%	93.6%	73.8%	67.1%	20.6%
Block D	75.4%	92.4%	73.4%	75.6%	26.8%
Block E	76.5%	98.4%	73.5%	90.1%	22.4%
Block F	72.8%	96.6%	69.2%	85.6%	22.7%
Block G	75.2%	94.4%	72%	78.6%	28.6%
Block H	64.7%	99.5%	61.5%	93%	20.1%
Block I	69%	96.9%	66.7%	73.9%	28.2%
Block J	72.6%	99.5%	69.7%	92.5%	18.7%
Block K	95.6%	96%	94%	76.4%	36.5%
Blocks average	**76%**	**96.8%**	**73.4%**	**83.3%**	**25.7%**

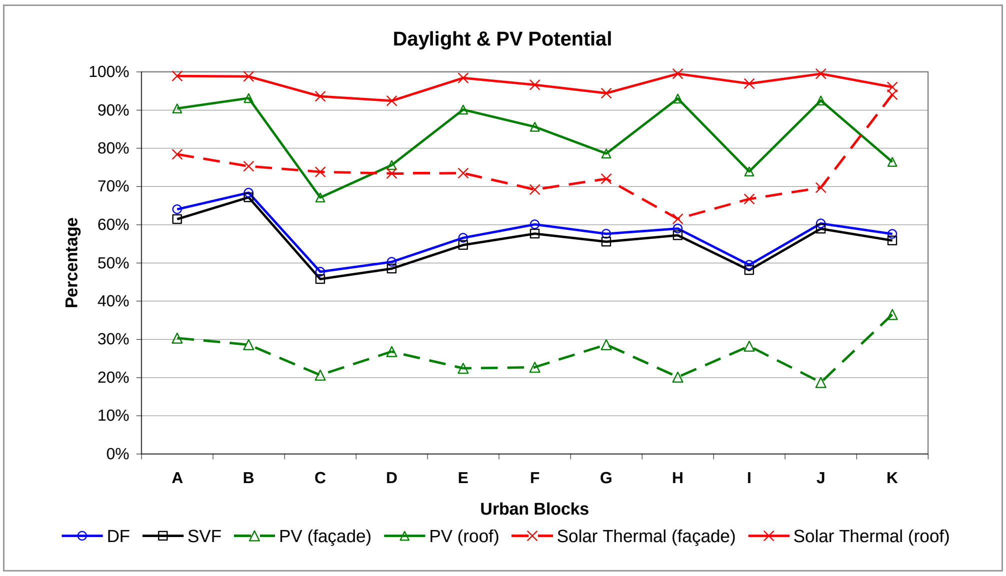


Figure 178: Daylight and solar potential of the urban blocks in the Luz district.

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

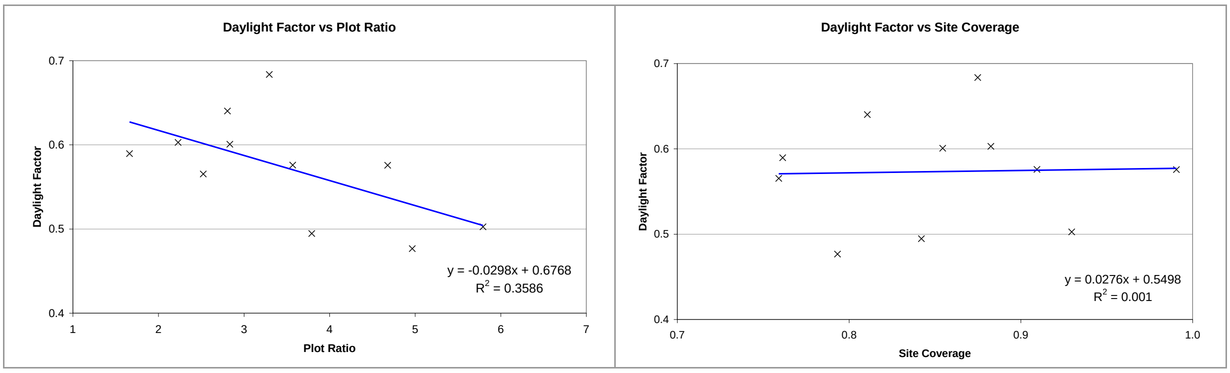


Figure 179: Daylight factor and built density of the urban blocks in Luz district.

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

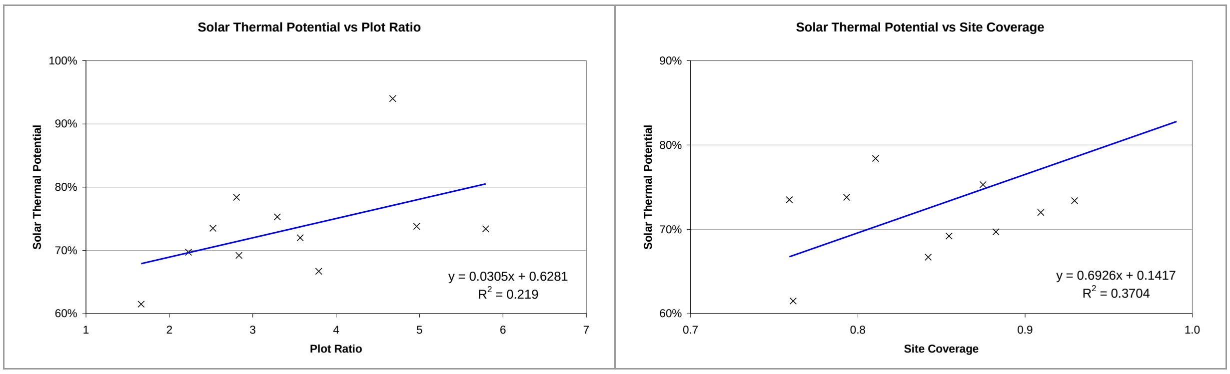


Figure 180: Façade solar thermal potential and built density

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

Daylight and solar potential

Figure 178 shows that the daylight factor and sky view factor on building envelope follow similar patterns, as well as solar thermal and photovoltaic potential on roofs, whose curves have the same pattern. On the other hand, the solar thermal and photovoltaic potential on façades behave diversely. In order to understand this discrepancy and its relationship with built density, daylight factors representing the former group and facade solar thermal potential representing the later group have been studied separately.

Daylight factor and built density

Densities were examined in two ways, i.e. plot ratio and site coverage: plot ratio is defined as the ratio of total floor area to site area, and site coverage is the ratio of building footprints to site area. The site coverage expresses the percentage of the built surface to the site area. It relates to the plot, to the urban area, to the housing sector or to the city. In Figure 179, the study firstly correlates the parameters of the built density, i.e. the coefficient of the plot ratio and the coefficient of the site coverage with the daylight factor. It can be seen that the coefficient of the plot ratio is poorly correlated with the daylight factor (R^2=0.36), whereas the part played by the site coverage is completely negligible (R^2=0.001), which is not surprising. In fact, at first sight it seems logical that the plot ratio influences the daylight factor more than the site coverage; on the other hand, that does not mean that the effect of the latter is completely negligible.

In order to understand this issue a factor known as “the compactness index” has been introduced, which includes the plot ratio factor and the site coverage. The “compactness index” is defined as the ratio of plot ratio to site coverage. Expressed in different terms, it represents the ratio of total floor area to building footprint (i.e. the average number of floors).

Figure 181 shows the correlation between the compactness index and the daylight factor. The latter indicates that there is a rough correlation (R^2=0.46), which surpasses the one obtained using the plot ratio alone. This is also true for the sky view factor as well as the solar thermal and photovoltaic potential on roofs, where R^2 is equal to 0.46, 0.77 and 0.75 respectively. Consequently, the compactness index, as one of the factors established in urban density, seems to be useful for the prediction of the daylighting and the solar potential of the roofs.

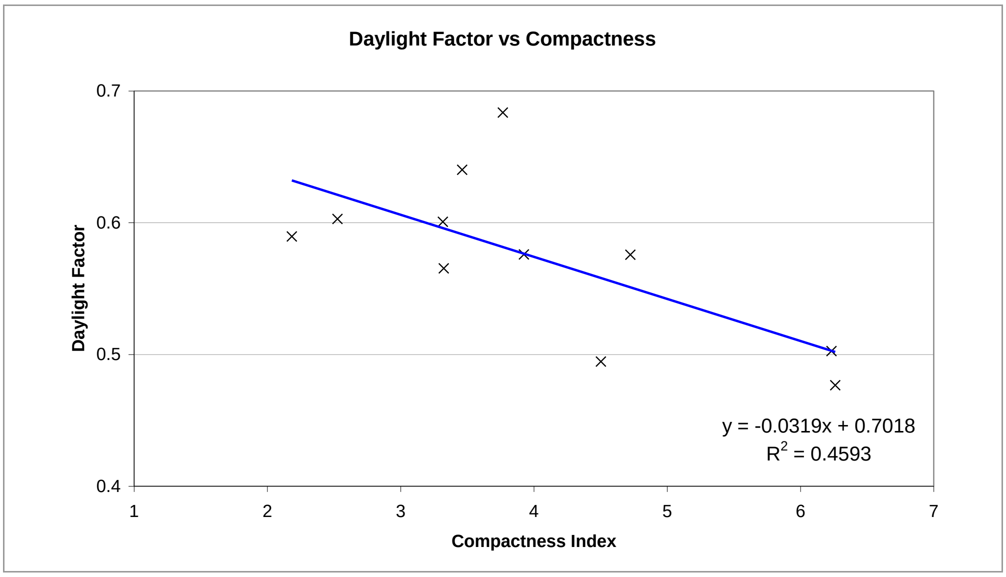


Figure 181: Daylight factor and compactness index

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

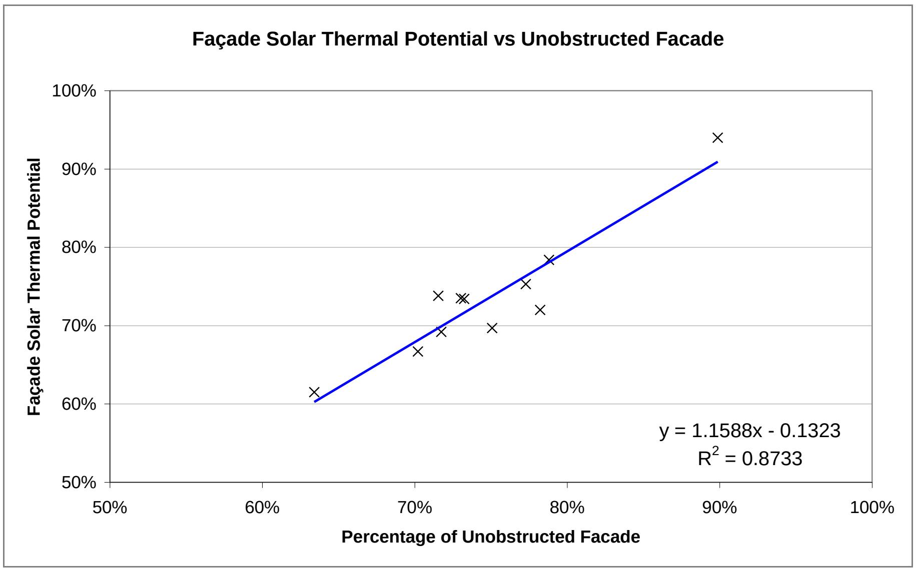


Figure 182: Daylight factor and compactness index

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

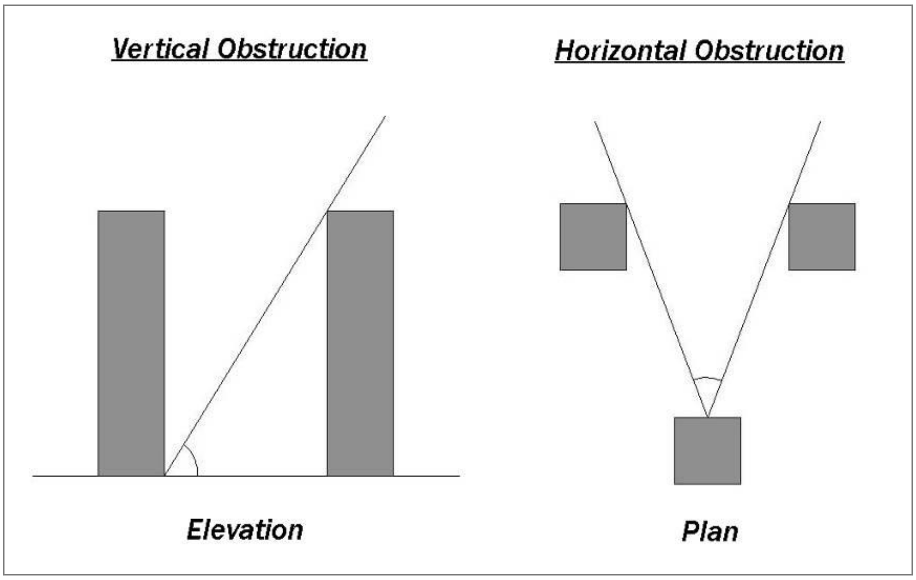


Figure 183: Vertical and horizontal obstruction in urban setting

Source: Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). Compact cities in a sustainable manner. In *Solar Cities Congress, 2nd International Solar Cities Congress*, 3-6 April, Oxford.

Solar thermal potential and built density

Figure 180 shows the correlations between façade solar thermal potential and plot ratio (1) as well as site coverage (2). In comparison to plot ratio (R^2=0.22), site coverage (R^2=0.37) appears to have a larger influence on the façades' solar thermal potential; the result is opposite to that obtained with roofs. A study of the correlation between compactness index and façade solar thermal potential shows an even worse result (R^2=0.13). Nevertheless, there is a very good correlation between the façades' solar thermal potential and the percentage of weighted unobstructed façade area* (R^2=0.87) (see Figure 182). This close linkage with unobstructed façade, however, is not valid for daylight factor (R^2=0.07).

Balance of the Barra Funda and Luz districts analyses

To sum up, the daylight and solar potential of an urban development are primarily determined by the amount of solar radiation that falls on the surfaces. In this sense, there are two parameters, namely the vertical and horizontal obstruction angles, which could be influential. Vertical obstruction affects light coming from the top whilst horizontal obstruction affects light coming from the sides. Figure 183 illustrates the two obstruction angles in an urban setting.

In conclusion, the Luz case study further reveals the complexity of the issue. It appears that the different manifestations of built density (i.e. plot ratio, site coverage and compactness index) play different roles in determining urban daylight and solar potential. According to the results of this particular case study, daylight and solar performance indicators such as daylight factor, sky view factor and solar thermal and photovoltaic potential on roofs are more correlated to the plot ratio and compactness index. This would suggest that these quantities are more influenced by vertical obstruction, in other words, more dependant on light coming from the top. On the other hand, solar thermal and photovoltaic potential on façades are better correlated to site coverage and unobstructed façade area, therefore these quantities are more influenced by horizontal obstruction, which means more dependant on light coming from the sides.

As a final remark, there are some limitations to this study. Firstly, the urban block study in Luz mainly provides a better understanding of the influences of built density and urban form on daylight and solar potential. In order to minimize the interference from other factors, the effect of surrounding obstructions were not taken into account: the results are more suitable for comparison than for an absolute performance evaluation.

Secondly, the solar potential obtained from the Luz case study is derived from the region's typical sky condition. As for the low geographic latitude of Luz (23.5°S), the sky condition is characterized by high solar altitudes, which results in appreciable differences between façade and roof illumination. Hence, it is possible that the findings could not be generalized for places with different latitudes.

Lastly, the study is essentially based on first order regression analysis, which might not be able to account for some factors, lying outside the scope of this study.

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* The weighted unobstructed façade area A (m^2) is defined as: $A = \sum_i \frac{SVF_i}{0.5} \cdot A_i$

where i is the total numbers of measuring points in PPF simulation and A_i is the total façade area. For a totally unobstructed façade, SVF_i = 0.5. (Compagnon, 2000)

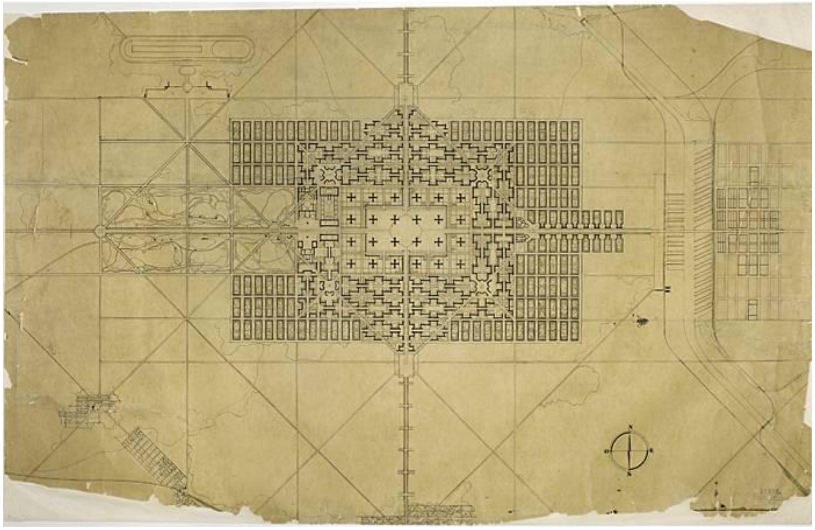


Figure 184: Le Corbusier. The Contemporary City of Three Million Inhabitants, 1922 ©FLC.

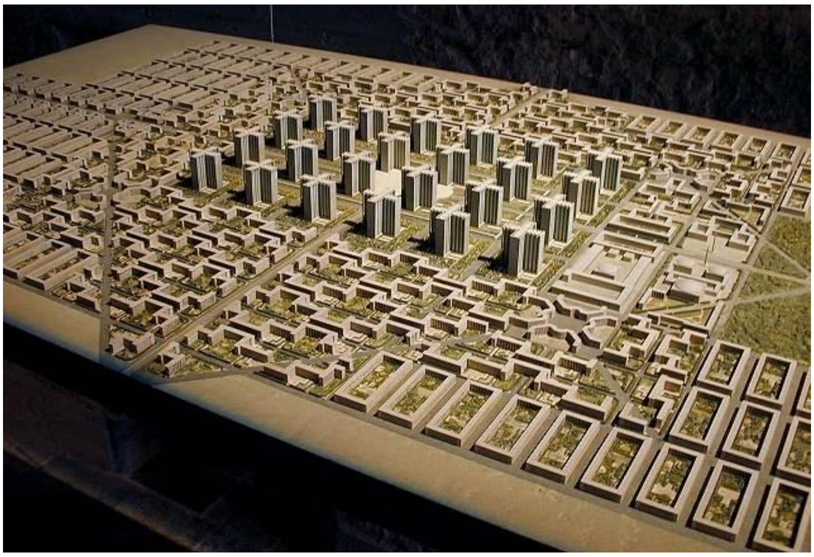


Figure 185: The Contemporary City of Three Million Inhabitants. Mock-up presented at the A la recherche de la cité idéale exhibition in la Saline d'Arc-et-Senans (France), 2000.

Source: [online] URL: http://www.athenaeum.ch/corbu3m1.htm (Consulted on January 13nd, 2006).

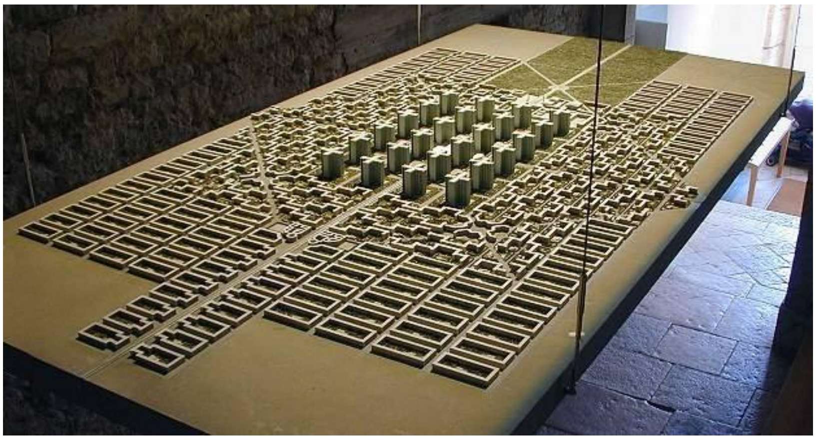


Figure 186: Contemporary City of Three Million Inhabitants. Mock-up presented at the A la recherche de la cité idéale exhibition in la Saline d'Arc-et-Senans (France), 2000.

Source: [online] URL: http://www.athenaeum.ch/corbu3m2.htm (Consulted on January 13nd, 2006).

4.9 The Contemporary City of Three Million Inhabitants, Le Corbusier (1921-1922)

For an investigation of urban design it was invaluable to examine the proposals made by Le Corbusier in his famous *Contemporary City of Three Million Inhabitants*, the *City of Tomorrow* (Montavon, Steemers et al. 2006). This work consisted of a comparison between purely theoretical generic built forms and real existing urban blocks. The *Contemporary City*, which did not explicitly refer to the city of Paris (48,85 latitude), is legendary in the history of contemporary town planning. Le Corbusier's proposals, though never adopted, suggested solutions to the problem of a hyper-dense city which today – more than ever - are a topic of debate in urban planning.

Gaston Bardet, a renowned French city planner and theorist, argued in his book *Pierre sur Pierre* (Bardet 1945) that the design of *La Ville Radieuse*[61] (Radiant city) was not, in fact, environmentally sound, in terms of urban microclimate and human comfort. Bardet, through his drawings of shadow casting, illustrated that the design and layout of building blocks in *La Ville Radieuse* would actually create many overshadowed zones which for long periods during Winter months would not receive any sunlight. In conjunction with wind flow and cold temperature, these overshadowed zones would produce intolerable thermal conditions to pedestrians during the coldest months.

In response to Bardet's remarks and the propositions of Le Corbusier, this study combined daylight and solar modelling of the *Contemporary City of Three Million Inhabitants* in order to address the following questions:
- Were the propositions made by Le Corbusier in the design of the *Contemporary City* better than a more traditional design, in terms of daylighting performance?
- What are the most important characteristics or factors that influence the success or failure of the *Contemporary City*, with respect to daylighting performance?
- What can we learn from the *Contemporary City* about the design of high density solar cities?

According to Le Corbusier, the *Contemporary City* could increase the urban capacity and at the same time improve the urban environment and the efficiency of the city. Therefore the present study examines the solar potential of this utopian city in order to assess Le Corbusier's propositions.

This study employed computer simulation to evaluate the daylight and solar performance of The *Contemporary City* with reference to daylight design in order to draw conclusions about the design of high density solar cities. The results obtained are discussed at the end of the study. This final section begins with an overview of its organizational principles along with the steps of its 3D digital modelling.

4.9.1 Description of case study

Le Corbusier imagined the *Contemporary City of Three Million Inhabitants* in 1921-1922; his intention was to prove the unsuitability of city planning of that time for the needs of contemporary city-dwellers. His utopian city model was based on:
- rational road facilities;
- shopping malls with services functionalities;
- sharing of downtown residences;
- other suburban residential sharing.

Le Corbusier conceived three ideal city planning projects which respected certain health requirements:
- the *Contemporary City of Three Million Inhabitants* (1921-1922);
- *La Ville Radieuse* (1930);

[61] 2nd version of utopian city. Le Corbusier, in his studies of *La Ville Radieuse* (Radiant city) set aside the concentric of The *Contemporary City* for a linear organization. On the other hand, he kept the same kind of buildings as the ones studied for the *Contemporary City*.

- and the industrial *Ville Linéaire* (Linear City);

the last project was a futuristic megapolis, which brought together wide-scale European-style cities following two North-South and East-West axes.

He presented an urban planning system that tried to combine a high population density with green spaces, natural ventilation and daylight provision. His view of the city at the beginning of the 20th century was very critical: he considered it to be sick and chaotic with the potential to trigger a revolution. He tried to conceive a rational urban plan that the emerging industrial world could integrate harmoniously into new cities. The concept of this city was virulently disputed by Gaston Bardet (1945) and by Jean Lebreton (1945) as explained by Harzallah (Harzallah 2007).

The *Contemporary City* was first exhibited in November, 1922 at the *Salon d'Automne* in Paris. The corresponding diorama, which was part of the urban art section, was set in a virtual terrain with hardly any identifiable topography landmarks; Le Corbusier was obviously referring to Paris, whose population exceeded three million in 1919, and which had not stopped growing since then (see Figure 184, Figure 185 and Figure 186). Later on, he adapted his utopian cities to Barcelona, Buenos-Aires, São Paulo and Algiers.

The objective of Le Corbusier was to establish a green city for a million and a half inhabitants according for the following basic principles:
- pedestrian ways must be free of motor traffic, the main axes exclusively devoted to automobiles must be located far away from buildings (to avoid accidents with pedestrians);
- principles for urban settlement were established in order to influence the articulation of the linear residential buildings (to achieve a rectangular angle);
- the various functional areas were ordered inside regular squared cells (to achieve an appropriate zoning).

Three main urban areas were defined in this way:
- a business district and institutional buildings, such as university and governmental buildings, located North near the railway station and the airport (comprising also hotels and embassies);
- an industrial area, located South, split up into heavy and light industries, as well as warehouses;
- a residential area, located between the business district and the industrial area, protected by a green strip from the industrial zone.

Streets cut across the settlement orthogonally or diagonally for high-speed travelling, railways make up an external belt, the metropolitan rail network is located underground.

The street blocks, shaped by the road mesh, make up 400 meter squares which differ from the historical subdivision into smaller fractions. They are laid out in a way that can offer large open adjacent areas for public usage: in order to achieve this result, expropriation of the current buildings was envisaged.

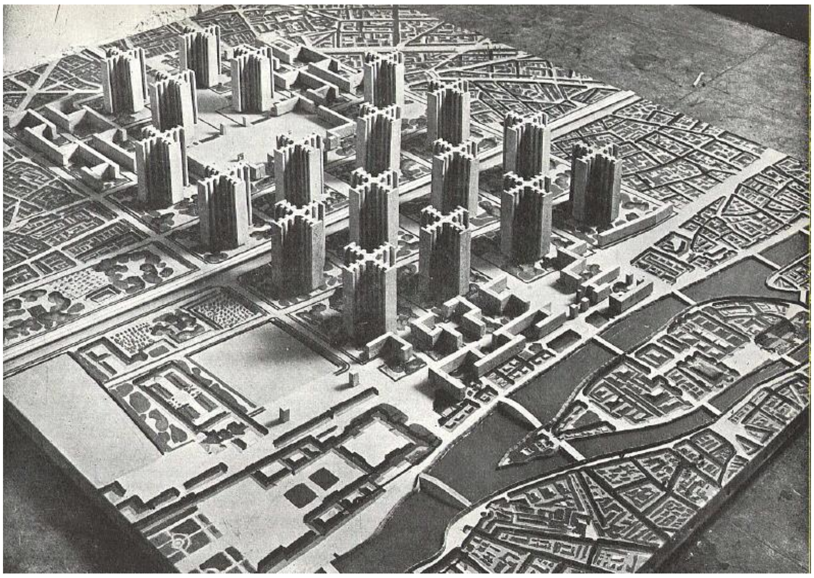
Starting from a standard gross area of 14 m^2 per inhabitant, the accommodations were sized with a view to minimizing the built-up surfaces: the result is 11% of the total covered area and an urban density of 1,000 inhabitants per hectare or 10 m^2 per inhabitant (1,000 inhabitants per 2.5 acres). Construction-free zones were mainly dedicated to green recreational areas. Pathways inside the park, protected by awnings, were reserved for pedestrians. Access roads had three different section types (54 m with a lateral tramway, 40 m and 28 m). The streets penetrated into the building blocks according to their entrances, where parking lots would be available. Diagonal high-flow streets were elevated on pilings.

Residential accommodations were provided by linear eleven-storey macro buildings at right angles to each other (residential buildings of the *Contemporary City* had a height of 50 metres). The ground, entirely built on pillars, was completely adaptable to any kind of configuration. It was thus possible to configure it anywhere within the park's surface and to distribute social and entertainment services as required.

There were two kinds of factory buildings:
- a double unit with a central corridor oriented north-south (16 meters wide);
- a simple unit oriented east-west with apartments to the south and the north (9 meters wide).

After the November 1922 exhibition at the *Salon d'Automne*, a first application of the principles suggested by Le Corbusier was presented in 1925 at the *Exposition internationale des arts décoratifs*, as the result of a research project funded by the car manufacturer Gabriel Voisin (see Figure 187 left). The *Plan Voisin* proposed the demolition and reconstruction of 593 acres (240 hectares) of the centre of Paris. The area considered is centred on a main East-West axis, located between the Rue des Pyramides, the circular square of the Champs-Élysées, the Saint-Lazare railways station and Rue de Rivoli. The site would involve the development of residential buildings (single dwellings), a shopping centre, sitting astride a secondary axis from the River Seine towards the north, along which cross-shaped skyscrapers would be located. Only a few monuments were left undemolished (the Louvre and the Place Vendôme for instance); they were often shifted from their initial location and replaced by huge areas devoted to the green parks. From 1930 on, Le Corbusier, in his studies of *La Ville Radieuse* set aside the concentric shape of The *Contemporary City* for a linear organization. On the other hand, he kept the same kind of buildings as the ones studied for the *Contemporary City* (see Figure 187 right); the industrial area is now visible in the map. In that project the garden cities at the outskirts of the city disappear, as well as the population classification, characteristic of the *Contemporary City*. This concept led in 1935 to the publication of a manifesto which aimed to solve the problem of mass-housing by taking advantage of the rising trend of the so-called "*machiniste*" culture shown in *La Ville Radieuse*. The contemporary man's needs were reduced to the minimum: the suggested architectural solutions ranged from a living cell to an urban structure. From the juxtaposition of *La Ville Radieuse* with other urban plans, one can easily notice the large urban scale which was introduced by Le Corbusier in his time (see Figure 188).

Le Corbusier's contribution had a considerable impact far beyond Paris. From 1924 onwards, it was passionately discussed by Ludwig Hilberseimer and Werner Hegemann in Germany. Nowadays, even though his projects sometimes leave us with the sense of a *dystopian*[62] vision, Le Corbusier himself was convinced that he could improve the fate of the human race. He relied on Saint-Simon's and Fourier's ideas, Ema's Italian monastery being among his sources of inspiration (Le Corbusier 1935).



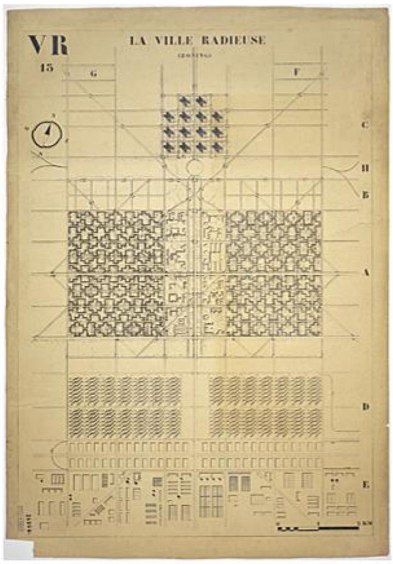


Figure 187 left and right: Le Corbusier. The *Plan Voisin* and *La Ville Radieuse*, 1930 ©FLC.

[62] A dystopia is the vision of a society that is the opposite of utopia. A dystopian society is a state in which the conditions of life are extremely bad, characterized by human misery, poverty, oppression, violence, disease, and/or pollution.

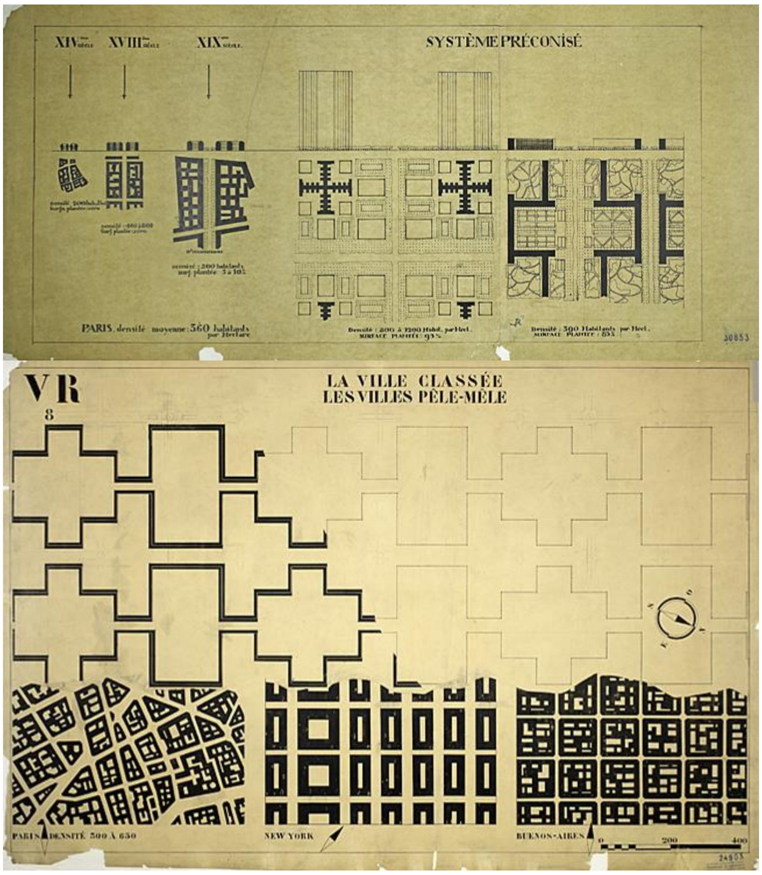


Figure 188 top and bottom: Le Corbusier. Juxtaposition of La Ville Radieuse with other town plans 1930©FLC.

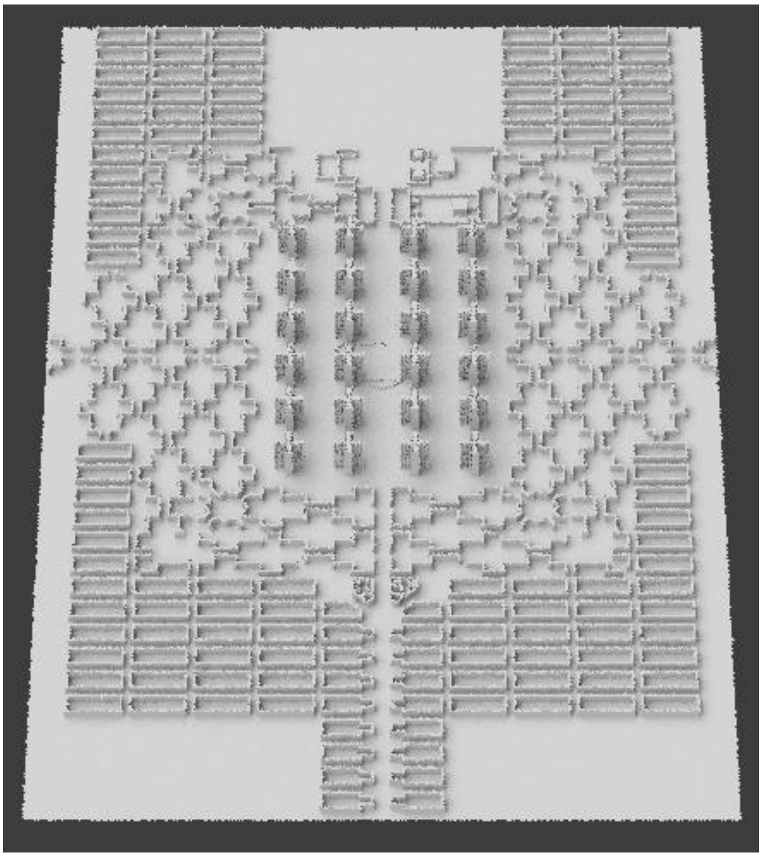


Figure 189: East view of Contemporary City of Three Million Inhabitants (RADIANCE rendering).

4.9.2 Description of 3D digital model

The 3D digital model of the *Contemporary City* was elaborated using the architectural plans published by Le Corbusier in his book *La Ville Radieuse* (Le Corbusier 1935). Some complementary information came from the archives of the *Fondation Le Corbusier* in Paris whenever it was necessary to clarify some aspects of his original plans or to locate missing data.

The transformation of the sites' buildings into a 3D digital model was carried out with the same technique that was used for the Bellevaux district in Lausanne: the operation was performed without the benefit of a 2D digital cadastral plan that could have been be used as a basis for the erection of the buildings' façades. A simple digitalization of the original Le Corbusier drawings was impossible due to the fact that their scale had been considerably reduced and also due to the inaccuracy of the drawings' lines.

Footprints of buildings were approximated using selections from Le Corbusier's writings and original sketches. The implementation method of the digital model via AutoCAD (function 3D FACE function) is described in Section 4.3. Similar buildings were simply cut and pasted from the footprints, which saved time for the different modelling steps. Figure 189 and Figure 190 illustrate the final digital model of Le Corbusier's utopian city.

The PPF software required no specific modifications to recognize 3DFACE objects and layers in order to build the 3D model (terrain, façades and roofs). This task was made easier after starting the 3D modelling of Matthaeus district in Basel. Good organisation was important, together with the arrangement of the 3DFACE directly in the appropriate AutoCAD layer (3DF_DTM, 3DF_FASSADEN and 3DF_DACH) to avoid confusion. 3DFACE objects could be imported using the *get3df* translator. The various tests made using PPF were quickly conclusive. However, as this was an imaginary city, the modelling was not very accurate. The initial goal was to estimate the potential of this planning proposal and to compare it with the earlier Parisian blocks.

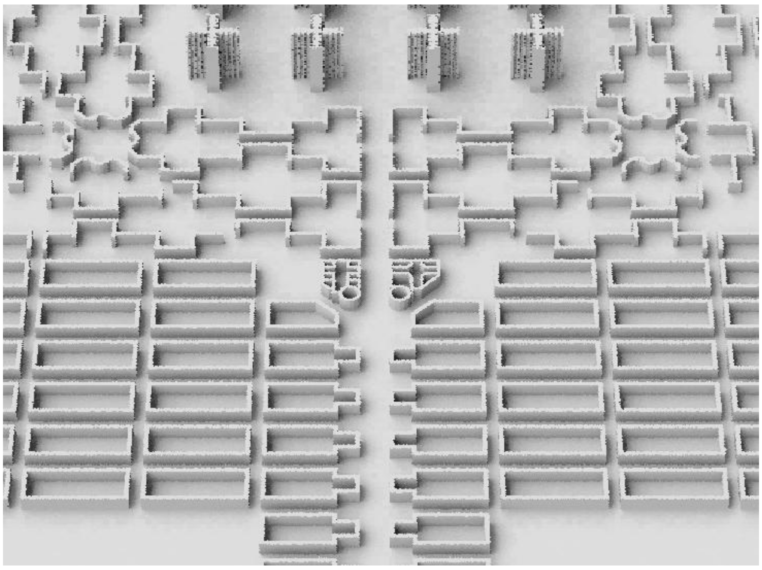


Figure 190: Zoom/East view of Contemporary City of Three Million Inhabitants (RADIANCE rendering).

4.9.3 Solar performance indicators

Different performance indicators can be used to assess the daylight and solar potential of the proposal of the *Contemporary City*. Daylight viability was the major performance indicator employed in this study. Assuming an internal required illuminance of 500 lux and a utilisation coefficient of 0.05 (typically a vertical opening), it was defined as the percentage of façade area which annually receives an average illuminance of 10,000 lux or more. The simulation was conducted using the typical annual sky conditions of Paris in Winter and Summer. In addition, a set of simulations was carried out using the typical annual sky conditions in São Paulo. This data could provide a basis for adapting Le Corbusier's proposals and design principles to other parts of the World (Compagnon 2004).

As previously mentioned, the plan of the *Contemporary City* can be divided into three major districts: the business district, the industrial area and the residential district. Skyscrapers are predominant in the business district, whilst the residential district comprises three different housing blocks. These housing blocks are named housing "set-backs", housing "cellular" and "garden cities". In the simulation, only the skyscrapers, housing "set-backs" and housing "cellular" were included. Apart from that, the industrial area, which had its own specificity and which was beyond the scope of this study, was not taken into consideration.

Urban Density

In this study, urban density was described in three different ways:
- inhabitation density, i.e. the ratio of number of inhabitants to site area;
- plot ratio, i.e. the ratio of total floor area to site area;
- site coverage, i.e. the ratio of building footprint area to site area.

Figure 191 shows the three different built forms; Table 36 shows the densities of each one.

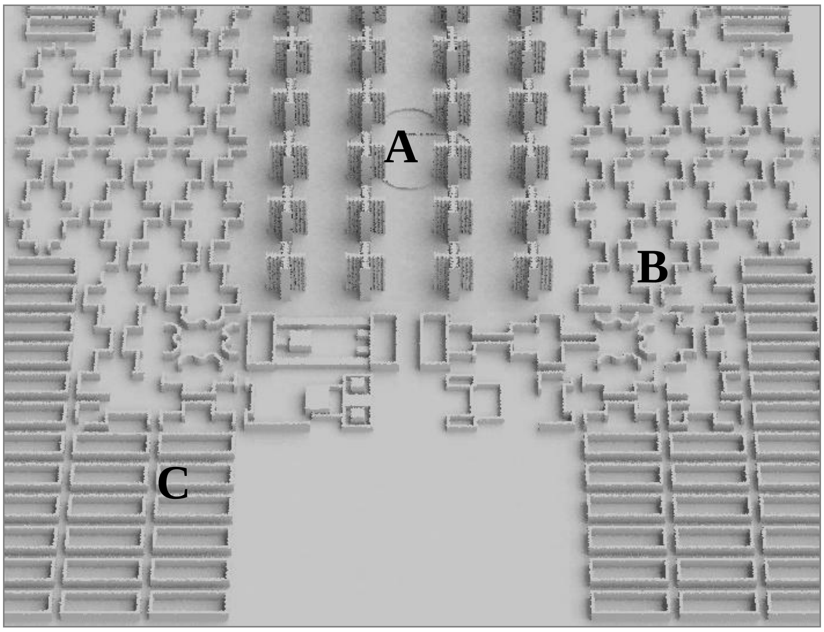
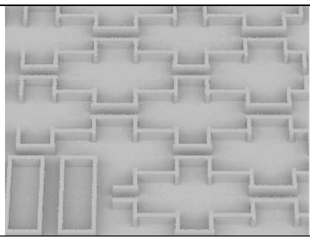
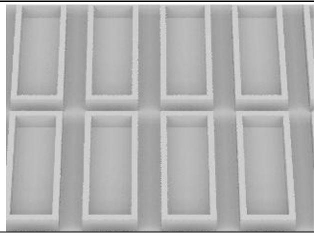


Figure 191: The three different built forms included in the study.

Table 36: Summary of cases being studied

Density	**Skyscraper (A)**	**Housing “Set-Backs” (B)**	**Housing “Cellular” (C)**
			
Sizes	H=220 m, W= 190 m	H= 50 m, L= 1300 m	H= 50 m, L=360 m, W= 140 m
Occupancy rate	0.3 Inhab./m²	0.03 Inhab./m²	0.03 Inhab./m²
Plot Ratio	3.8	0.8	0.9
Site Coverage	6.30%	12.50%	19%

Daylighting Performance of Skyscrapers

The daylighting performance of the skyscrapers is the most controversial element in the proposal of the *Contemporary City*. Throughout its development, three versions of the design of the skyscrapers can be found in Le Corbusier’s papers. The most important modification among these three versions of design was the modification of the façade surfaces from “uniform planes” to “deeply serrated” shapes as shown in Figure 192. According to Le Corbusier, the advantage of the “serrated” shape is that it forms true light traps[63].

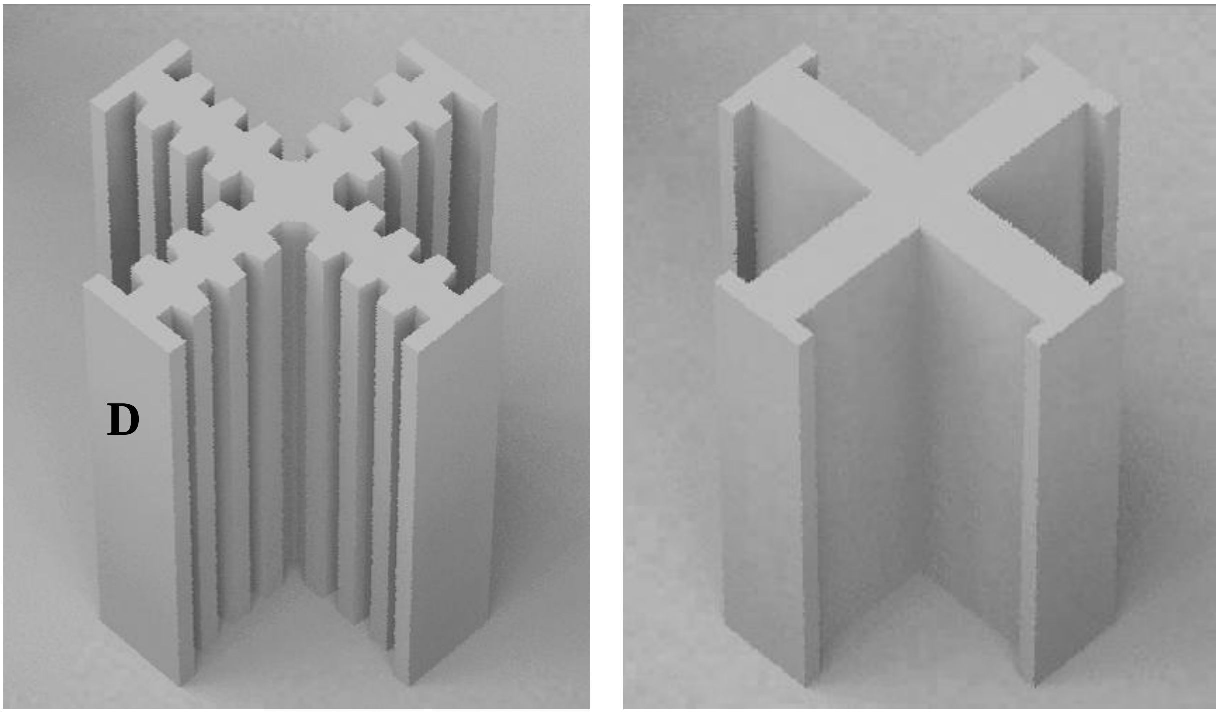


Figure 192: (left) The “deeply serrated” designs and (right) “uniform plane” of the skyscrapers.

[63] *Radiateur à lumière* in French in Le Corbusier (1935). *La Ville Radieuse*. Boulogne, Editions de l'Architecture d'Aujourd'hui.

The orientation rose (Compagnon 2000) appearance indicates that the site is obviously influenced by a South-West/North-East pair of azimuths. The urban character of the "deeply serrated" skyscrapers site is responsible for a significant reduction of the sky fraction enjoyed by the building façades. Most of the building façades are subject to rather unfavourable conditions: Sky View Factor values lie between 5% and 20%. Consequently, some façades are largely obstructed and therefore fail to perform as potential daylight collectors (SVF corrected) (see Figure 193).

Figure 194 shows Obstruction Illuminance Multiplier (OIM) (Compagnon 2000) distributions computed for all surface orientations. These graphs show that the "deeply serrated" skyscrapers are affected by obstructions. All façade surfaces have OIM lower than 1 with peaks in the ranges of 0.05 and 0.4 far below 1. During the heating season, when the sun elevation angle is low and upon high surface reflectance, OIM increases from 0.4 up to 1 for a couple of façades. This indicates that their surrounding obstructions act poorly as effective reflectors.

Daylight simulation was carried out to evaluate the performance of the modified "deeply serrated" design and the original "uniform plane" design. The annual and Winter daylight viability of the "serrated" design is 23.7% and 8.5% for 309,965 m^2 façade area, whilst the viability of the "uniform plane" design is 45.9% and 16.5% respectively for 206,505 m^2 façade area. The results show a significant reduction of daylight potential as a result of the modified "serrated" design, -22.2% annually and -8% in Winter. These values would be reduced further if the simulation did not take lateral plane façades of the skyscraper wings into consideration (see D in Figure 192). They are so large that they mislead the simulation by augmenting the fraction of façades available for the solar utilisation potential. Actually, they might be the ones which capture light instead of the deeply serrated façades.

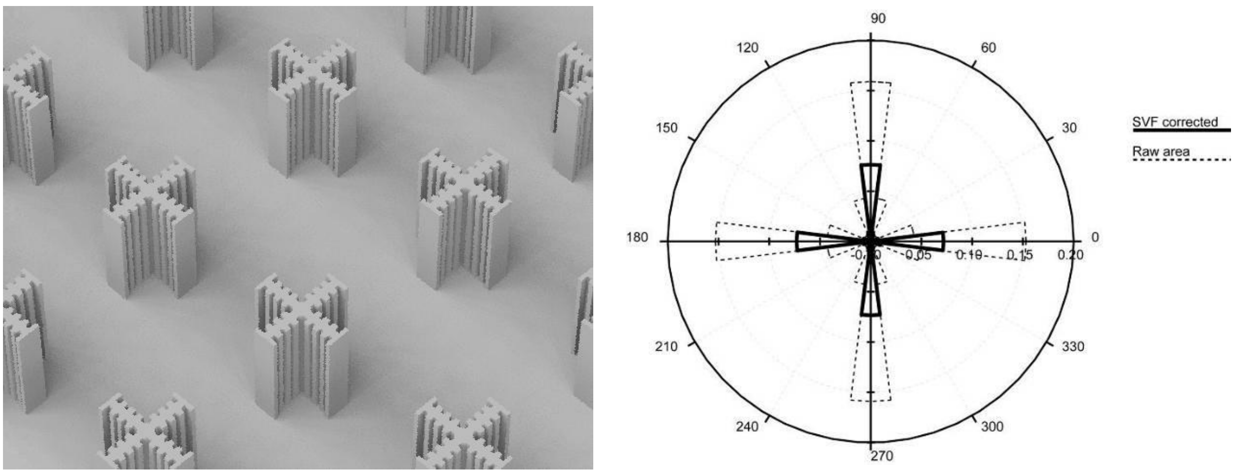


Figure 193: The "deeply serrated" skyscrapers' site (left) and orientation rose of the overall "deeply serrated" façades of the skyscrapers (Raw area and Sky View Factor corrected) (right).

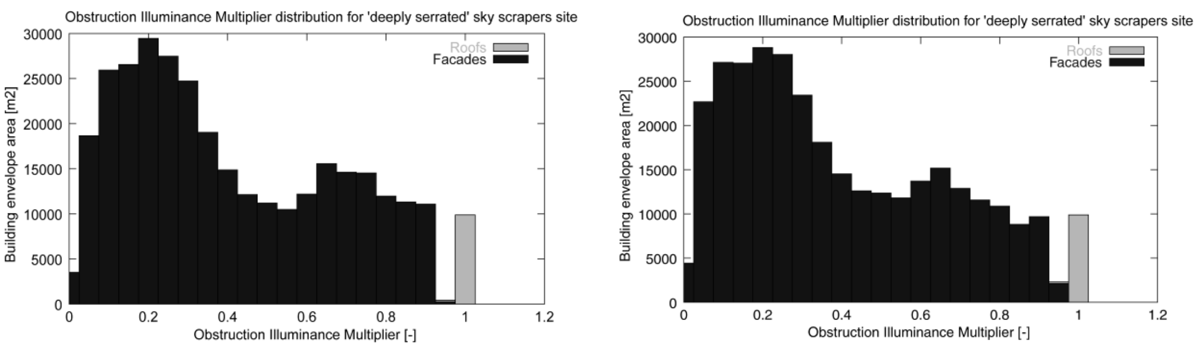


Figure 194: Obstruction Illuminance Multiplier(OIM) distribution for the "deeply serrated" skyscrapers'site. During the entire year (left) and during the heating season only (right).

However, although the daylight viability is reduced with the “deeply serrated” design, the benefit of this shape is that all offices have a visual access toward the outdoors, when compared to a square tower where the majority of offices are windowless (see Figure 195). Despite this option, most of the indoor spaces are poorly lit: 76.3% of the façades receive a daylight viability factor under a threshold of 10 klx. While compared to the “uniform plane”, the offices under that threshold will be very deep and gloomy at the bottom of the room.

According to the meticulous studies of the architect Diestel of Hamburg (Germany), the economic advantages disappear above the eleventh floor; from that height upwards, the importance of the small-sized yard providing light also disappears. At this point, the actual towers begin with artificially lit and ventilated rooms (Neufert 1983).

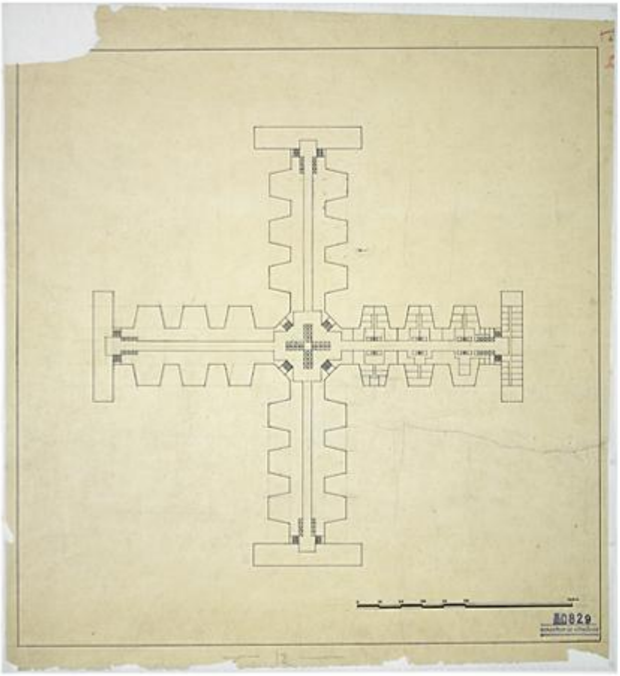


Figure 195: Le Corbusier. Typical floor plan of the “deeply serrated” skyscraper, 1922 ©FLC.

In 1930, besides the modification of individual building blocks, Le Corbusier also proposed to direct the whole plan of *La Ville Radieuse* to the so-called heliothermic axis described in Section 2.3.5. The heliothermic axis changes with geographic location: it is 19° towards the East for Paris as shown in Figure 196. Le Corbusier believed that directing the whole plan to this heliothermic axis could improve the overall daylighting performance.

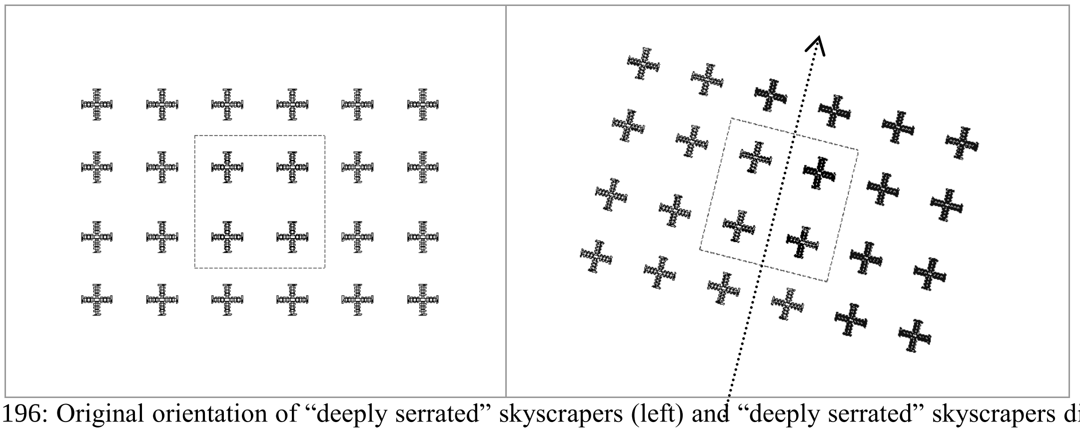


Figure 196: Original orientation of “deeply serrated” skyscrapers (left) and “deeply serrated” skyscrapers directed on the heliothermic axis towards the East at 19° (right).

The annual and Winter daylight viability of the “deeply serrated” skyscrapers in the new orientation are 22% and 9.8% respectively, whilst those of the “uniform plane” design are 42.8% and 18.5%. The results show a slight improvement in Winter (+1.3% “serrated”, +2% “uniform plane”) though; the annual daylight viability is reduced simultaneously (-1.7% “serrated”, -3.1% “uniform plane”).

Another way to evaluate the performance of the skyscrapers was to compare it with the urban blocks in Paris when the plan was proposed in 1922. In the 1900’s, the town councillors of the city of Paris designated about twenty so-called unhealthy street blocks that were to be demolished in order to receive healthier accommodations. Le Corbusier tackled the unhealthy block number 6 (see Figure 197) by using it to demonstrate a modern urban planning thesis. The restructuring of the district according to the precepts of Modern Architects was, to him, a first step towards the thorough redevelopment of the city.

Instead of the earlier houses dating from the seventeenth and eighteenth centuries, 50 metre- high towers and housing buildings would be erected. Lacking information, it was impossible to model block number 6. On the other hand, two typical building blocks, representing urban Paris as it was in the early twentieth century and as it is today, were chosen for the simulation. Figure 198 shows these two typical urban blocks.

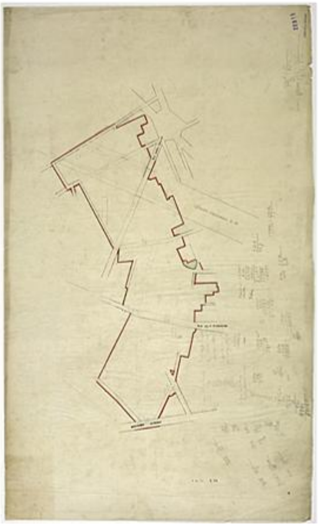
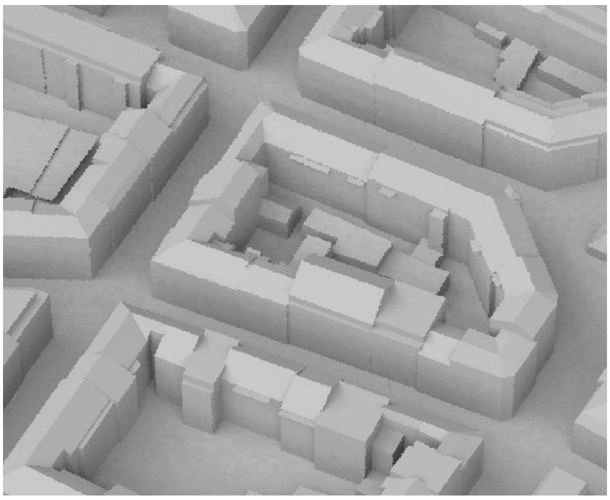


Figure 197: Le Corbusier. Drawing of boundaries of block number 6 in Paris (left) and perspective overview of the study project with serrated buildings and stadium (right), 1937 ©FLC.



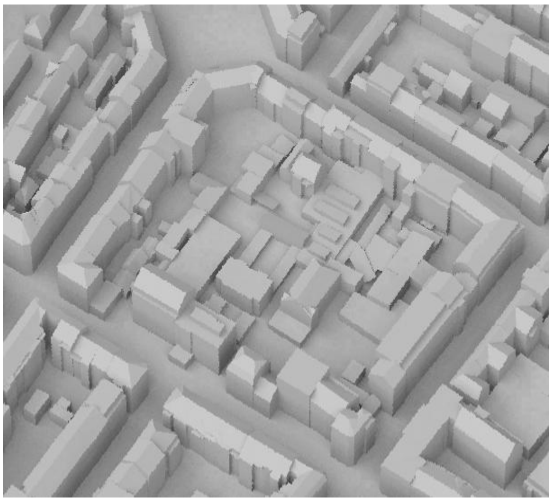


Figure 198: 3D Radiance rendering for Paris Urban Block 1 (left) and Urban Block 2 (right).

The annual and Winter daylight viability of Urban Block 1 is 34.6% and 14%, whilst that of Urban Block 2 is 48.9% and 20.3% respectively. The daylight viability of both urban blocks is significantly higher than the skyscrapers; hence the results suggest that Le Corbusier's skyscraper proposal might not be such an effective design option, in terms of daylighting performance.

However, the merit of the skyscraper proposal is obviously in the huge amount of usable floor area and open area it provides. The plot ratio of the skyscraper proposal is 3.8; those of Urban Block 1 and 2 are respectively 1.5 and 2. Hence, with typical urban blocks, 2 to 2.5 times more land is needed in order to provide the same amount of usable floor area as the skyscrapers and this does not take into account the amount of open space available in the skyscraper proposal. If the open space had to be taken into account, a further 1.3 to 2 times more land would have been required.

Daylighting performance of residential blocks

The results of the simulation of housing blocks reveal an interesting phenomenon. Annually, the housing "cellular" performs better than the housing "set-backs"; the daylight viability of the former is 65.7%, whilst the latter is 60.7%. Nevertheless, the situation is reversed during the Winter months. The daylight viability of the housing "cellular" is 14.6% in Winter, which is significantly lower than the 30.5% obtained with housing "set-backs".

As can be seen from the results, both housing blocks have significantly better daylighting performance than the skyscrapers, which is certainly due to the very different building forms that were made up of numerous façades (or facets for skyscrapers) and which were orientated in different directions.

The annual daylighting performance of these two housing blocks is a lot better than the typical Paris urban blocks that are shown in Table 37. The results suggest that the housing "set-backs", which have a fairly good daylighting performance annually and an outstanding performance in Winter, would offer a viable design option, in terms of daylighting performance.

Though the daylighting performance of the housing "set-backs" is greatly appreciated, the lower less usable floor area available in this layout might be a drawback. The plot ratio of the housing "set-backs" is 0.7, which is much lower than the 1.5 and 2.1 plot ratios of Paris urban blocks. This means that, in order to provide the same amount of usable floor area as the Paris urban blocks, 2-3 times more land area will be needed with the housing "set-backs" layout.

Table 37: Summary of results with different built forms

Cases	Plot Ratio	Site Coverage	Daylight Viability (Annual)	Daylight Viability (Winter)
Skyscrapers	3.8	6.30%	23.70%	8.50%
Housing "**Set-backs**"	0.7	12%	60.70%	30.50%
Housing "**Cellular**"	0.9	18%	65.70%	14.60%
The *Contemporary City (Paris)**	0.83	11.40%	53.20%	10.50%
Urban Block1 (Paris)	1.5	28%	48.90%	20.30%
Urban Block2 (Paris)	2.1	52%	34.60%	14%

* Overall performance including skyscrapers, housing "set-backs" and housing "cellular"

The overall performance of the *Contemporary City* as seen from Table 37 does not appear to be significantly better than the Paris urban blocks. Although it has a higher daylight viability, its performance in Winter is worse than the Paris urban blocks. Moreover, if density is to be taken into account, the proposal of the *Contemporary City* was significantly inferior to the Paris urban blocks.

As in the case of the skyscrapers, simulations of the housing “set-backs” and housing “cellular” were conducted in the orientation to heliothermic axis. Table 38 shows the results. The findings reveal an improvement in Winter daylight potential and a reduction in annual daylight potential. This is comparable to the findings and previous observation in skyscrapers.

Table 38: Summary of results with different built forms

Cases	**Daylight Viability Original Orientation**		**Daylight Viability Heliothermic axis**	
	(Annual)	**(Winter)**	**(Annual)**	**(Winter)**
Skyscrapers	23.70%	8.50%	22%	9.80%
Housing “**Set-backs**”	60.70%	30.50%	61.40%	30.50%
Housing “**Cellular**”	65.70%	14.60%	60.90%	19.20%

In this study work, the housing “set-backs” and housing “cellular” were directed exactly according to the heliothermic axis, which was not the case in Le Corbusier’s time. Harzallah (Harzallah 2007) writes that Le Corbusier did not direct his housing “set-backs” exactly following that axis, namely 20° in comparison to the north-south axis, 19° in Paris. In the *Contemporary City*, he gave housing blocks a North-South direction, whereas in *La Ville Radieuse* he gave a 26° angle starting from the North, the other way round in comparison to the heliothermic axis. The plans of *La Ville Radieuse* were therefore incorrectly directed. Only the arrow representing the heliothermic axis needed to be corrected in order to conform to the theory of *La Science des plans de villes*[64] . This superimposition gave a strange look to the plan of *La Ville Radieuse* and showed at the same time that Le Corbusier had taken the liberty of interpreting scientific theories in his own way, whatever the contradictions of the heliothermic axis. Furthermore, he applied the heliothermic orientation to housing “set-backs” showing different orientations, when initially it was meant for parallel block development layout as explained in Section 2.3.5. This organization induced cast shadows’ effects that the heliothermic theory did not consider. It must be emphasized that the first version of a utopian city, *Contemporary City of Three Million Inhabitants*, was directed according to the North-South/East-West axis by Le Corbusier (see Figure 199).

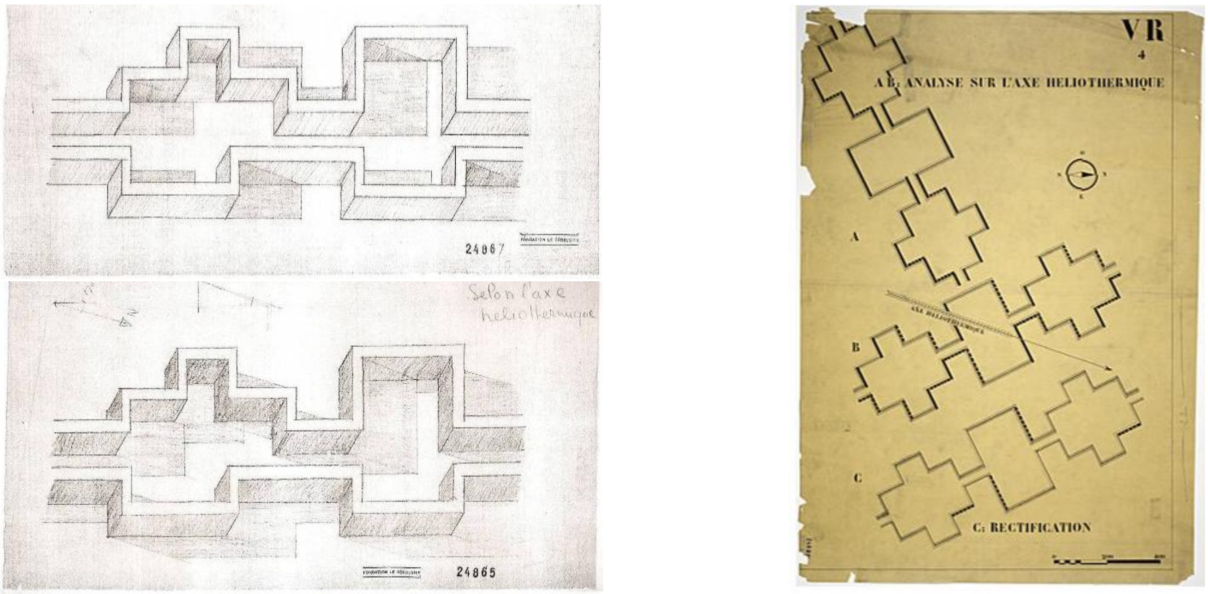


Figure 199: Le Corbusier. Jeu de La Ville Radieuse (left top and bottom); analysis on the heliothermic axis, combination plan on housing “set-backs” with solar radiation (right), 1930 ©FLC.

[64] Rey, A.-A., Pidoux, J., Barde, C. (1928). *La science des plans de villes : ses applications à la construction, à l’extension, à l’hygiène et à la beauté des villes : orientation solaire des habitations*. Lausanne, Payot.

Apart from the change in orientation, Le Corbusier also reduced the building height of the two housing blocks from 50 m to 30 m, which corresponds to a 40% reduction in usable floor area. The intention behind this modification was to obtain maximum solar radiation over the whole internal and external development of the housing “set-backs”. The reduction in building height results in significant improvement in daylighting performance. The increase in annual daylight viability for the housing “cellular” block is about 30% and the increment in Winter daylight viability ranges from 80-94% - which represents a significant difference. Obviously, in this case there is a trade-off between density and daylighting performance.

Finally, Harzallah (Harzallah 2007) writes that the simultaneous use of housing “set-backs” and the heliothermic axis was awkwardly exploited by Le Corbusier. The principle of the set-backs was to form unaligned blocks to enable these façade parts to be exposed according to a favourable orientation (see Figure 200), whereas the housing “set-backs” designed by Le Corbusier made up blocks which cast shadows on each other.

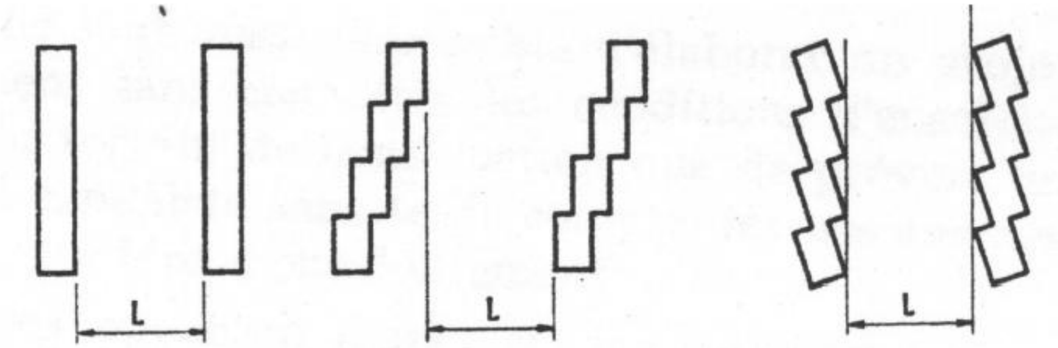


Figure 200: Twarowski. Housing “set-backs” development Layout, 1967.

Source: Harzallah, A. (2007). Emergence et évolutions des préconisations solaires dans les théories architecturales et urbaines en France, de la seconde moitié du XIXème siècle à la deuxième guerre mondiale. *Thèse de doctorat. Ecole Nationale Supérieure d'Architecture de Nantes*. Université de Nantes

Comparison of Paris and São Paulo

The simulation of annual daylight viability for the skyscrapers, housing “set-backs” and housing “cellular” was repeated with the original orientation and the heliothermic axis using the sky conditions in São Paulo. The heliothermic axis of São Paulo was found to be the same as Paris i.e. 19° towards the East. Table 39 is a summary of the results.

Table 39: Summary of results for Paris and São Paulo

Cases	**Daylight Viability Original Orientation**		**Daylight Viability Heliothermic axis**	
	Paris	**Sao Paulo**	**Paris**	**Sao Paulo**
Skyscrapers	23.70%	32.80%	22%	33.50%
Housing “Set-backs”	60.70%	80.90%	61.40%	85.60%
Housing “Cellular”	65.70%	87.50%	60.90%	87.30%

The results show significant differences between Paris and São Paulo and can be explained by the high solar altitude and the higher solar radiation availability in São Paulo. Nevertheless, one interesting result was the positive effect of the heliothermic axis. In previous observations of Paris, the heliothermic axis was beneficial in Winter but unfavourable annually. Nevertheless, the results in São Paulo generally showed positive effects of the heliothermic axis on annual daylighting performance. The phenomenon is worth further study and will be discussed in detail in the next section.

Effect of the Heliothermic Axis

As explained in Section 2.3.5, the heliothermic axis represented the most desirable orientation of the buildings for solar access and for the natural heating and cooling processes. It was first devised by Augustin Rey, who established the concept of the heliothermic axis as the relationship between solar duration and air temperature. Le Corbusier considered it one of the most important principles in urban design. Figure 201 is an illustration of the heliothermic axis of Paris.

In order to understand more about its effect, daylight simulation of standalone surfaces facing various orientations was conducted. Table 40 and Table 41 illustrate these results.

Table 40: Results of wall experiment for Paris

Surface*	Illuminance [klux] Original Orientation		Illuminance [klux] Heliothermic axis	
	Annual	**Winter**	**Annual**	**Winter**
N / NE	9.2	6.3	9.5	6.3
E / SE	16.7	11	17.7	12.3
S / SW	22.7	18.9	21.6	18.2
W / NW	14.8	10.6	13.1	9.1
∑ Sum	63.4	46.8	61.9	45.9

* A / B: A - orientation in original case and B - orientation to the heliothermic axis

Table 41: Annual results of wall experiment for São Paulo

Surface*	Illuminance [klux] Original Orientation		Illuminance [klux] Heliothermic axis	
	0°	**19°**	**0°**	**19°**
N / NE	9.2	9.5	24.9°	23.9
E / SE	16.7	17.7	20	17.9
S / SW	22.7	21.6	12.9	13.3
W / NW	14.8	13.1	21	21.8
∑ Sum	63.4	61.9	78.8	76.9

* A / B: A - orientation in original case and B - orientation to the heliothermic axis

As can be seen from Table 40 and Table 41 orientation towards the heliothermic axis generally results in higher illuminance level on the N/NE and E/SE surfaces, whilst it causes reduction in illuminance level on the S/SW and W/NW surfaces. On the other hand, the results for São Paulo shown in Table 41 reveals an increment on the S/SW and W/NW surfaces and decrement on the N/NE and E/SE surfaces.

When the overall performance is taken into account, the effect of the heliothermic axis is negative as it results in a lower total illuminance. This comparison, however, is not completely reliable as the calculation of the sum assumes equal areas on all sides; the results could vary a lot if the building is not regularly shaped. Hence, the comparison suggests that the shape of the building has significant influence on the effectiveness of the heliothermic axis.

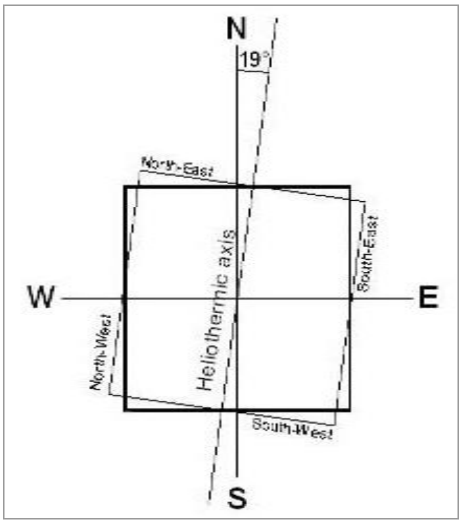


Figure 201: The Heliothermic axis of Paris.

Balance of the *Contemporary City of Three Million Inhabitants* analyses

Numerical simulations carried out over several typical buildings of the *Contemporary City of Three Million Inhabitants*, one of the precursory projects of *La Ville Radieuse* proposed by Le Corbusier, showed that Bardet's and Lebreton's criticisms were well-founded. In a chapter entitled *La Ville dite radieuse* (The so-called radiant city) published in *Pierre sur Pierre* (Bardet 1945), Bardet analysed in a very critical way the various elements of *La Ville Radieuse*. Nothing was left aside, neither the hyperconcentration intended by Le Corbusier, the housing "set-backs" used, nor the supposed suppressed corridor-like streets. Bardet also pointed out that the solar potential of indoor and outdoor spaces of that city that would suffer, in his opinion, from insufficient exposure to the sun and from the casting of huge shadows that would produce a cellar microclimate at the bottom of the city walls. Lebreton also criticized the hyperconcentration, the density of shadows and, in particular, questions the orientation and sunlight issues of that city: he deemed it obsolete to resort to heliothermic theories (Harzallah 2007).

The comparison of density and daylight potential between the *Contemporary City* and the old Paris urban blocks suggested that the claims made by Le Corbusier for this ambitious urban plan may not be totally valid. The proposal might be effective in terms of transportation and in the availability of large green and open areas; however, from the point of view of exposure to daylight, it did not seem to perform better than the more traditional designs. Moreover, Le Corbusier overlooked the significant ground-level shadows cast by such high buildings.

The daylighting performance of the skyscrapers was particularly poor. The findings appeared to suggest that the skyscraper proposal was, indeed, an ineffective design option for Central Paris.

On the other hand, both housing "set-backs" and housing "cellular" showed good daylighting performance. Nevertheless, the much less usable amount of floor area available in these layouts could be a drawback.

The effect of the heliothermic axis is ambiguous. Although Le Corbusier considered it as "the framework of the city plan[65], its effect on daylight potential was not confirmed in the study. However,

[65] *L'armature du tracé urbain* in French in the text.

the latter could have been somewhat biased as the effect of the heliothermic axis was evaluated purely in terms of illumination; the results might have been different if other factors such as solar heat gain/loss had been taken into consideration.

From 1927 until 1934, a first attempt at the construction of low-rent dwellings was carried out in Paris and especially in its outlying districts. Twice during those years, the architect Le Corbusier, a huge admirer of Haussmann's work, attempted to modify Paris' urban planning—at first through *Le Plan Voisin* and then again in 1937. These projects, as outrageous as they may seem, were presented seriously at that time. They reflected a new concept of the city, as well as an almost pathological obsession to generate modernity.

In summary, the *Contemporary City of Three Million Inhabitants*, the rational and systematic urban plan designed by Le Corbusier, does not seem to be an effective design option for either density or daylighting performance. The architect seemed to aspire to a global and drastic reform of the urban fabric of the capital. To serve that purpose, he mentioned health regulations that existed in the urban thinking of his own era, yet which today are lacking in scientific rationality. His intention to generalize this system to the scale of a city would turn out to be problematic and questionable. On the other hand, the more random traditional pattern, which showed similar daylight potential and possibly higher density, might have been a more appropriate choice.

One has to acknowledge that Le Corbusier's architecture principles were innovative for that time and that they helped to solve the problem of the housing crisis. Moreover, he was also planning cities that functioned and where the inhabitants could move around on foot. It must be borne in mind that a city has to be a complete and harmonious entity, adapted to all of modern man's needs, which is contrary to the notions of bedroom residential areas or dormitory suburbs.

4.10 Conclusion

Chapter 4 presented the different studies undertaken within the framework of national and international research. As a first step, six existing urban sites in Switzerland and Brazil, as well as two projects in the United Kingdom, a few generic models and a utopian city, were modelled and analyzed. The results obtained from these different case studies revealed large variations of the potential for solar energy collection on the buildings' façades and roofs.

The principal findings of this study confirm that, Matthaeus district in Basel has very large façade and roof areas which open up good prospects for the utilisation of solar energy. As the high density of the urban site reduces the sun and daylight access to the buildings, part of the area does not benefit from yearly average solar irradiances and daylight illuminances that are technically and economically appropriate for direct solar technologies. However, assessment of the relative fraction of suitable façades and roofs, based on the minimum required irradiation and illuminance thresholds, shows that a very significant part of these areas remains appropriate for solar technology operations, despite the urban character of the site.

The study of the generic urban forms case in Basel reveals that the most efficient urban form in terms of daylighting and solar potential is "Blocks", followed by "Slabs", "Terraces", and "Pavilions". The urban form "Blocks" would allow one to address the crucial problems which are crying out for a solution in the towns: namely an alarming lack of dwellings and the necessary densification to safeguard the green belts of the town periphery.

The pilot building "Aloys-Fauquez N°29-31" study on the Bellevaux district in Lausanne confirm that the total useable solar irradiation that falls on the façades and roofs theoretically meets the demand to install solar thermal collectors on the façade. The irradiation per floor area evaluated by PPF is three times larger than the thermal energy, which should cover the yearly hot water and heating requirements for the building. Concerning the electricity needs, the effective output of the BiPV plant is not large enough to cover the total demand for electricity, which is necessary for the proper functioning of the building. In fact, this demand is twice as large as the output from the BiPV roofing installations.

The satellite town of Meyrin in Geneva developed in the spirit of the hygienist movement is generally typified by the parallel blocks development layouts, which show a South-West/North-West orientation and have a larger potential than the other configurations. Those buildings with a South-East/North-West orientation should be a little further from each other for optimal performance.

Concerning Les Pâquis 1&2 district in Geneva, the potential of urban densification provided by raising the existing buildings is relatively limited by the 2007 governmental bill. Few apartment blocks would be concerned by these transformations and would find it difficult to remain economically viable without them. The increased elevation of the buildings permitted by law had a minimal effect on the solar performance indicators of the buildings, the latter being not significantly affected.

Tower Work's site results in Leeds show that neither the "Final project" nor its integration into its urban context are convincing from the point of view of solar utilisation potential. Architectural considerations took precedence over environmental aspects. The modelling of the "Draft project" and its use without obstructions have distorted the analyses and have certainly produced errors affecting the continuation of the project.

The results of "Eastern Quarry -Flat topography with cliff" in London show that the proposed gradation of the site up towards the north has a positive effect. This is more significant for Winter solar availability on south-facing façades. The potential of "Eastern Quarry -Flat topography without cliff" is almost invariably lower than the one of "Eastern Quarry -Flat topography with cliff". This means that the slope of the site has a positive influence on the various solar strategies excepting passive solar gains in Winter. In conclusion, the buildings that are erected on a sloping site remain less affected by the urban texture, which means they have a better view of the sky vault and that shadowing effects are limited: the sloping site significantly favours the solar potential and daylighting of the buildings.

Barra Funda and Luz analyses in São Paulo reveal that the different manifestations of built density (i.e. plot ratio, site coverage and compactness index) play different roles in determining urban daylight and solar potential. According to the results of this particular case study, daylight and solar performance indicators such as daylight factor, sky view factor and solar thermal and photovoltaic potential on roofs are more correlated to the plot ratio and compactness index. This would suggest that these quantities are more influenced by vertical obstruction, in other words, more dependent on light coming from the top. On the other hand, solar thermal and photovoltaic potential on façades are better correlated to site coverage and unobstructed façade area, therefore these quantities are more influenced by horizontal obstruction, which means more dependence on light coming from the sides.

The *Contemporary City of Three Million Inhabitants*, the rational and systematic urban plan designed by Le Corbusier, does not seem to be an effective design option for either density or daylighting performance. The architect seemed to aspire to a global and drastic reform of the urban fabric of the capital. To serve that purpose, he mentioned health regulations that existed in the urban thinking of his own era, yet which today are lacking in scientific rationality. His intention to generalize this system to the scale of a city would turn out to be problematic and questionable. On the other hand, the more random traditional pattern, which showed similar daylight potential and possibly higher density, might have been a more appropriate choice.

Finally, this conclusion ends with a general evaluation concerning the impact of density on the cities that were studied as well as a reminder about the implications of particular decisions concerning:
- Façades’ exposure;
- Daylight and solar potential availability related to façades' exposure;
- Building height, street width or distance between buildings and orientation of streets;
- Annual and Winter daylight availability in courtyards;
- Orientation and degree of inclination of the section roofs (solar collectors).

Putting to one side the graphics relative to the impact on plot ratio and the impact on obstructions, this evaluation has been carried out for each specific case with the help of an identical generic form – so as not to favour or to neglect certain sites. Consequently, these results are uninfluenced and are in no way dependent on the nature of the urban forms, except for the subsection Impact on density, which was conducted on existing sites.

Impact on density

To curb urban sprawl there is an increasing demand for further densification of urban areas. There have also been numerous controversial debates arguing for further densification on the basis of (net) energy consumption. It is interesting therefore to explore the results in relation to site density in order to identify whether any interesting relationships emerge.

The solar energy efficiency index related to site and buildings used in this conclusion was determined in Section 4.3.3 – Section “Generic urban forms studies”. Figure 202 shows that a large site area with a weak plot ratio will have a relatively low solar energy efficiency index related to site: such is the case for the Meyrin site which possesses a plot ratio of 0.19 and a solar energy efficiency index of 0.12. Compared to this, “Les Pâquis street block 2” with a plot ratio of 6.04 possesses with 3.30 the highest solar energy efficiency index related to site. With only one exception, these two curves are therefore strongly correlated, which is hardly surprising. Nevertheless, for the Bellevaux site the solar energy efficiency index related to site exceeds the plot ratio. This means that for the Bellevaux site with an average plot ratio of 0.50 and a solar energy efficiency index related to site of 0.68 its efficiency is relatively higher in relation to its plot ratio. In addition, the curve of the solar energy efficiency index related to site draws nearer twice as much as the two urban sites, Meyrin and Eastern Quarry, yet without falling below. These results may be partly explained by a weak obstruction at the Bellevaux, Meyrin et Eastern Quarry districts as well as by an increased percentage of their façades being located in the favourable South-West sector, and not least by the condition of the sloping terrain at Bellevaux and Eastern Quarry. Notwithstanding, these suppositions do not always explain the marked difference of Bellevaux from the other districts.

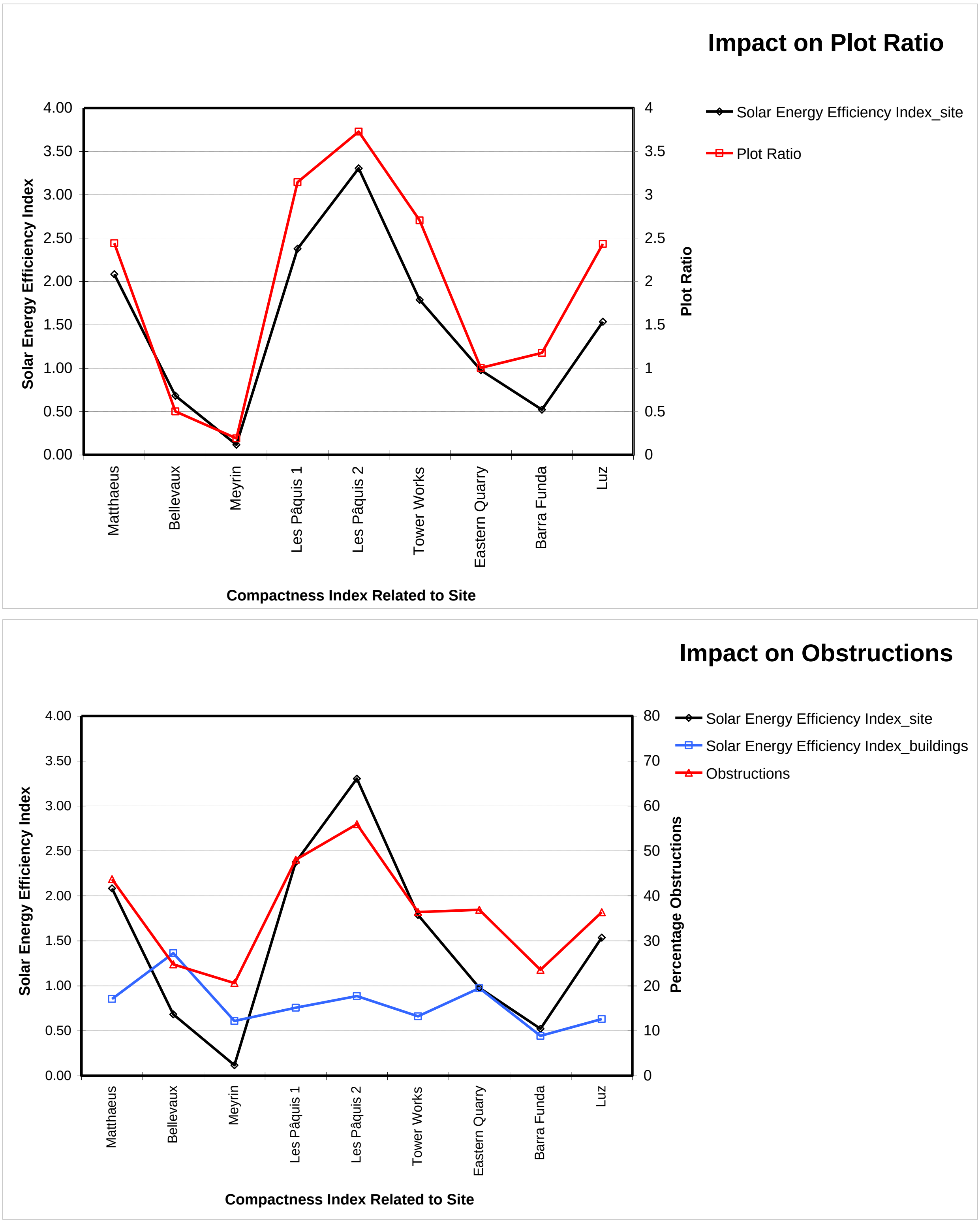
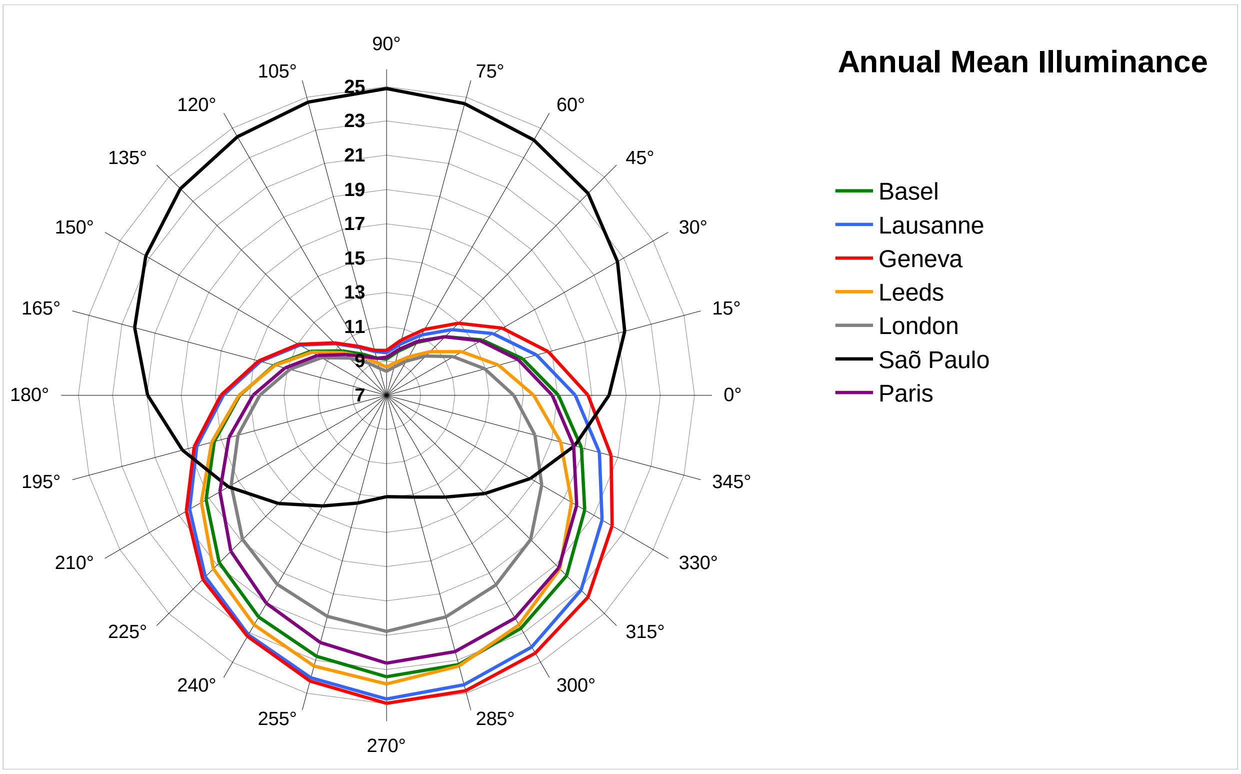


Figure 202: Impact on plot ratio (top) and impact on obstructions (bottom).



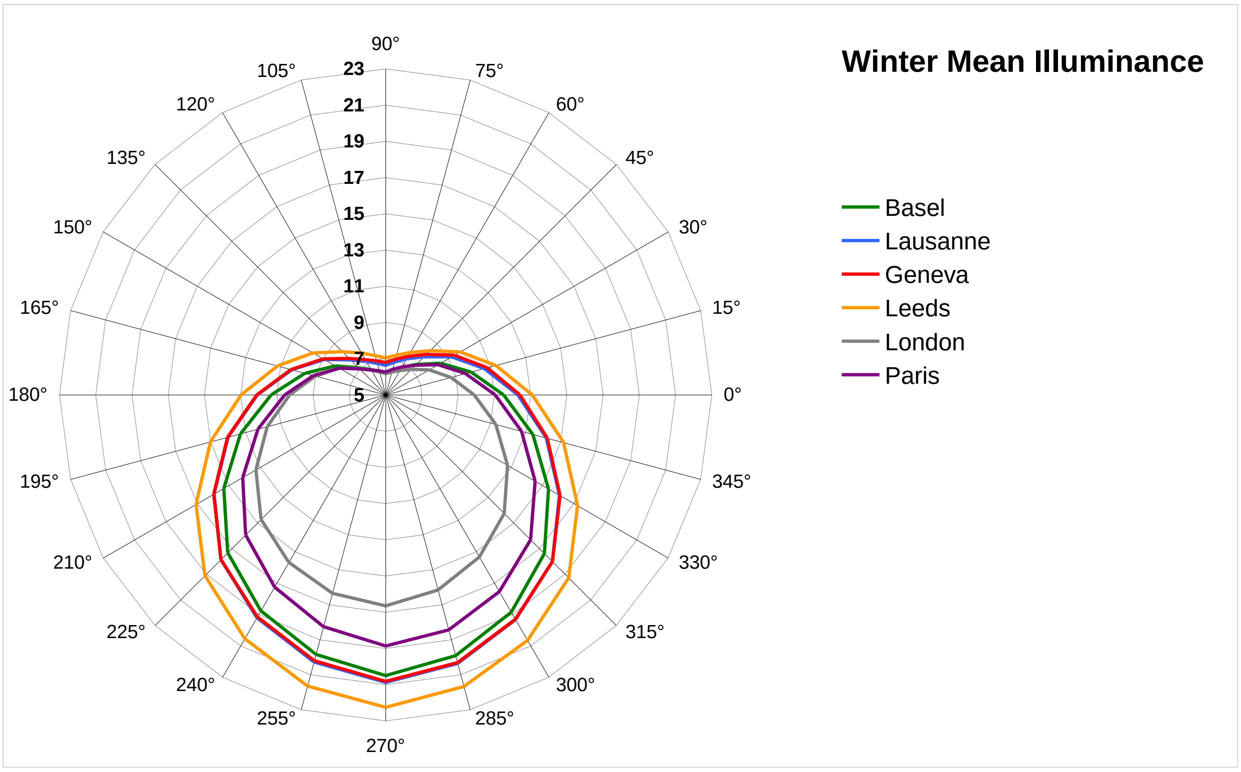


Figure 203: Annual and Winter illuminance in [kLux] for a façade according to its localisation and orientation: North (90°), South (270°), East (0°) and West (180°) façades.

To take this a step further, Figure 202 shows that the solar energy efficiency index related to the urban sites and the obstructions follows similar patterns. On the other hand, the solar energy efficiency index related to buildings is less well correlated.

The Bellevaux district has – with 25% of obstructed façades and the façades occupying the NE and NW (both 25% with a slight predominance towards the direction SW (28%) – the strongest solar energy efficiency index related to buildings and Barra Funda the weakest. Matthaeus district comes in second place after Bellevaux. This histogram also demonstrates that “Les Pâquis street block 2” – with 56% of obstructed and an equal distribution of façades in the NE, SE and NW sectors, with a slight disadvantage for the south-west sector – performs better in terms of annual irradiation than Meyrin – with 20.6% of obstructed façades and the four directions NE, SE, SW and NW equally represented. The Eastern Quarry development holds up better than Tower Works at the level of the urban form, however its solar energy efficiency index related to site is inferior. Meyrin and Barra Funda are the two least obstructed sites, which – either urban form and site – perform least well in terms of solar energy efficiency.

A visual examination of the 3 curves reveals that “Les Pâquis street block 2” comes in first place, Matthaeus in second and Bellevaux in third – in terms of the solar energy efficiency index related to the urban sites and buildings. The favourable climatic conditions of Geneva certainly explain in part this performance for “Les Pâquis street block 2”, but they do not justify an equally good result in relation to Meyrin which was constructed under the influence of the hygienist spirit of that period and whose evaluation of solar potential was carried out with the typical Winter sky conditions of Geneva – in other words the same as “Les Pâquis street block 2”.

Façades’ exposure

Figure 203 shows the annual and Winter illuminance in kilo-lux of a vertical street façade according to its geographical location and its orientation, without taking the shadows cast by neighbouring buildings into account. In the figure representing the Annual Mean Illuminance, one can clearly distinguish 2 groups whose façades annually receive for the same given direction a maximum illuminance:
- North façade for São Paulo;
- South façade for Basel, Lausanne, Geneva, Leeds, London and Paris.

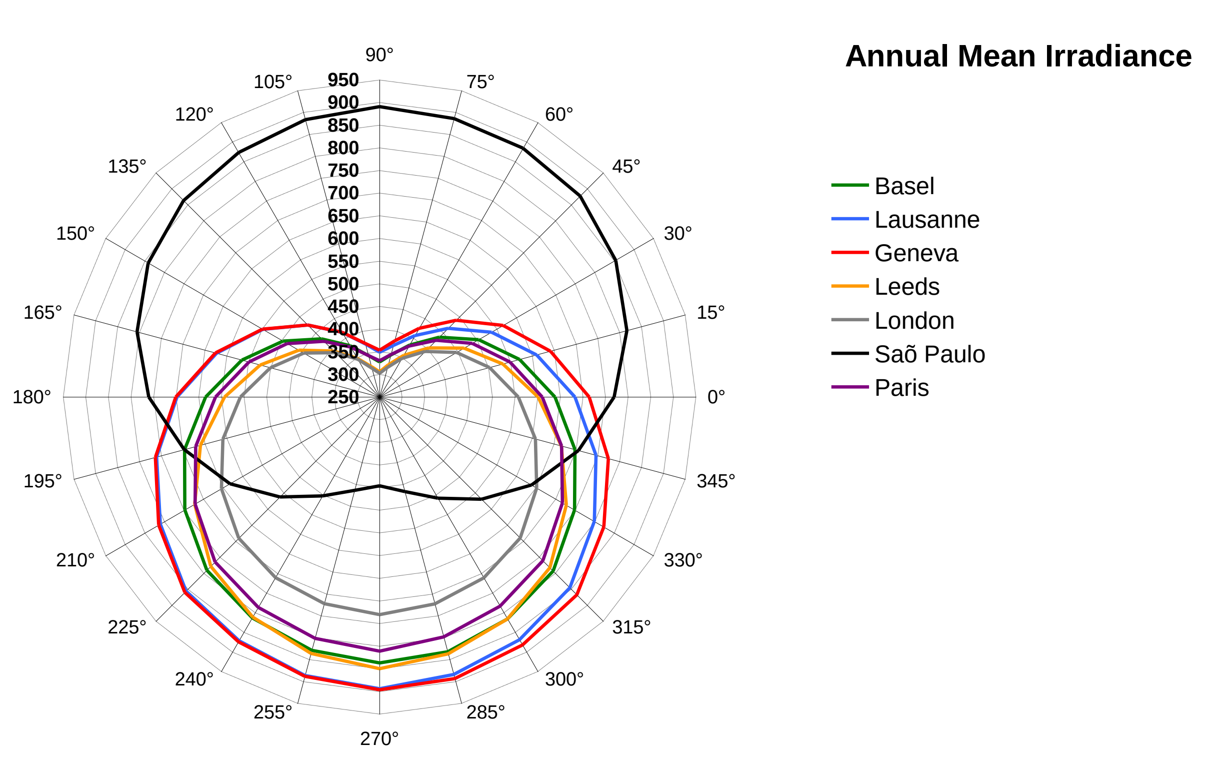
For the European sites, it is obviously those orientations which are closest to the South (-45° and 45°) which result in the strongest illuminance. However, in the group whose South façade is favourable, Geneva clearly stands out from the rest in displaying a dramatically stronger illuminance going from 9.61 to 24.97 kLux and which moves in the direction of the East. Basel, Lausanne and Paris reveal the same asymmetrical quality in veering towards the East, as opposed to Leeds which seems perfectly symmetrical. Once again, it has to be emphasized that London possesses the smallest annual illuminance (8.4 to 20.77 kLux) of all the sites and that naturally São Paulo with 12.92 to 24.88 kLux performs the best. It’s the Winter season which makes the difference here as there is not one day where the temperature is lower than 12°C.

In contrast to the annual calculation, the Winter Mean Illuminance regroups all the sites in the favourable direction South, except for the city of São Paulo which does not include a Winter season and for which consequently the calculation was not effective.

In Winter, it is the Leeds site which astonishingly presents the strongest illuminance and London the smallest. All the curves seem symmetrical and Geneva merges with the curve for Lausanne.

From this, one can therefore conclude that annually as in Winter the South direction seems to be the most efficient in terms of daylighting for the European sites, but that the directions South-West and North-East are still very suitable.

Figure 204 shows that the annual and Winter irradiation logically follow the same pattern as the annual and Winter illuminance. London possesses the smallest annual irradiance of all the sites going from 302.4 to 730.2 kWh/m^2.year and São Paulo with 446 to 890.6 kWh/m^2.year once again performs the best.



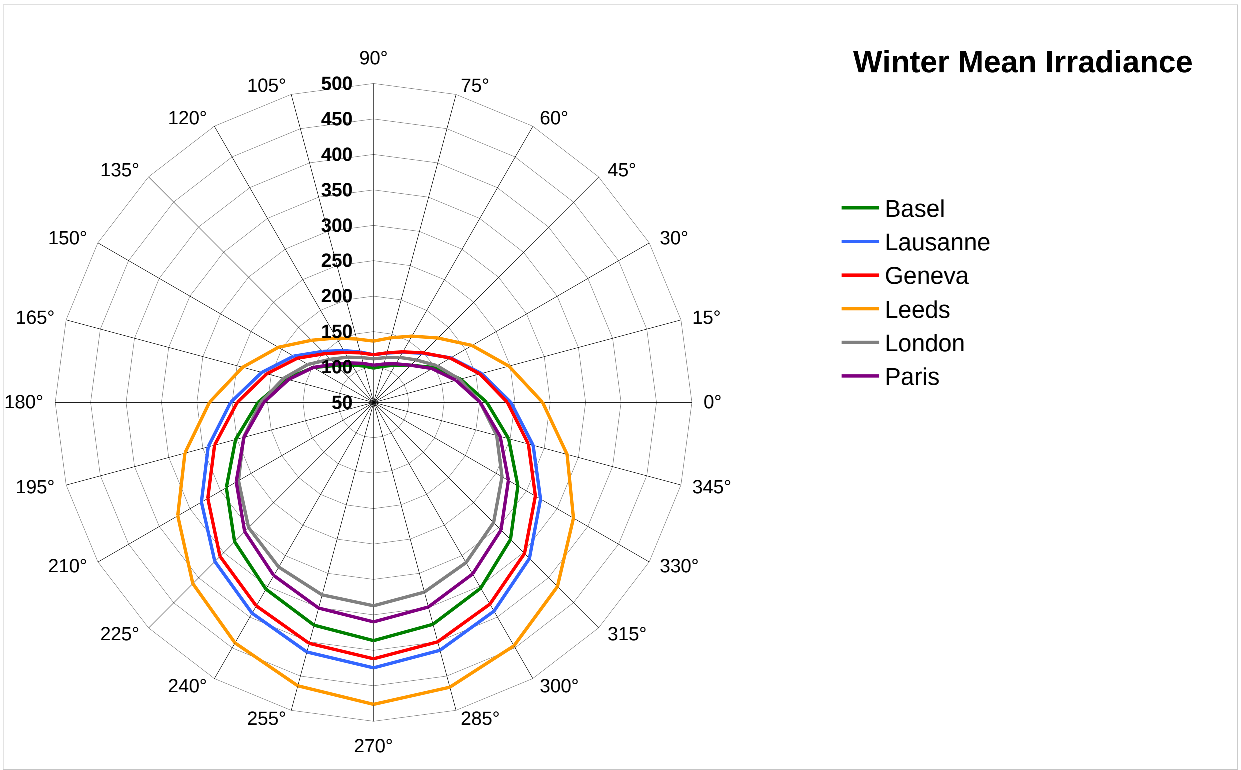


Figure 204: Annual and Winter irradiation in [kWh/m2.year] for a façade according to its localisation and orientation: North (90°), South (270°), East (0°) and West (180°) façades.

Daylight and solar potential availability related to façades' exposure

Figure 205 to Figure 208 illustrate the orientations of the façades adapted to the different solar technologies. These polar diagrams can help the architects and town-planners in adapting the orientations of the buildings to the various solar strategies which have to be used to meet all requirements. Daylighting is the technology which most of all encompasses the different polar diagrams relative to each site. Those cities which receive annually more than 90% of daylighting availability run from the direction North-East to North-West for:

- Basel : 60° NE to 150° NW;
- Lausanne : 60° NE to 135° NW;
- Geneva : 45° NE to 135° NW;
- Leeds : 45° NE to 150° NW;
- London : 45° NE to 150° NW;
- São Paulo : 0° to 360°;
- Paris : 60° NE to 150° NW.

The direction North-East displays a difference of 15° between Geneva, Leeds and London with Basel, Lausanne and Paris. As for the direction North-West, there is a difference of 15° between Lausanne and Geneva with the other European sites. Obviously, São Paulo has the most extensive daylighting with a possible orientation of the buildings from 0° to 360° conserving practically for all directions a daylight availability of 100%. Naturally, in Winter, there is less daylighting and the towns which receive more than 90% of Winter daylighting availability run in the direction North-East to North-West for:

- Basel : 0° E to 180° W;
- Lausanne : 15° NE to 180° W;
- Geneva : 15° NE to 165° NW;
- Leeds : 15° NE to 165° NW;
- London : 15° NE to 165° NW;
- São Paulo : No Winter season;
- Paris : 0° E to 180° W.

As for passive solar availability, it rises for:

- Basel : 15° NE to 165° NW;
- Lausanne : 15° NE to 165° NW;
- Geneva : 15° NE to 165° NW;
- Leeds : 30° NE to 150° NW;
- London : 15° NE to 165° NW;
- São Paulo : No Winter season;
- Paris : 15° NE to 165° NW.

Leeds is the city which potentially can most exploit its passive solar gains in Winter. The optimal orientations of active solar availability are close to those of daylighting:

- Basel : 45° NE to 135° NW;
- Lausanne : 60° NE to 120° NW;
- Geneva : 60° NE to 120° NW;
- Leeds : 45° NE to 150° NW;
- London : 30° NE to 150° NW;
- São Paulo : 0° to 360°;
- Paris : 45° NE to 135° NW.

As was the case with daylighting, São Paulo has the most extensive active solar availability with a possible orientation of the buildings from 0° to 360°. Leeds is the only city whose potential for orientations of active solar availability remain practically unchanged with regards to daylighting.

As one might well expect, the building-integrated photovoltaics show the least potential of all the other solar technologies:

- Basel : 300° SE to 240° SW;
- Lausanne : 315° SE to 210° SW;
- Geneva : 330° SE to 210° SW;
- Leeds : 300° SE to 240° SW;
- London : No viable potential;
- São Paulo : 15° NE to 90° N and 165° NW to 105° N;
- Paris : 270° SE to 225° SW.

The technical viability (not to mention the economic viability) of the photovoltaic systems is weak. São Paulo is the only city which displays a BiPV interesting enough to exploit this system in the façade. Furthermore, considering there is no Winter season, this solar technology functions throughout the year.

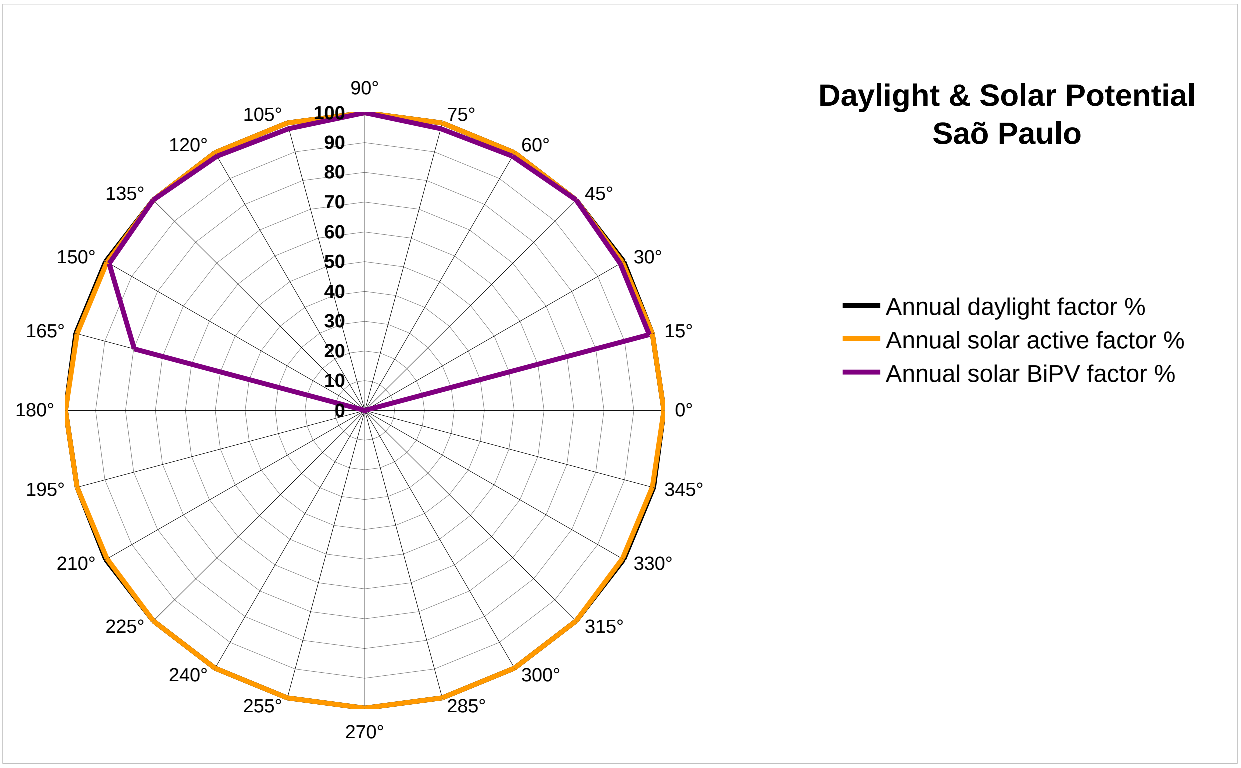
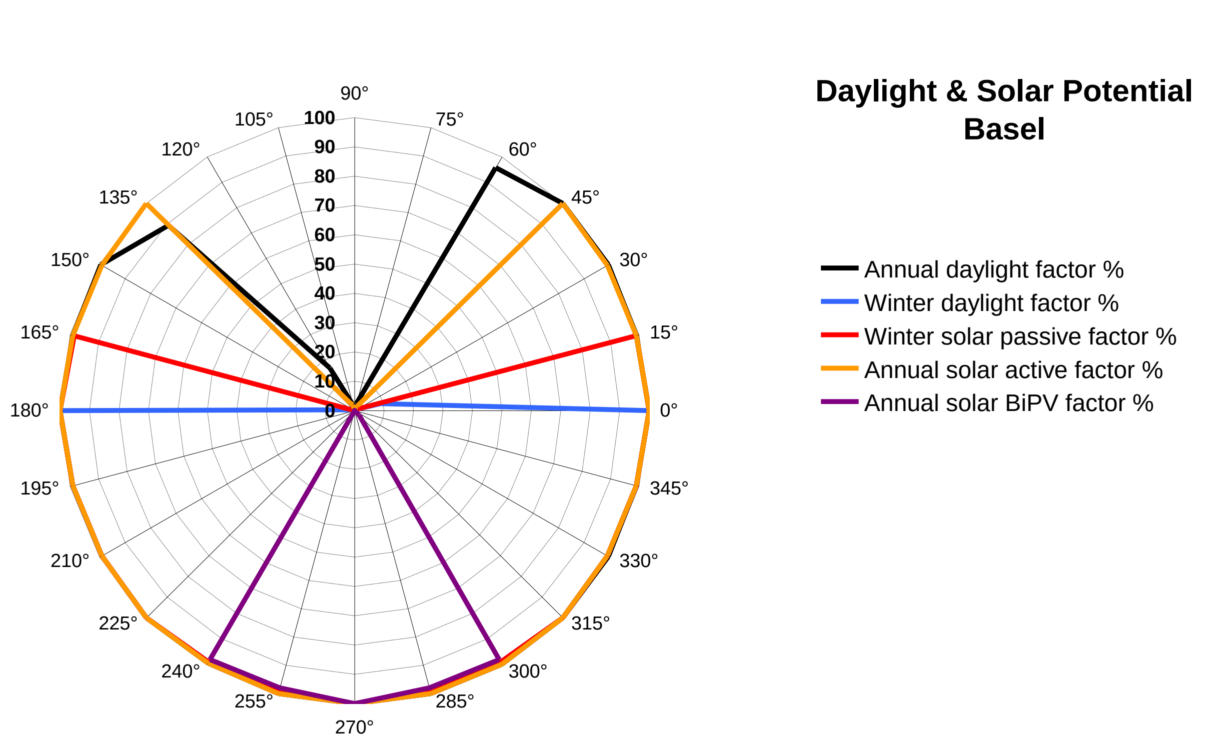


Figure 205: Saõ Paulo. Polar diagrams illustrating the orientations of the façades adapted to the various solar technologies. North is up.



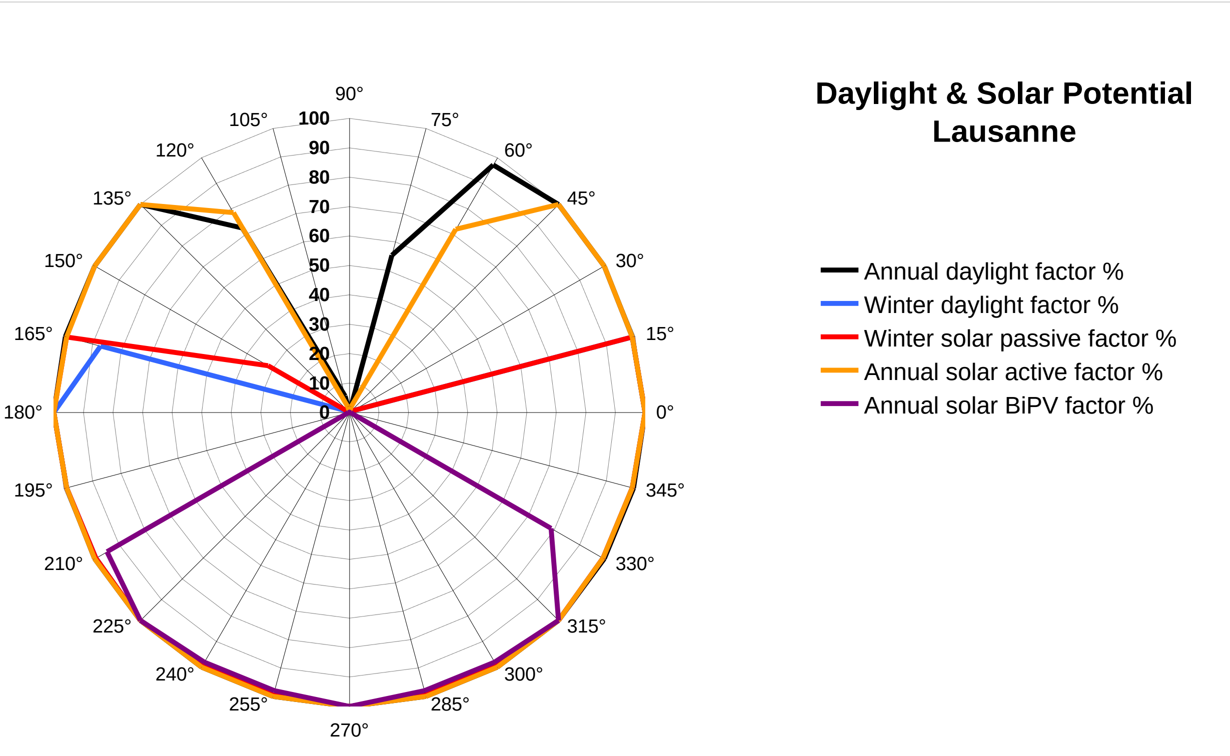
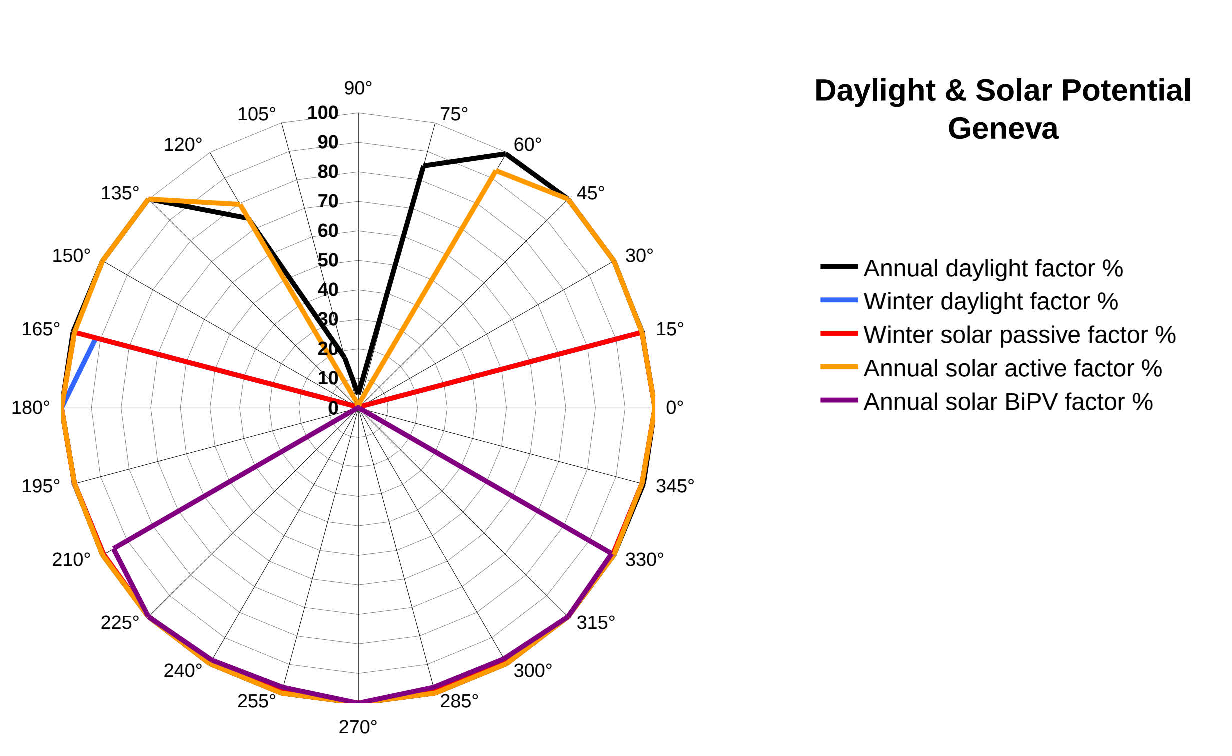


Figure 206: Basel and Lausanne. Polar diagrams illustrating the orientations of the façades adapted to the various solar technologies. North is up.



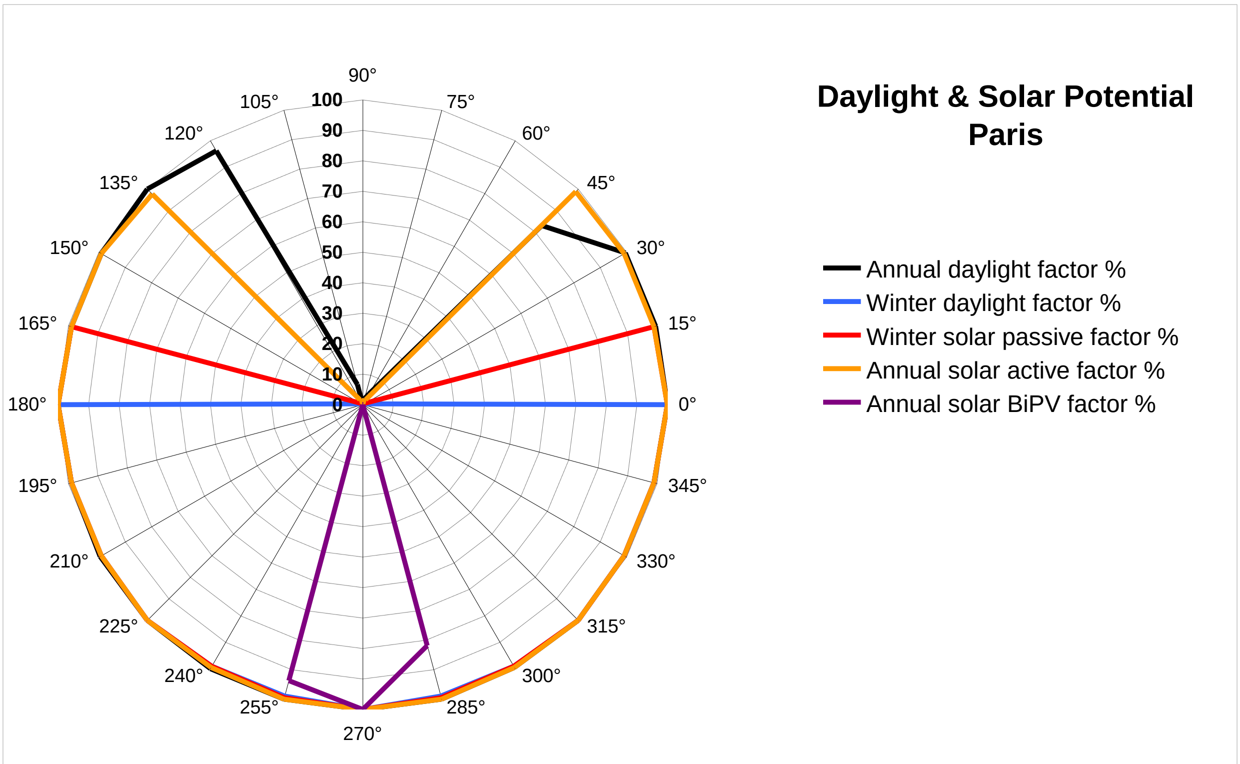


Figure 207: Geneva and Paris. Polar diagrams illustrating the orientations of the façades adapted to the various solar technologies. North is up.

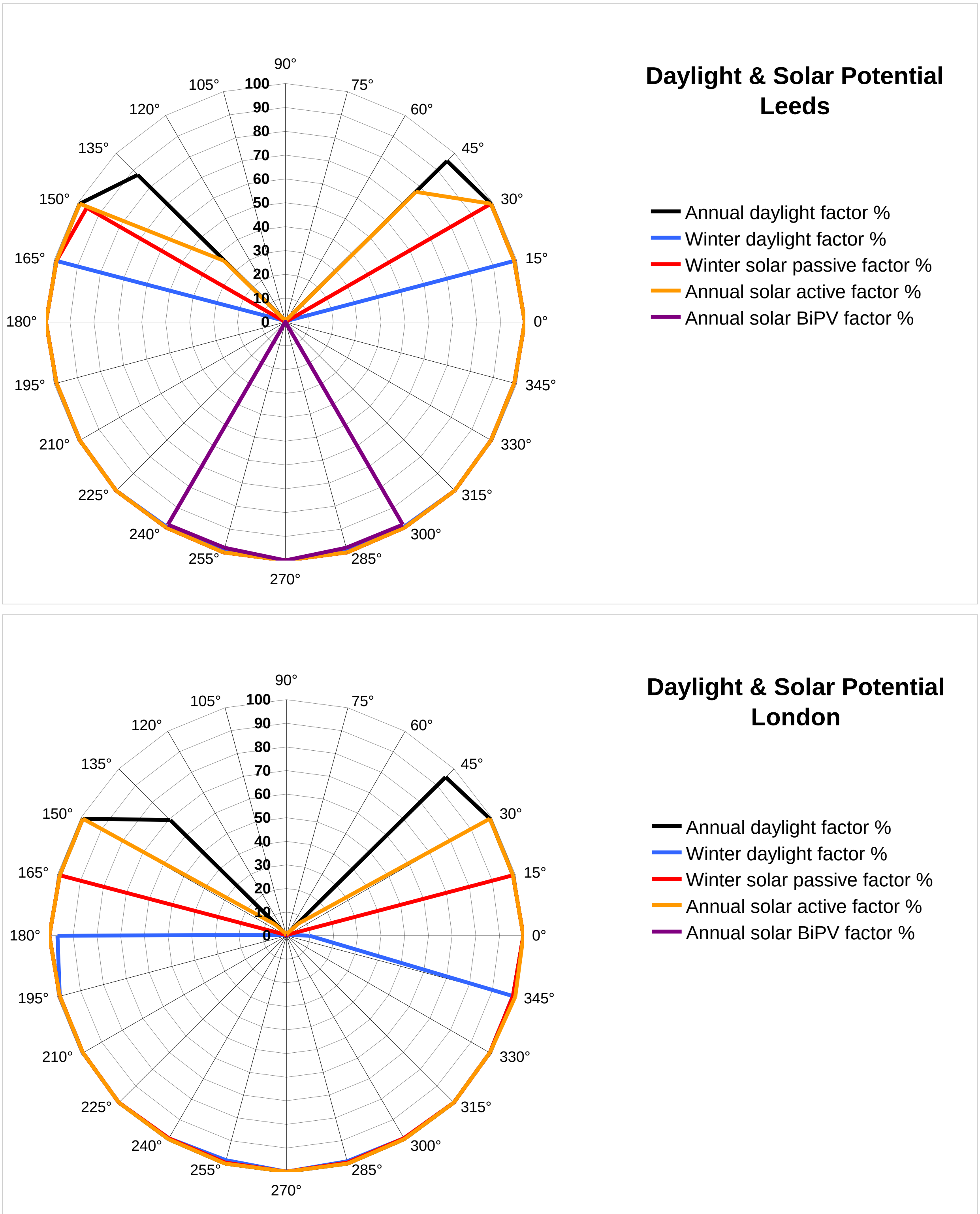


Figure 208: Leeds and London. Polar diagrams illustrating the orientations of the façades adapted to the various solar technologies. North is up.

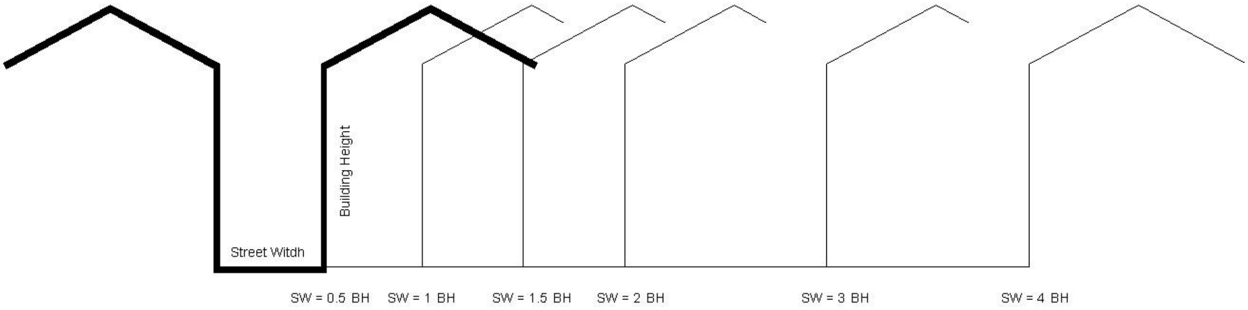


Figure 209: Analyzed building outlines.

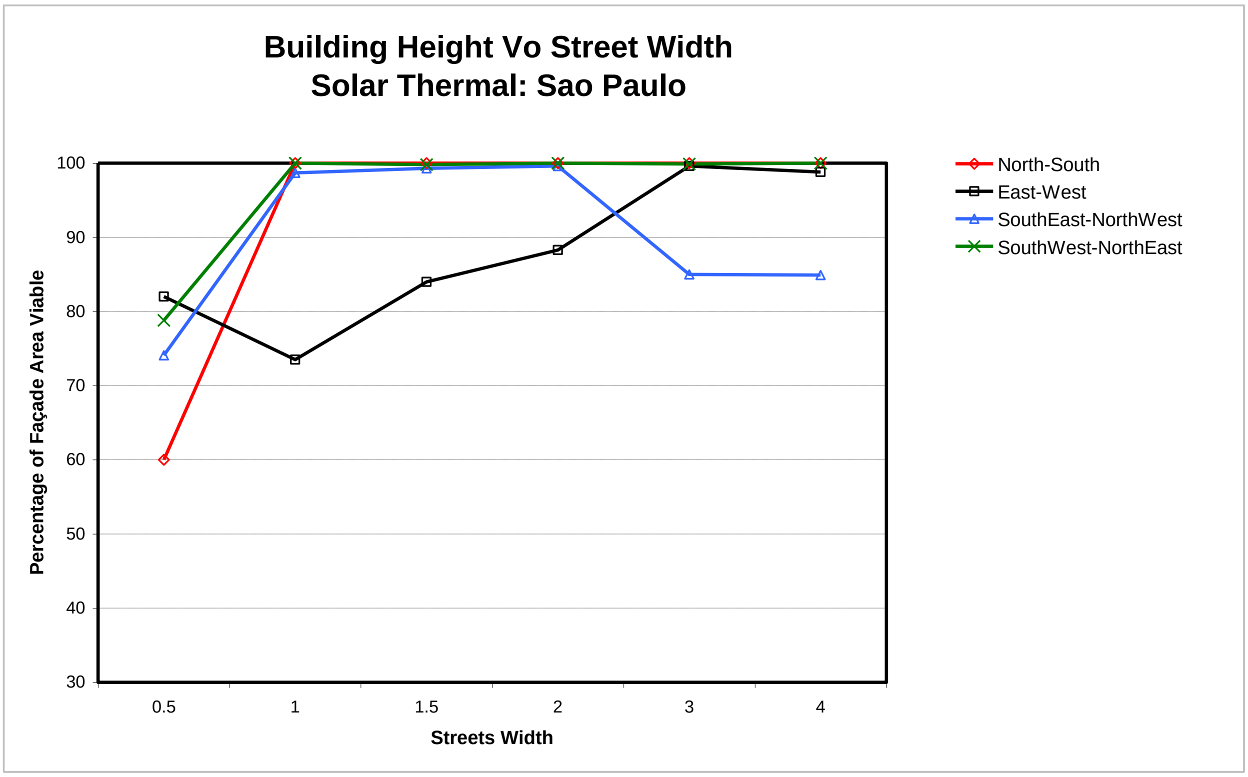


Figure 210: Saõ Paulo. Histograms illustrating the percentages of façade area viable for solar thermal in proportion to the ratio of building heights to the street widths.

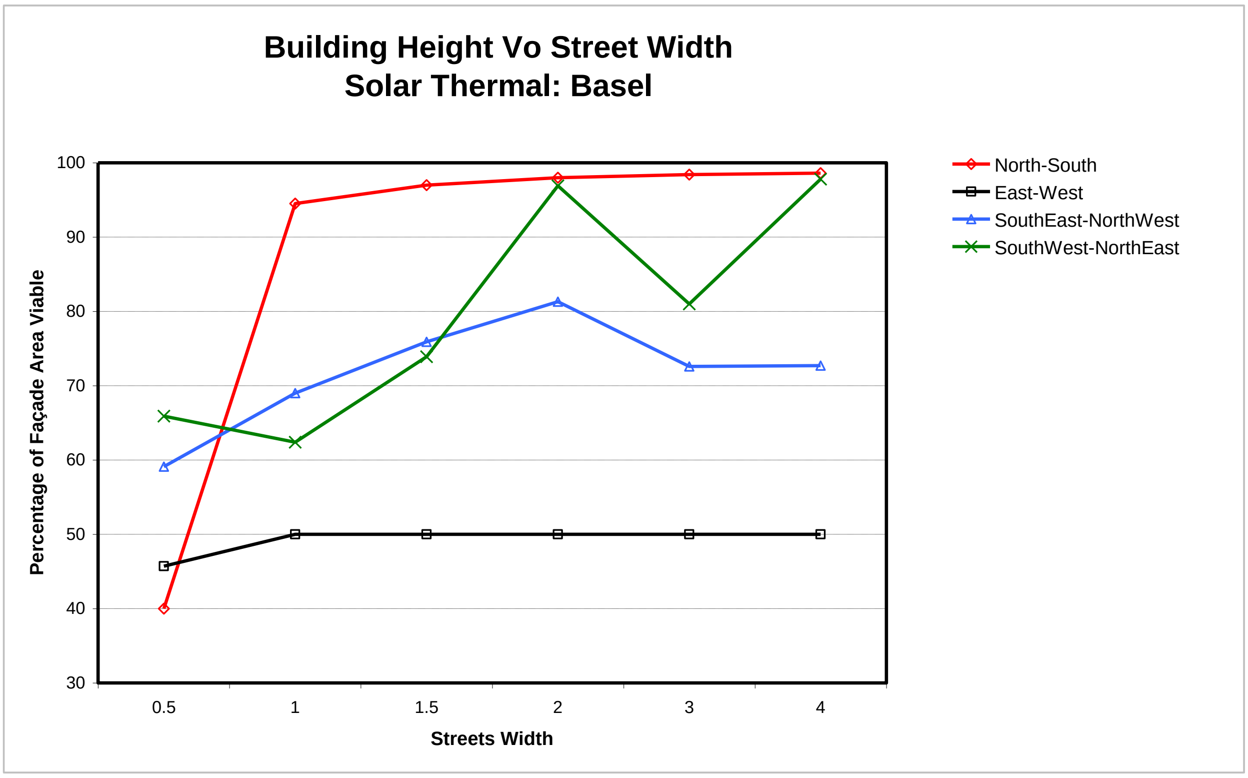
Building height, street width or distance between buildings and orientation of streets

As was already seen in Chapter 2, solar considerations play a crucial role in the definition of a street outline, as well as in the creation of the built front. This question is examined here from two aspects: the percentage of façade area viable for daylighting, for passive solar heating and for the thermal solar in proportion to the ratio of building heights to the street widths (see Figure 209). Furthermore, in the present study, those diagrams showing for instance the distance between buildings should be heeded to obtain an optimal production of these solar technologies.

For the European sites, one can estimate from Figure 210 to Figure 220 that the percentage of façade area viable for the thermal solar remains practically constant moving from a ratio of Street Width = 0.5 Building Height to Street Width = 4 Building Height. This is not the case for São Paulo where the relationship Street Width = 0.5 Building Height produces 82% of thermal solar on the façade only to dip to 73.5% in the relationship SW = 1 BH, increasing afterwards to100% in the ratio SW = 3 BH.

Moving from a ratio SW = 0.5 BH to SW = 1 BH, the orientation of the North-South streets quickly produces more potential for all the cities that were studied. As for the values of the façades located on streets with SouthEast-NorthWest and SouthWest-NorthEast orientations, they are located between the two first curves for the European sites. These axes are interesting for quarters located in Basel, Lausanne Geneva or Paris, but remain relatively weak for Leeds and especially for London. Indeed, in order to obtain 67.7% of viable surface for London and 77.4% for Leeds, a relationship of SW = 4 BH has to be reached. In a project such as the Eastern Quarry development, for example, this is equivalent to creating streets with a breadth from 60 m to 72 m instead of the10-18 m which was envisaged to obtain an optimal potential of active solar energy. This is obviously impossible to achieve, whether from the point of view of architectural design for the layout plan or from the consideration of adhering to the spirit of densification.

For practically all of these sites, one can observe a dipping of the two axes SE-NW and SW-NE starting from SW = 2 BH. This negative effect is undoubtedly due to the sky condition characterized by low solar altitudes in Winter. As for the city of São Paulo, its SE-NW and SW-NE axes are practically almost as viable as its North-South axis, but with a slight lowering of performance in the ratio SW = 0.3 BH for the SouthEast-NorthWest axis (see Figure 210 and Figure 214).



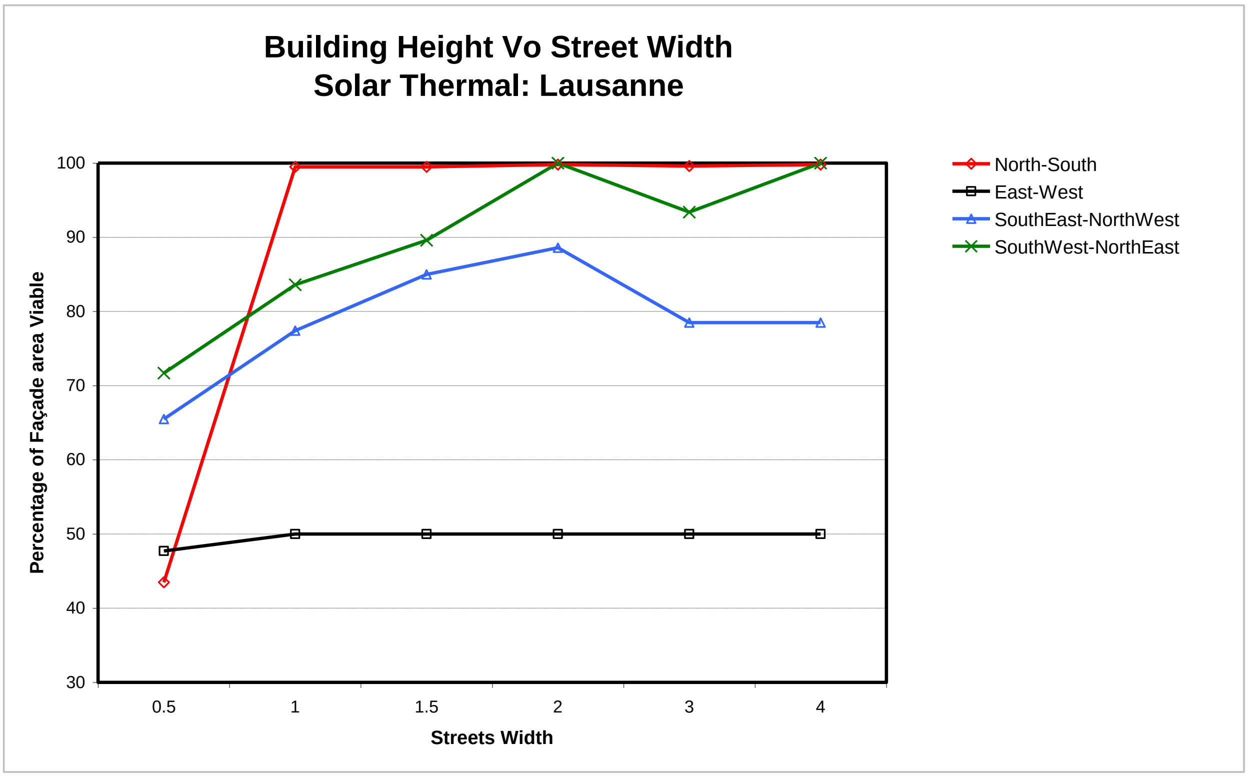
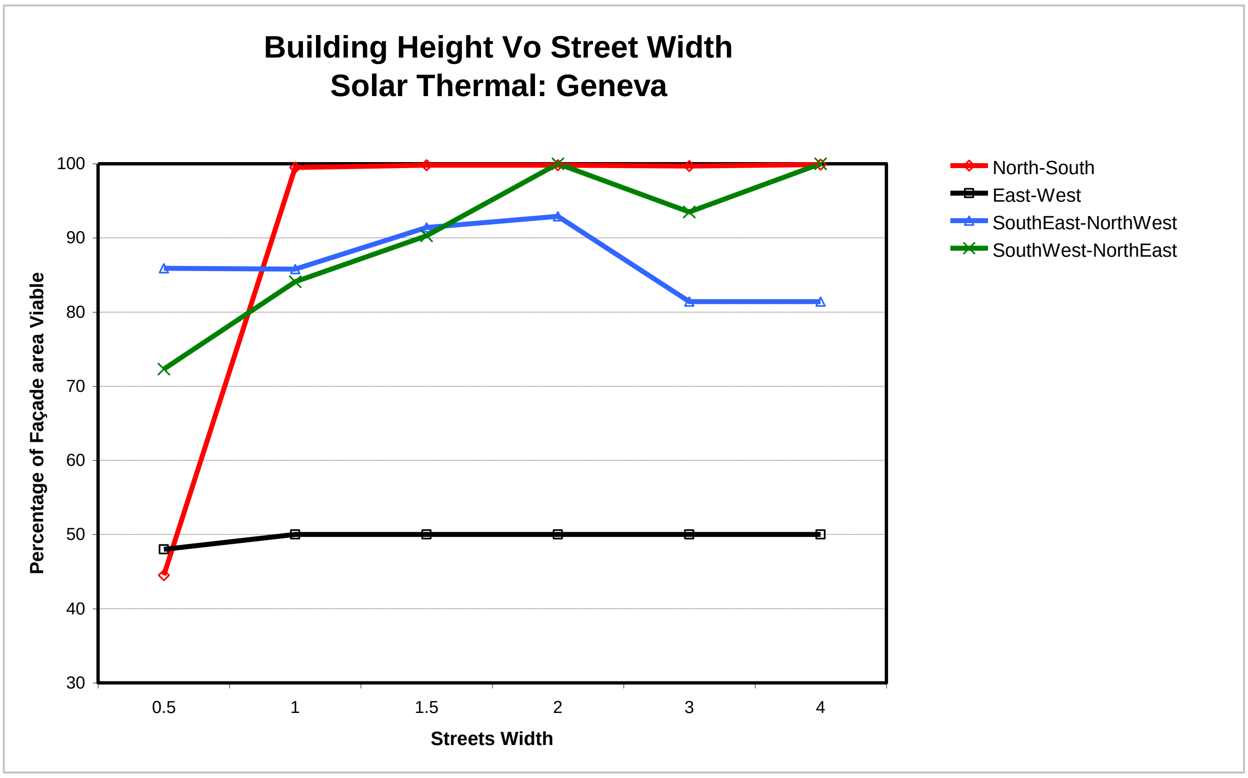


Figure 211: Basel and Lausanne. Histograms illustrating the percentages of façade area viable for solar thermal in proportion to the ratio of building heights to the street widths.



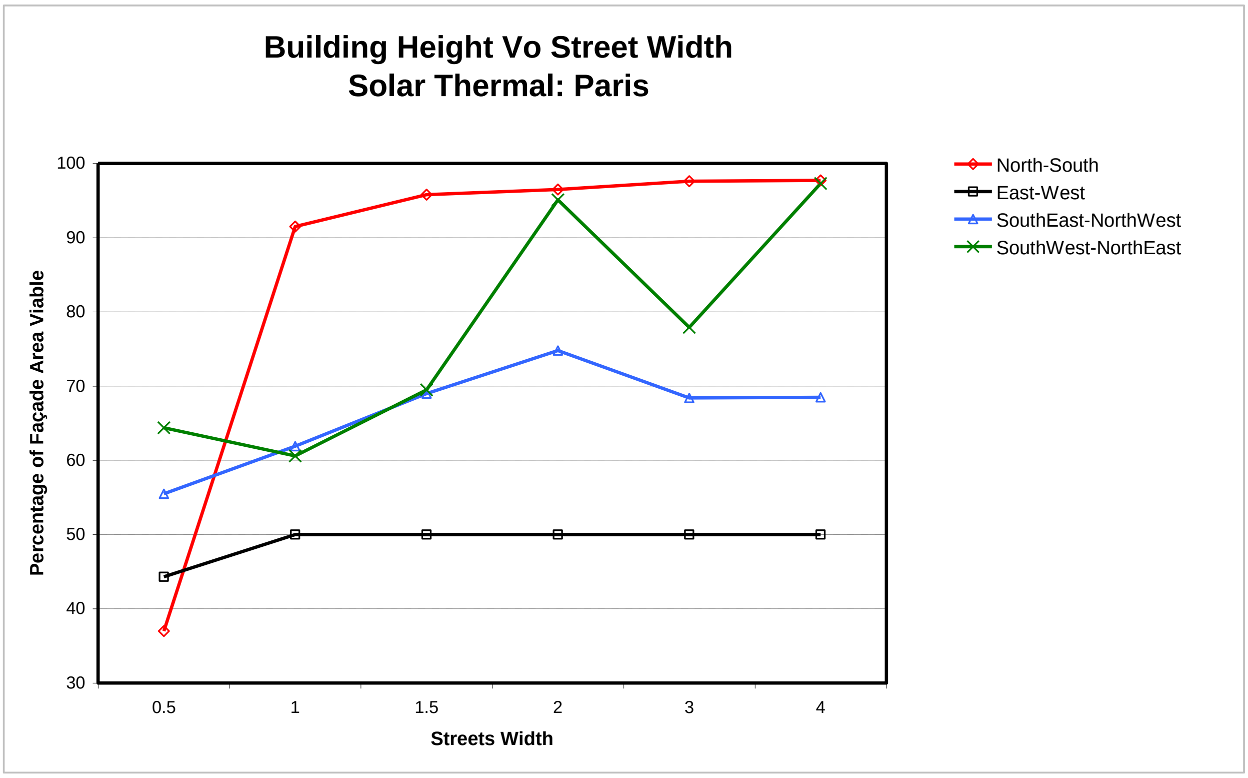
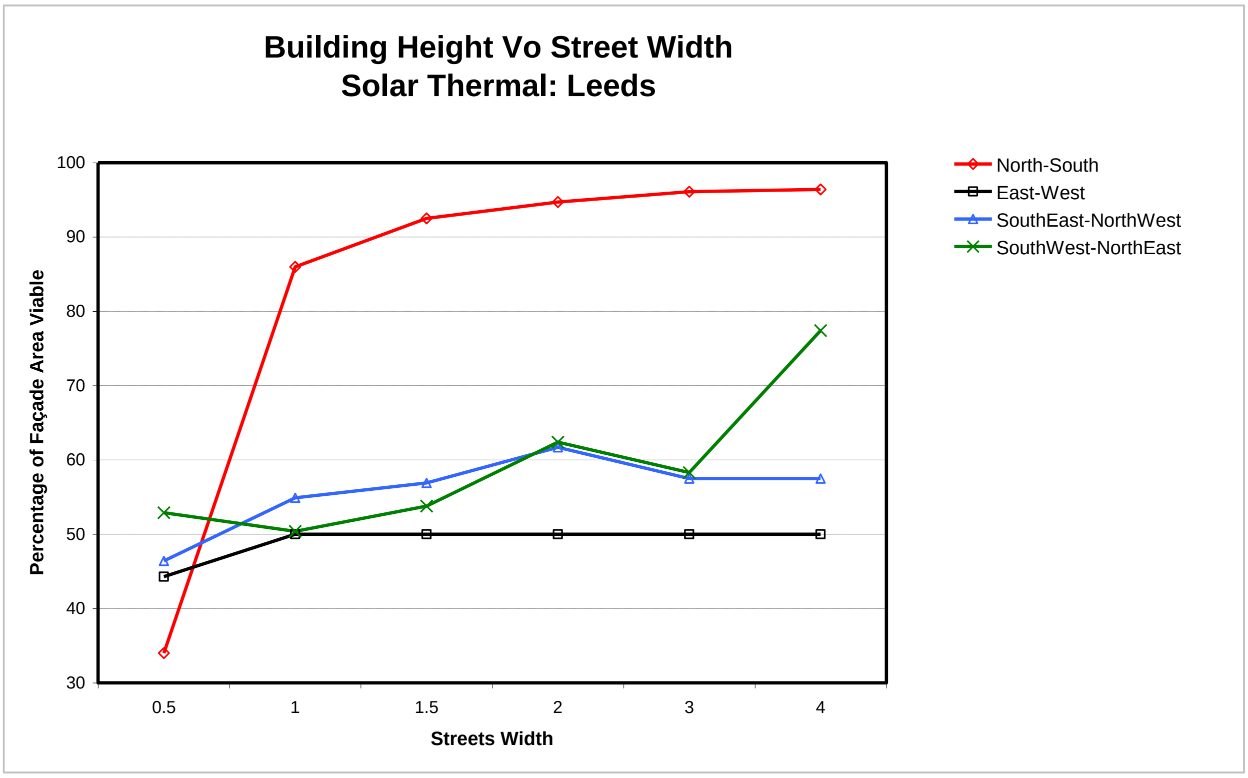


Figure 212: Geneva and Paris. Histograms illustrating the percentages of façade area viable for solar thermal in proportion to the ratio of building heights to the street widths.



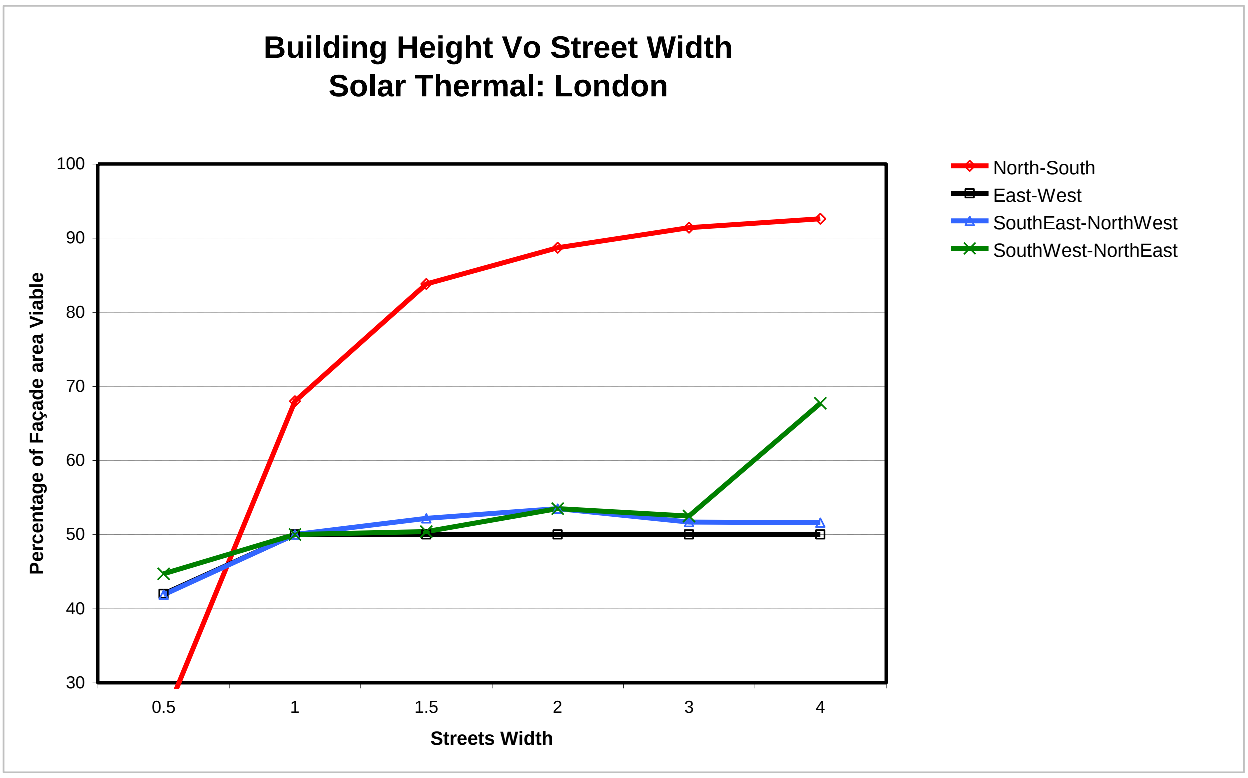


Figure 213: Leeds and London. Histograms illustrating the percentages of façade area viable for solar thermal in proportion to the ratio of building heights to the street widths.

As far as annual and Winter daylighting are concerned, the North-South axis possesses an optimal potential for Basel, Lausanne, Geneva and Leeds starting at Street Width = 1 Building Height. On the other hand, this axis does not have a good Winter potential for Paris and London, in contrast to daylighting for the entire year where it is located above 90% of the percentage of the viable area of façades starting at Street Width = 1 Building Height. The SE-NW and SW-NE axes also possess a good potential for the European sites that were studied. In the case of all these cities it is still noticeable that the annual SW-NE axis weakens starting at Width = 0.5 Building Height to1 Building Height to attain optimum performance afterwards starting at 2 Building Height and afterwards to drop down again. Once again, the East-West axis is the most constant of all, but at the same time is the least favourable in terms of annual and Winter daylighting.

As for São Paulo, all its orientations are practically at 100% of the percentage of the viable area of façades starting at Street Width = 1 Building Height. Only the SE-NW axis is an exception to the others and falls of starting at Width = 3 Building Height.

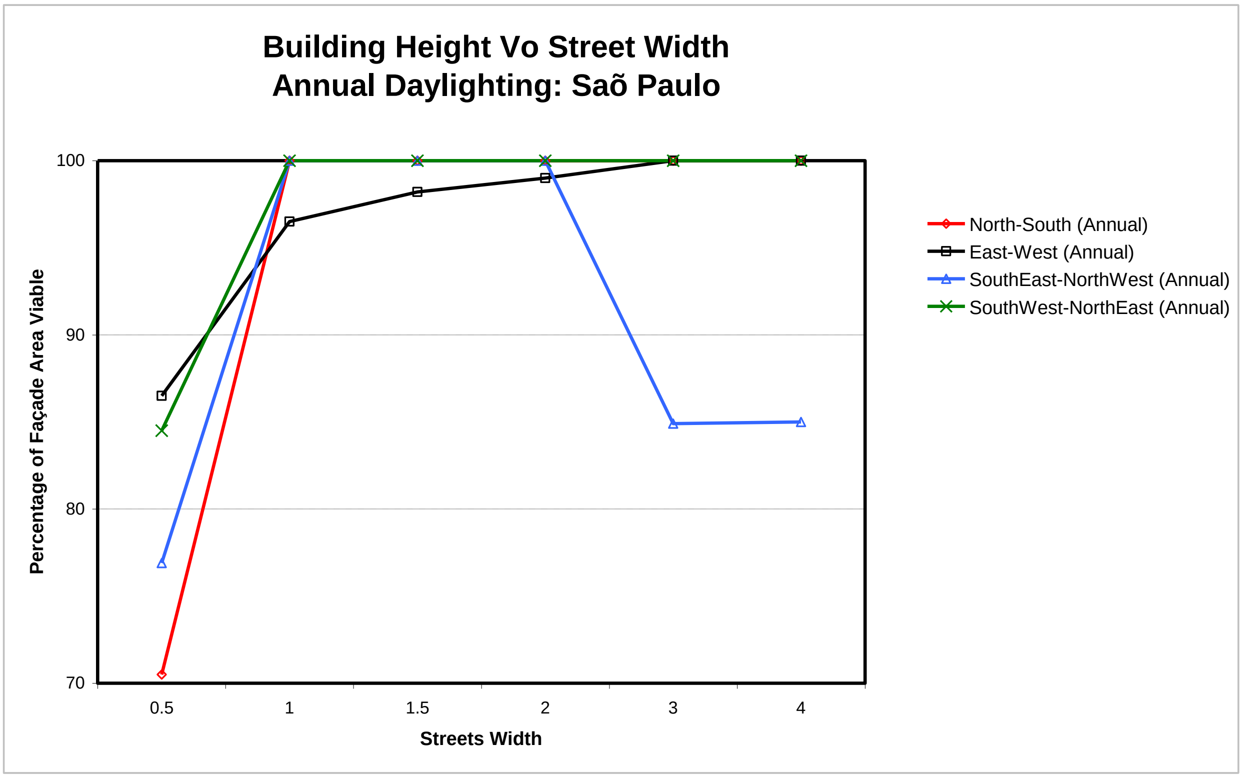
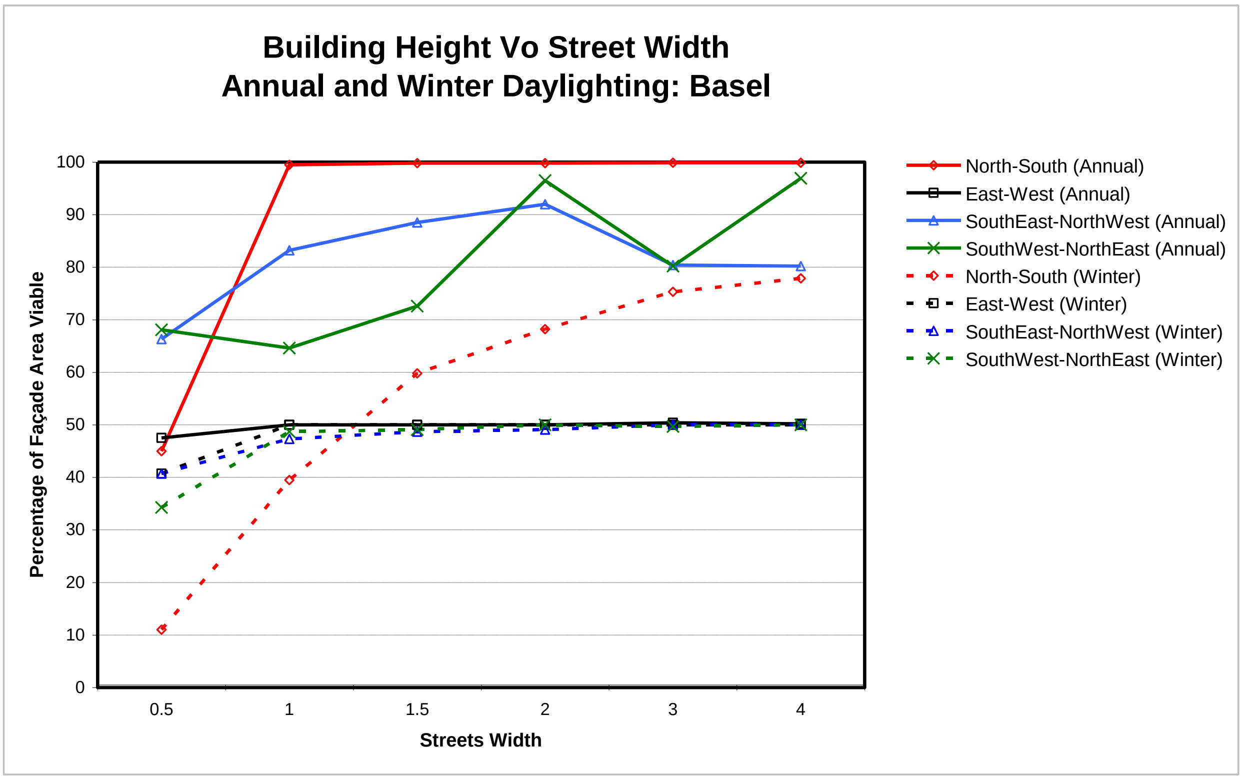


Figure 214: Saõ Paulo. Histograms illustrating the percentages of façade area viable for the annual and Winter daylighting in proportion to the ratio of building heights to the street widths.



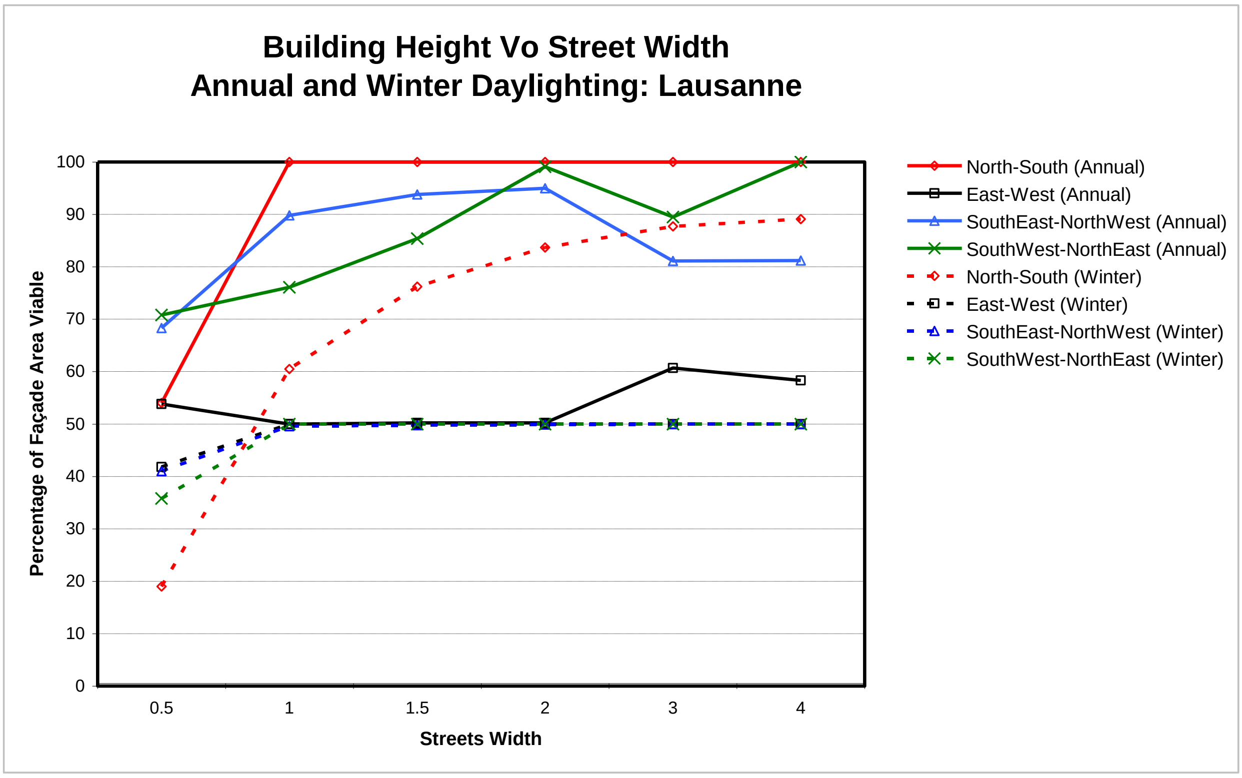
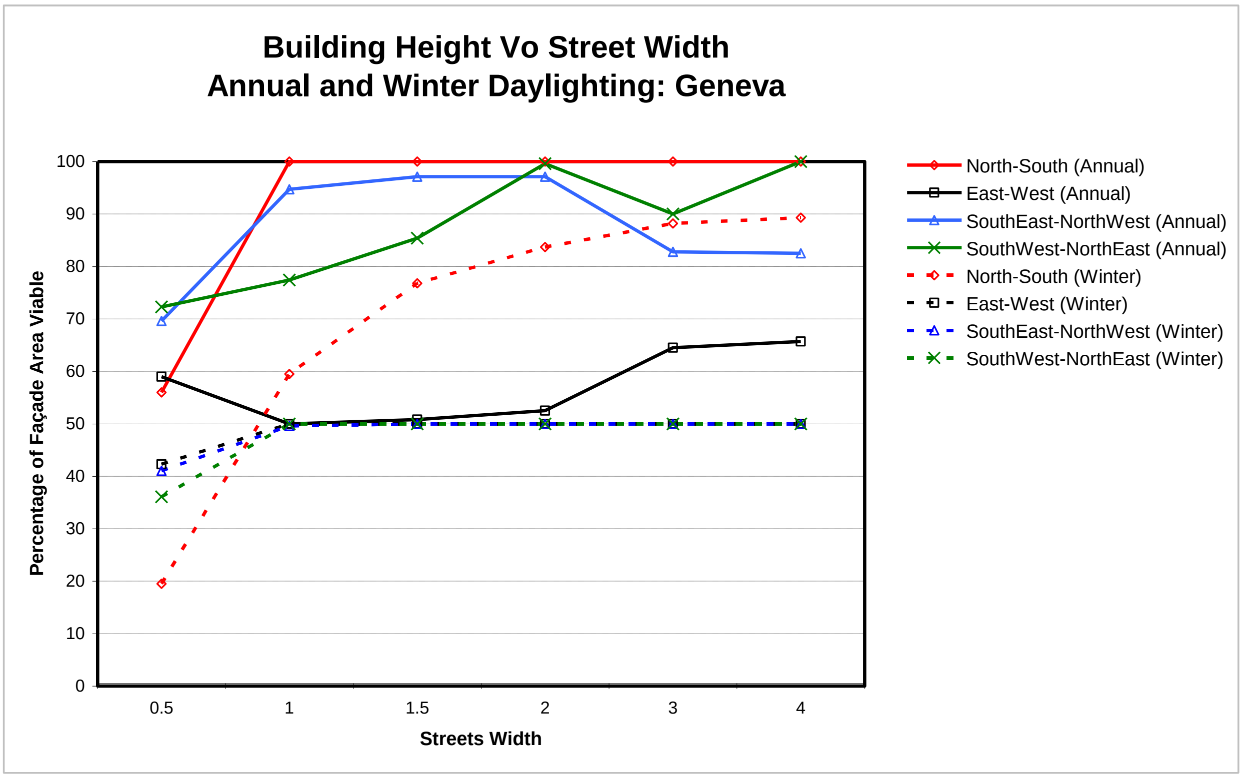


Figure 215: Basel and Lausanne. Histograms illustrating the percentages of façade area viable for the annual and Winter daylighting in proportion to the ratio of building heights to the street widths.



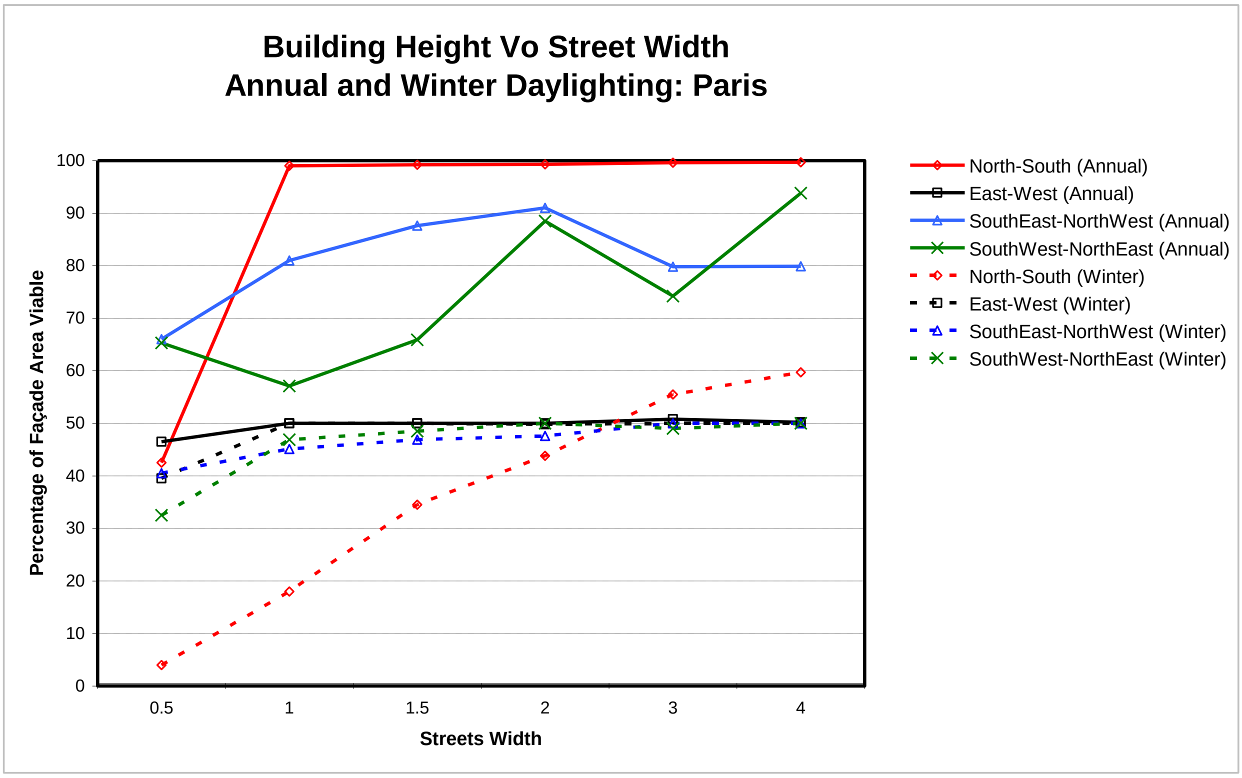
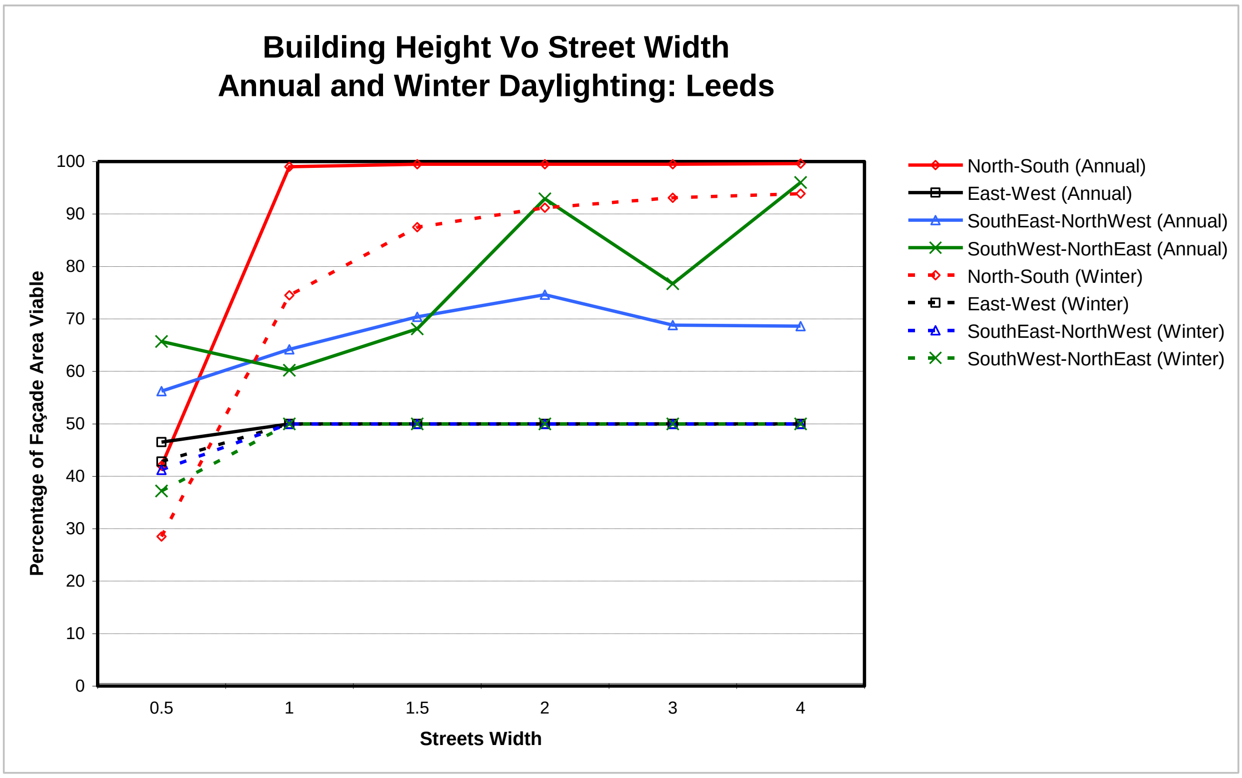


Figure 216: Geneva and Paris. Histograms illustrating the percentages of façade area viable for the annual and Winter daylighting in proportion to the ratio of building heights to the street widths.



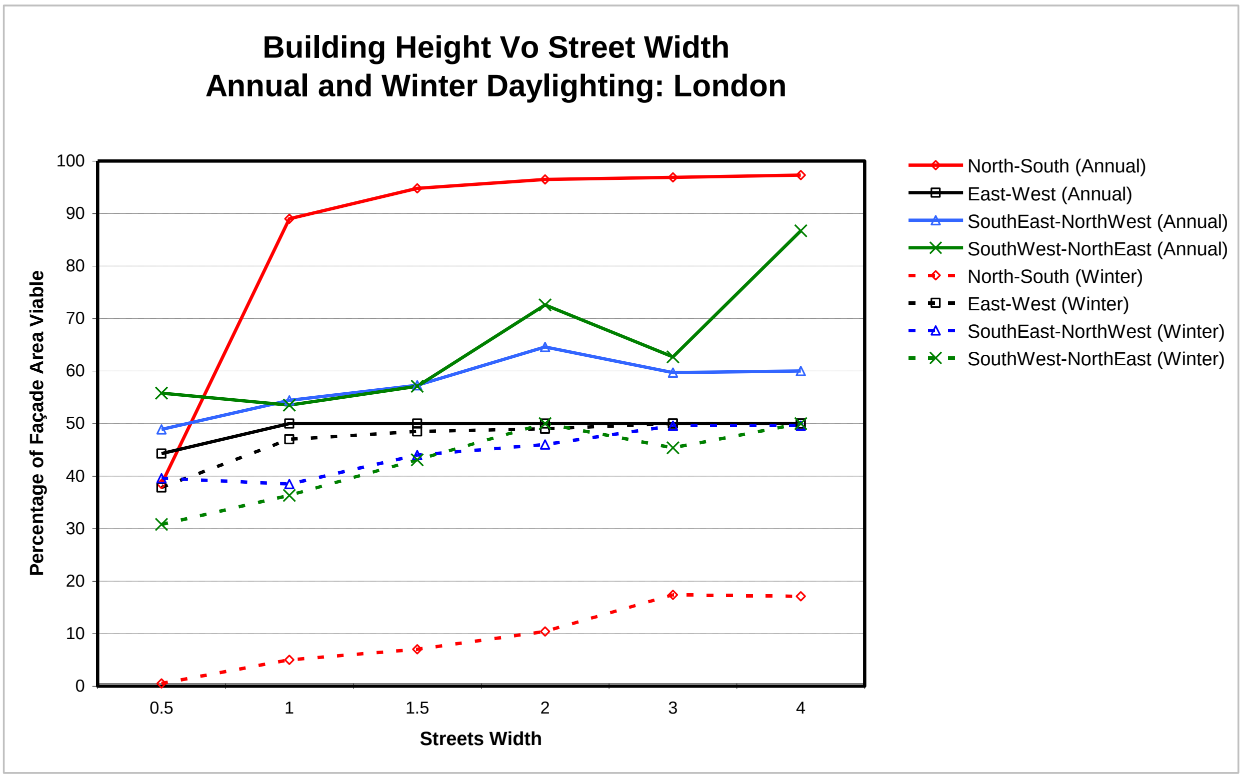
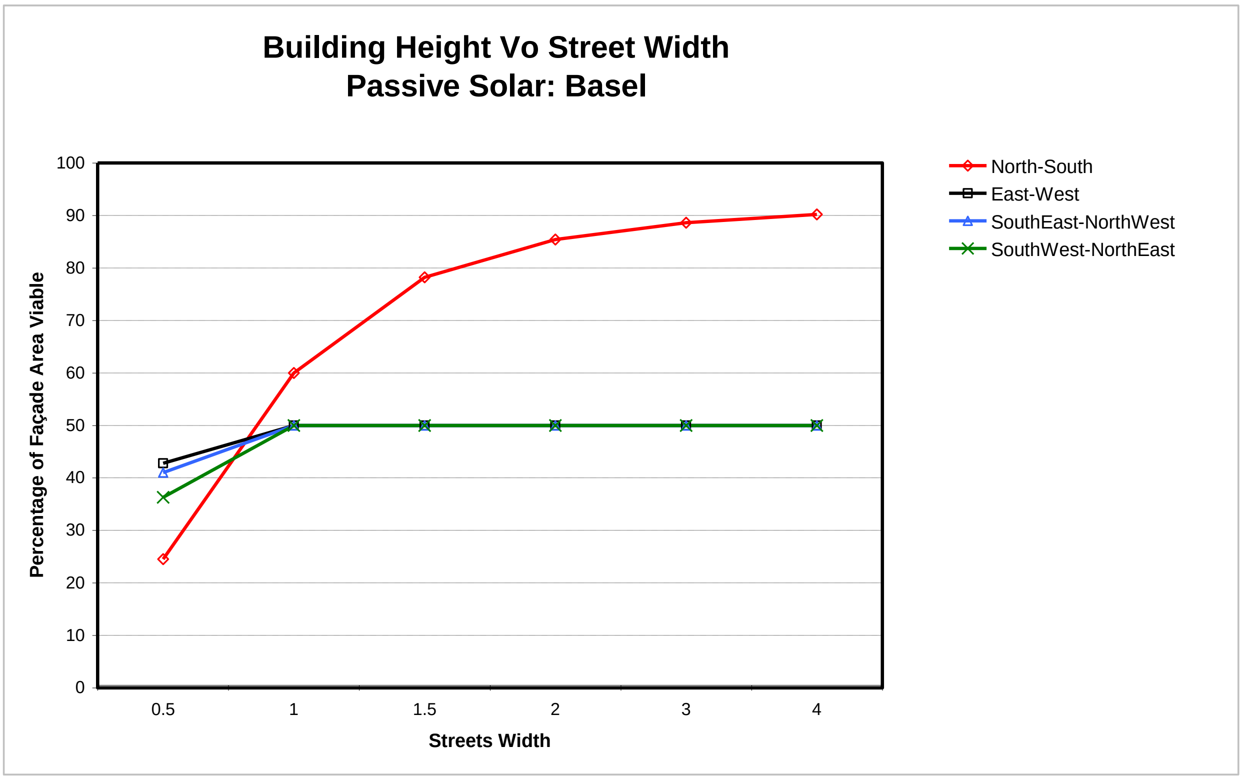


Figure 217: Leeds and London. Histograms illustrating the percentages of façade area viable for the annual and Winter daylighting in proportion to the ratio of building heights to the street widths.

The passive solar gains are the solar technology which performs least well in the present case. Apart from the North-South axis, all the other axes stop at 50% of the percentage of the viable area of façades starting at Street Width = 1 Building Height. This means that half of the façades do not allow for the exploitation of passive solar to heat the rooms in Winter. The North-South axis is therefore the most advantageous and performs really well starting at Street Width = 1.5 Building Height.



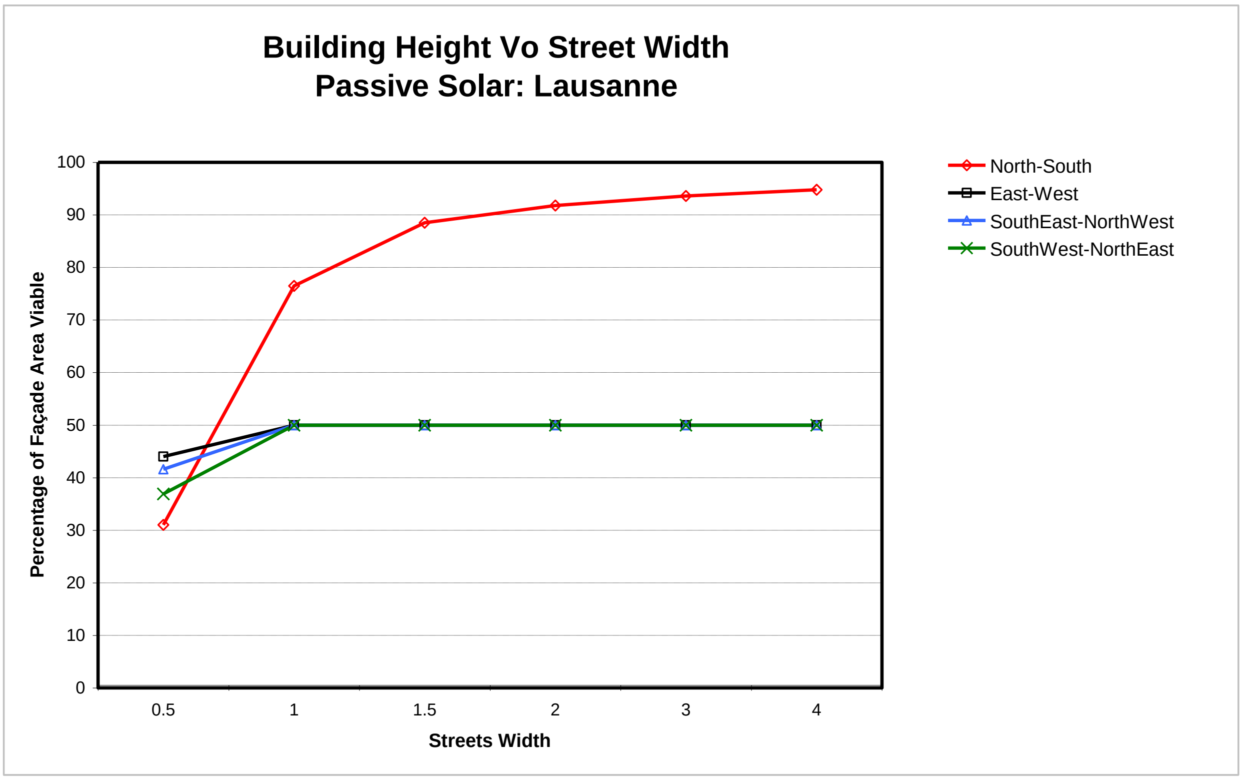
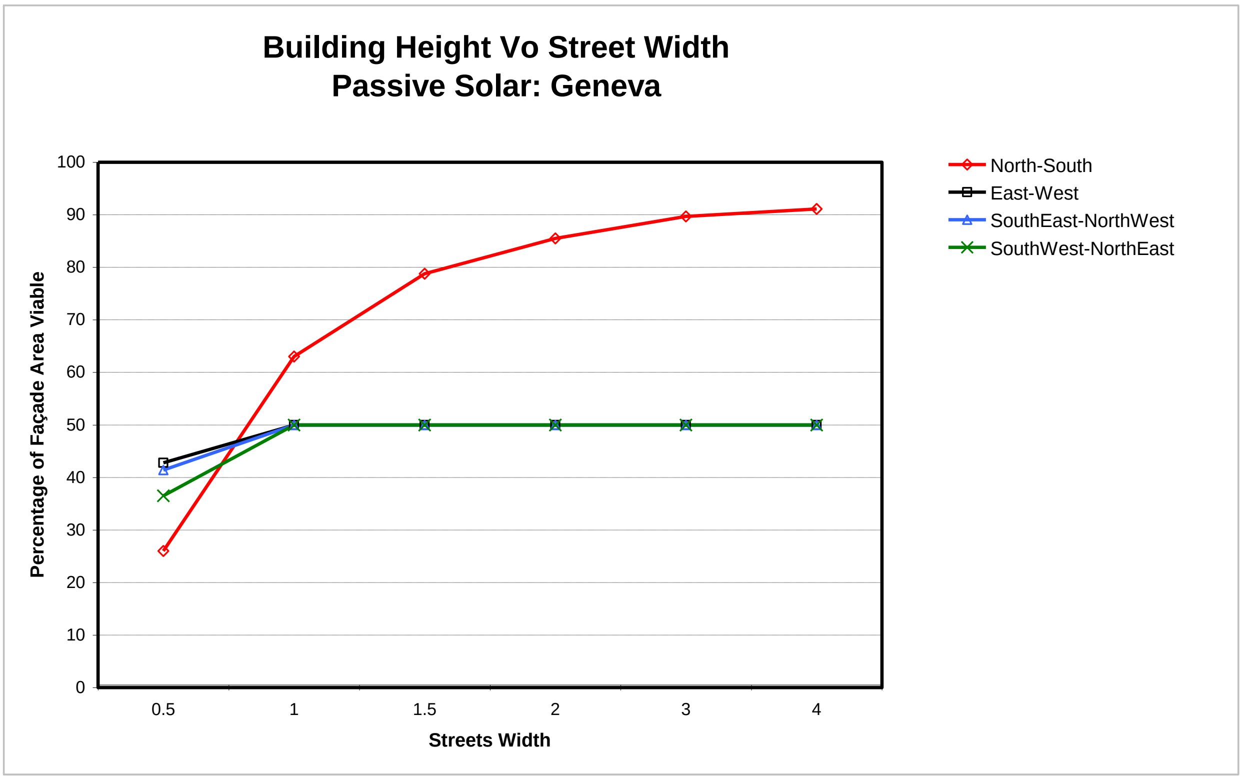


Figure 218: Basel and Lausanne. Histograms illustrating the percentages of façade area viable for the passive solar gains in proportion to the ratio of building heights to the street widths.



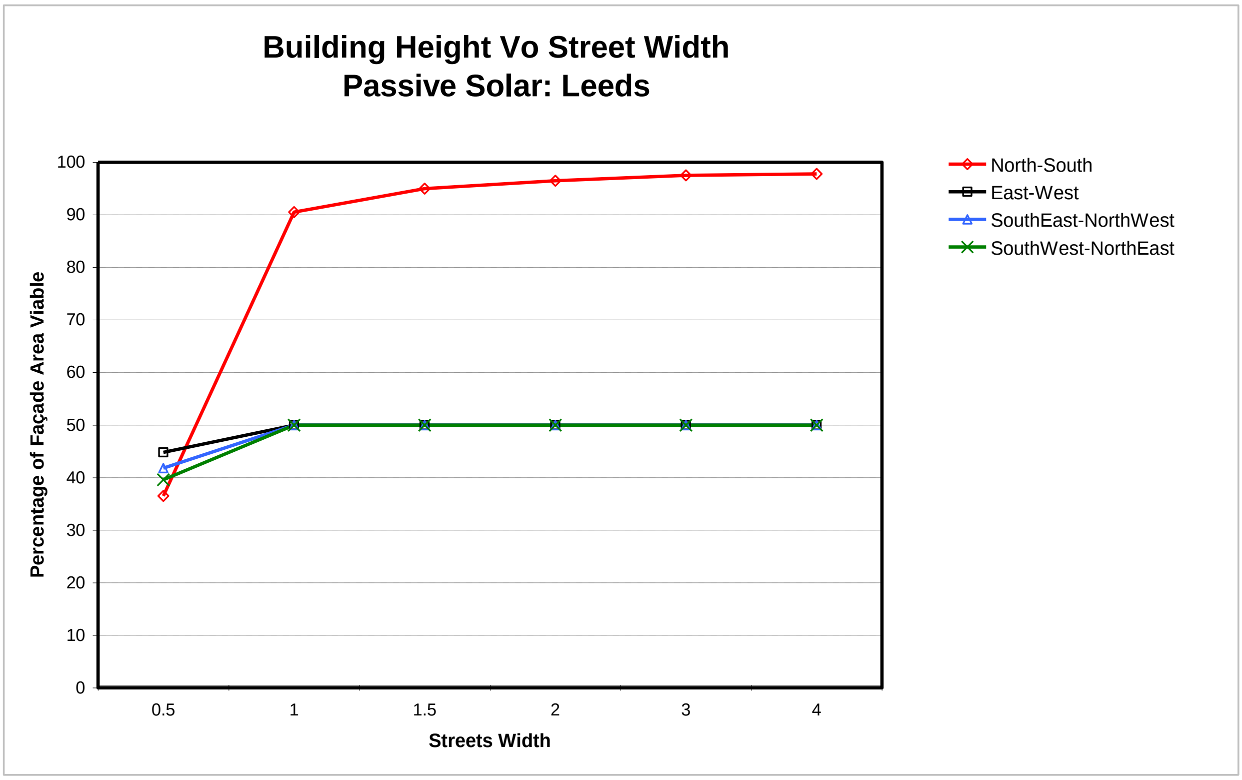
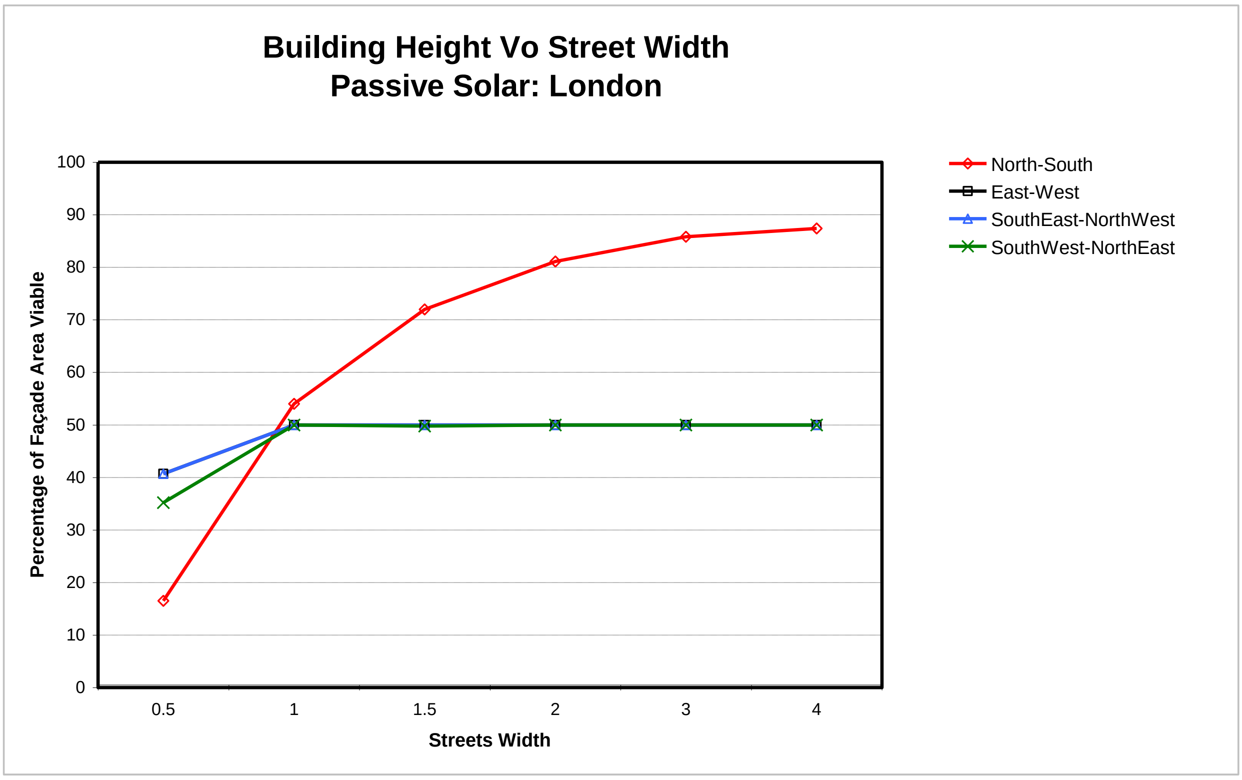


Figure 219: Geneva and Leeds. Histograms illustrating the percentages of façade area viable for the passive solar gains in proportion to the ratio of building heights to the street widths.



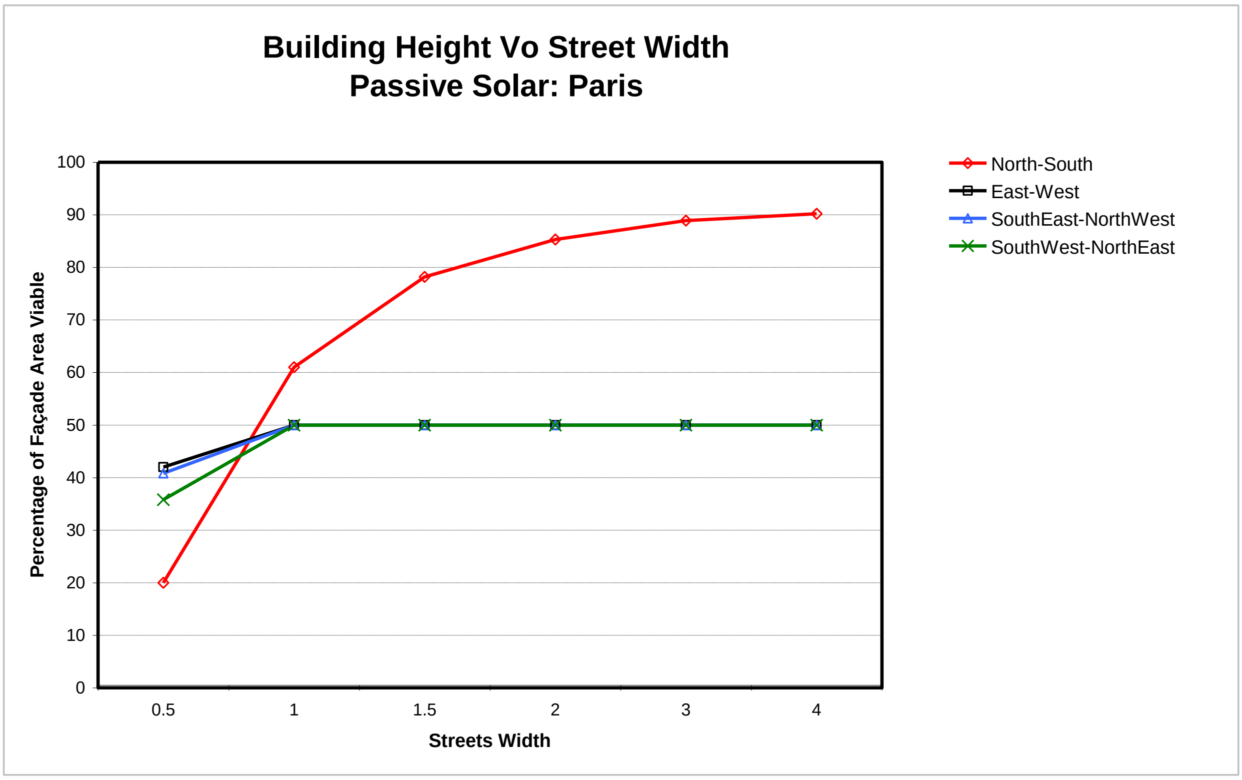
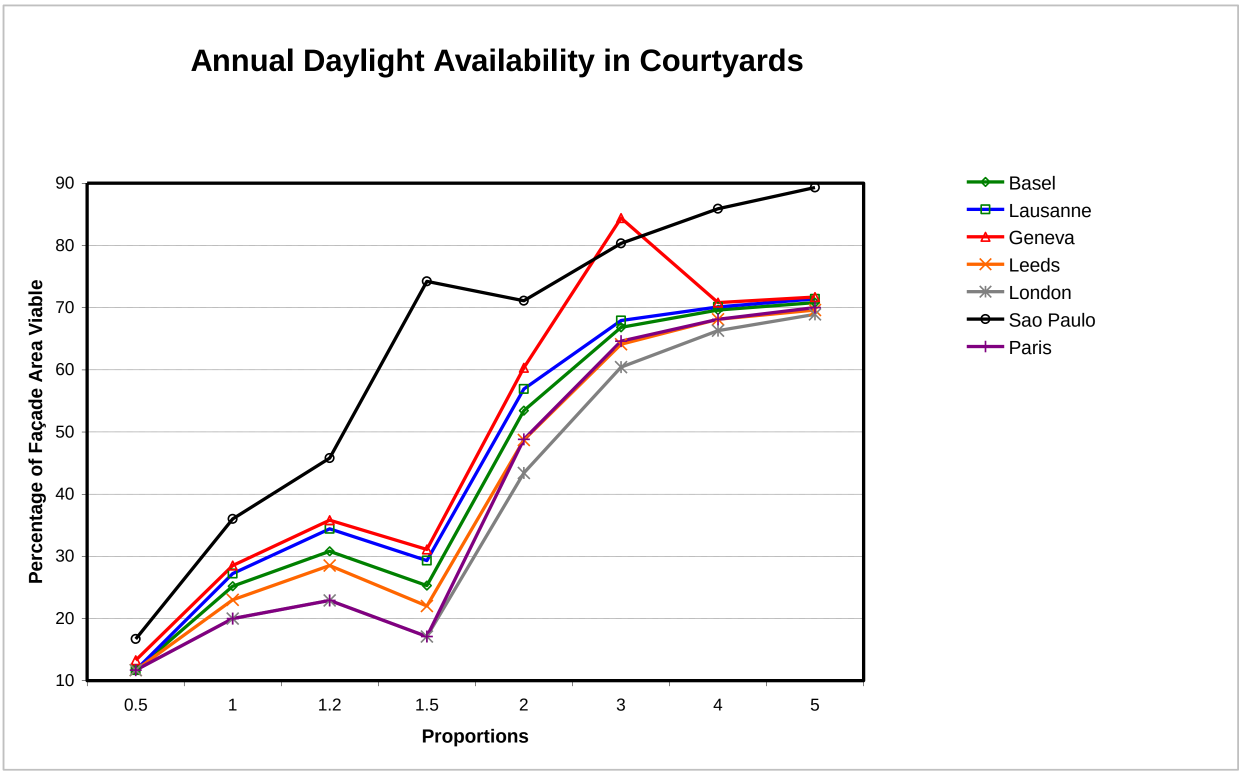


Figure 220: London and Paris. Histograms illustrating the percentages of façade area viable for the passive solar gains in proportion to the ratio of building heights to the street widths.



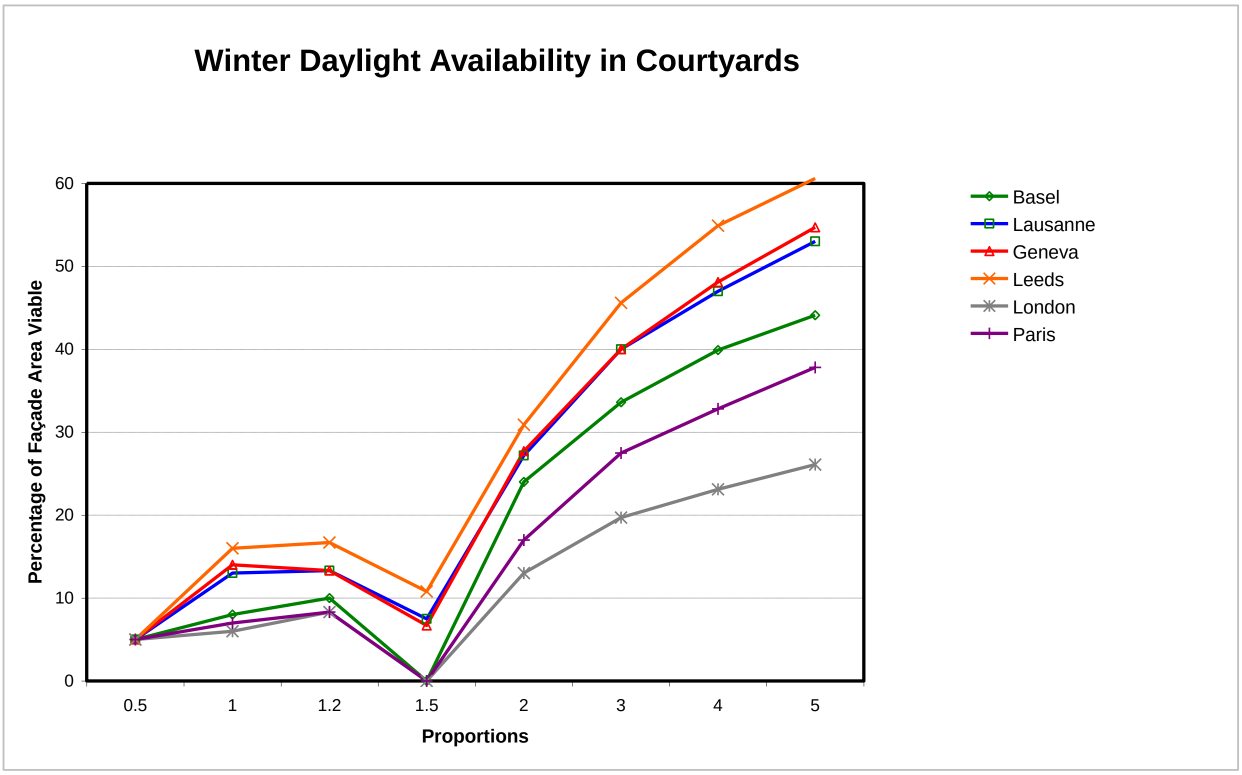


Figure 221: Histograms illustrating the percentages of façade area viable for the annual and Winter daylighting in proportion to the ratio of building heights to the width of the courtyards.

Annual and Winter daylight availability in courtyards

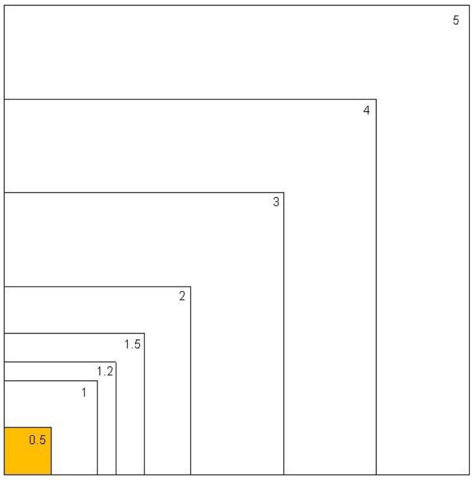


Figure 222: Ratio of building heights to the courtyards' width studied.

The analysis of curves of annual daylighting in courtyards represented in Figure 221 and Figure 222 demonstrates that the percentage of façade area viable for the European sites follows the same pattern, with the exception of Geneva to within one peak. The proportion Building Height = 1.2 Courtyard Width is more efficient than Building Height = 1.5 Courtyard, but nevertheless remains weak with annual daylighting values located between 35.8% for Geneva and 22.9% for London. The Geneva curve reaches a peak at BH = 3 CW to join the others afterwards at BH = 4 CW. In order to obtain a satisfactory daylighting, approximately 60% of percentage of viable façade area , the courtyard configurations would at the very minimum have to be 3 times wider than the height of the buildings.. For a 4-5 storey urban building this would mean a length of 36-45 m.

From the outset, the São Paulo site has been performing significantly better than the others. Its curve dips down at BH = 1.5 CW to 2 of Courtyard Width, only to increase constantly afterwards. At 1.5 CW, its value is already located at 74.2% percentage of viable façade area.

As far as Winter daylighting is concerned, this is where all the curves, except for São Paulo which has no Winter season, follow the same pattern. The curve of Leeds performs better than the others and the London curve is still just as weak. As for annual daylighting, at Building Height = 1.2 Courtyard Width, the curves dip, rising afterwards starting at Building Height = 1.5 Courtyard. In Winter the interior of the 3 CW courtyards offers a potential located between 45.6% for Leeds and 19.7% for London of percentage of viable façade area, if it is hoped to adapt this proportion to the annual proportion.

Orientation and degree of inclination of the section roofs (solar collectors)

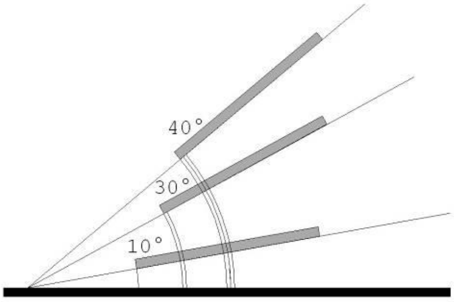


Figure 223: Better degree of inclination of the Southern section roofs.

The irradiation received by a solar collector varies considerably according to its location, its orientation, its inclination and the presence of possible obstructions. As far as possible, one has to avoid the obstructions casting shadows onto the surface of the collectors. Ideally, the collectors should be free of all shadows for at least 6 hours a day throughout the entire year.

Table 42: Summary of results for the Southern facing roof sections

Energy exploitation	Sites	Lat.	Southern facing roof sections or inclination of the solar collectors									
			0°*	**10°****	**15°****	**20°****	**25°****	**30°****	**35°****	**40°****	**45°****	**50°****
Solar thermal viability	**Basel**	47,55	100%	100%	100%	100%	100%	100%	100%	100%	100%	94.2%
	Lausanne	46,51	100%	100%	100%	100%	100%	100%	100%	100%	100%	94.2%
	Geneva	46,20	100%	100%	100%	100%	100%	100%	100%	100%	100%	94.2%
	Leeds	53,79	100%	100%	100%	100%	100%	100%	100%	100%	100%	89%
	London	51.49	100%	100%	100%	100%	100%	100%	100%	100%	100%	89%
	São Paulo	-23,53	100%	100%	100%	100%	100%	100%	100%	100%	100%	89.7%
	Paris	48.85	100%	100%	100%	100%	100%	100%	100%	100%	100%	91%
BiPV viability	**Basel**	47,55	100%	100%	100%	100%	100%	100%	100%	100%	100%	83.9%
	Lausanne	46,51	100%	100%	100%	100%	100%	100%	100%	100%	100%	84.5%
	Geneva	46,20	100%	100%	100%	100%	100%	100%	100%	100%	100%	84.5%
	Leeds	53,79	0%	100%	100%	100%	100%	100%	100%	100%	100%	79.4%
	London	51.49	0%	0%	0%	100%	100%	100%	57.6%	100%	99.5%	72.3%
	São Paulo	-23,53	100%	100%	100%	100%	100%	100%	100%	0%	46.3%	0%
	Paris	48.85	100%	100%	100%	100%	100%	100%	100%	100%	100%	79.4%
E/A [kWh/m2]	**Basel**	47,55	1073.7	1146.0	1145.2	1196.6	1140.3	1219.1	1198.0	1217.4	1212.3	1091.9
	Lausanne	46,51	1163.4	1240.7	1238.5	1292.7	1233.2	1316.3	1293.9	1312.9	1307.4	1177.7
	Geneva	46,20	1193.9	1271.2	1267.1	1322.7	1262.5	1343.6	1321.8	1337.9	1331.7	1198.3
	Leeds	53,79	971.8	1051.2	1057.5	1108.7	1048.2	1142.3	1118.7	1153.7	1149.2	1031.6
	London	51.49	913.4	974.2	975.4	1015.5	968.8	1034.7	1019.3	1035.0	1031.7	928.5
	São Paulo*	-23,53	1410.9	1332.7	1261.2	1223.8	1286.3	1095.1	1136.7	956.2	946.5	857.9
	Paris	48.85	1025.4	1093.6	1092.4	1139.8	1087.8	1160.2	1141.8	1159.0	1155.0	1039.7

* **Flat roof**
** **Degree of inclination of the South section roofs**
*** **The northern facing roof sections with an orientation of 10° are equivalent to 1480.3 kWh/m2.year for São Paulo**

Figure 223, and Table 42 show that the roofs or collectors receive better annual irradiation if they are oriented due South and inclined at an average of 30° in relation to the horizontal for the cities of Basel, Geneva, Lausanne and Paris. This angle moves to 40° for the English sites located in London and Leeds. A deviation of these same roof sections by 90° to the East or to the West constitutes a maximum loss located respectively between 260-310 kWh/m2.year and 240-270 kWh/m^2.year, which for both represents on average 20% less than the maximum South irradiation. Once again, it should be emphasized that for all the sites the East and West orientations are more efficient with an angle of 20° and 10° respectively.

Conversely, for the city of São Paulo, the North orientation is better than the South orientation and for example represents for a roof with a 10° inclination 1480.3 kWh/m2.year, which means 100% for both solar thermal and BiPV viability. This is equivalent to an irradiation of +147.6 kWh/m2.year (+10%) in comparison to the section of roof with a 10° South inclination. A deviation of the North section roof in other directions constitutes a maximum loss located between 60-150 kWh/m2.year (South section -10%, West section -8%, East section -4%). Furthermore, in Table 44 one can observe that flat roofs plates perform much better for the city of São Paulo.

Table 43: Summary of results for the Western and Eastern facing roof sections

Energy exploitation	**Sites**	**Lat.**	**Western facing roof sections or inclination of the solar collectors**					**Eastern facing roof sections or inclination of the solar collectors**				
			10°	**20°**	**30°**	**40°**	**50°**	**10°**	**20°**	**30°**	**40°**	**50°**
Solar thermal viability	**Basel**	47,55	100%	97.1%	98%	98.3%	90.5%	100%	100%	96.2%	94%	88.9%
	Lausanne	46,51	100%	97.1%	98%	98.3%	92.2%	100%	100%	100%	95.7%	92.0%
	Geneva	46,20	100%	97.1%	98%	98.3%	92.2%	100%	100%	100%	96.1%	92.4%
	Leeds	53,79	100%	96.4%	97.1%	97.5%	87%	100%	100%	96.2%	93.6%	88.2%
	London	51.49	100%	96.4%	97.1%	97.5%	85.9%	100%	100%	95.5%	93.1%	86.1%
	São Paulo	-23,53	100%	100%	100%	100%	97.7%	100%	100%	100%	100%	94.4%
	Paris	48.85	100%	96.4%	97.5%	97.9%	89.3%	100%	100%	96.2%	94%	88.9%
BiPV viability	**Basel**	47,55	100%	90.5%	54%	42.2%	17%	56.8%	100%	17.3%	10.3%	8.7%
	Lausanne	46,51	100%	93.4%	94.3%	94%	45.4%	94.9%	100%	91.1%	80.3%	42.7%
	Geneva	46,20	100%	94.2%	94.8%	94.8%	72.9%	95.5%	100%	91.1%	84.5%	78.1%
	Leeds	53,79	0%	0%	0%	0%	0%	0%%	0%	0%	0%	0%%
	London	51.49	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%%
	São Paulo	-23,53	100%	100%	100%	98.9%	92.3%	100%	100%	90.4%	91%	79.4%
	Paris	48.85	0%	0%	0%	0%	0%	56.8%	0.9%	0%	0%	0%
E/A [kWh/m2]	**Basel**	47,55	1032.1	991.4	985.6	974.3	872.3	1016.5	1040.3	971.7	926.5	871.8
	Lausanne	46,51	1122.3	1080.9	1075.8	1062.6	953.3	1100.2	1122.1	1046.3	997.5	939.2
	Geneva	46,20	1145.7	1100.5	1093.9	1080.7	969.0	1131.7	1160.6	1083.5	1034.8	973.0
	Leeds	53,79	934.3	897.9	893.9	884.3	788.7	915.4	946.3	887.2	845.3	799.7
	London	51.49	878.7	847.2	841.7	833.9	747.3	864.7	886.7	830.4	792.6	748.0
	São Paulo	-23,53	1361.3	1335.6	1315.8	1291.4	1199.6	1420.8	1376.2	1235.9	1219.9	1118.1
	Paris	48.85	986.5	949.7	944.6	934.2	837.4	970.5	993.4	927.6	885.0	832.6

To conclude this chapter a telling quotation from "Urban forms: the death and life of the urban block" "*Nevertheless, the fact of having brought the block to the foreground has had some perverse effects. It has brought the careless reader or the hurried designer to transform the issue into a caricature: city = block or modernity = single building. The new neighbourhoods of the new town or modest urban renovations were thus fitted with pseudo-blocks, which are but the urbanistic rendering of a valueless postmodern formalism*" (see Figure 224) (Panerai, Castex et al. 2004).

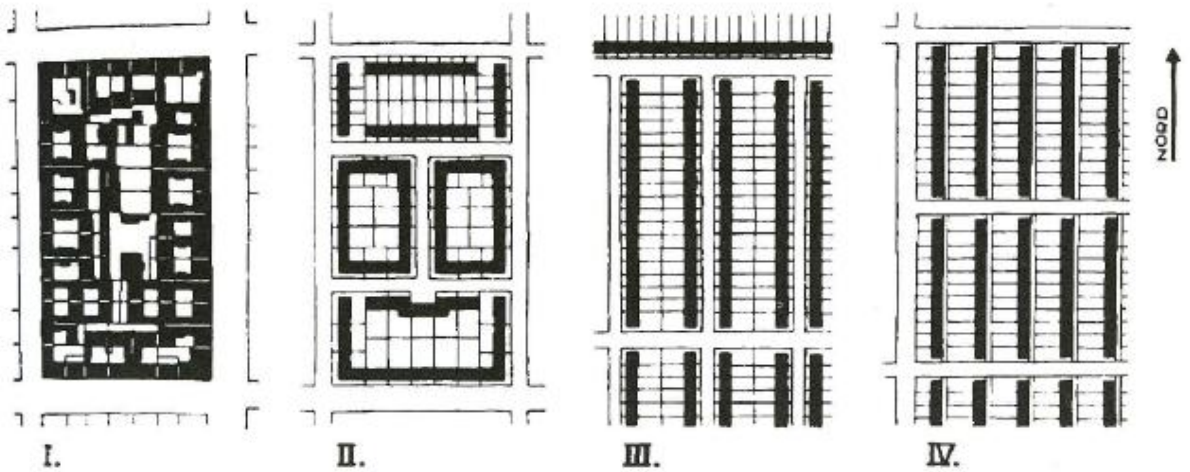


Figure 224: Boehm. Planning evolution of buildings estates in the 20th century: I. Antihygienist Block, II. Block surrounded by a single layer of habitations, III. Opening of the block at the two ends leading to a double row, IV. Suppression of the opposition street x courtyard: construction in a single row: economy of viable surface and underground construction allows the desired amount of sunshine, removes gardens with unproductive façades.

Source: Gaston Bardet (1941). *Problèmes d'Urbanisme.* Paris, Dunod.

Chapter 5: Achievements and future outlook

5.1 Achievements

The principal aim of this doctoral thesis was the evaluation of the gross and useful solar radiation and daylight flux which are impinging the envelopes of buildings in representative urban environments located in Switzerland, the United Kingdom and Brazil. It focuses on the relatively large scale of urban districts and involves eight urban sites in the world which were modelled and analyzed.

The method adopted for all computer simulations consisted in modelling—via a computer-aided drawing piece of software, namely AutoCAD— the digital model of each building or group of buildings prior to their export toward a urban performance analysis software (PPF software package). Spatial distributions of solar irradiation and daylight fluxes over the overall building façades and roofs were calculated using ray-tracing simulation techniques in order to determine the appropriate placement of different solar technologies (passive and active solar, photovoltaic and daylighting). Several performance indicators were used to assess the solar utilisation potential of these urban sites (e.g. statistics of sky view factors and daylight factors) in order to identify optimal solar strategies for these urban contexts.

The second objective of this thesis was the comparison of conceptual urban planning and design in order to explore the impact of different indicators of building density in an urban context. To achieve this, four different types of representative built forms in Basel and in the other European cities were compared for their daylighting and solar potentials. In addition, comparisons between the urban sites and various density indicators were carried out.

Finally, the third objective of this study was to examine some of Le Corbusier's original architectural concepts. To this end, numerical simulations were carried out using a rational approach applied to Le Corbusier's proposition concerning the "solar theory" he used in his urban projects.

This study also presents the various works and sun-related recommendations that have appeared principally since the end of the 19th century, together with the various related scientific models and software tools. Many theories, tools and methods have been suggested by physicians, engineers and physicists, as well as by the architects themselves. What emerges from the latter regarding the various solar orientations alternatives is the existence of a persistent problem from the 19th century until the beginning of the 20th. Even today, in spite of our increased scientific knowledge of solar energy, this choice is frequently problematic and restrictive. This study offers some alternative approaches, but as the field is so vast and the time so limited some of these questions will regrettably for the time being remain unanswered.

Before concluding this research, it is worthwhile to look again at the three statements of the thesis set down at its beginning:

Hypothesis 1: ***The shape and spatial layout of the buildings can considerably improve their solar energy incomes.***

This hypothesis was analyzed throughout Chapter 4 using concrete examples and case studies. The shape and buildings layout can drastically modify the main façades' orientation from which solar energy collection depends. Indeed, it is necessary to juggle with all the directions to provide an appropriate response to all the practical constraints and improve the viability of solar technologies. For certain towns, the margin of manoeuvrability is broader than for others. However one has to choose the predominant parameters of a design project and conversely abandon those, which are not achievable or have an insignificant impact on the final results, such as implementing PV panels on façades in a dense urban area.

Hypothesis 2: ***High density does not always reduce the utilization potential of solar energy in an urban context.***

This hypothesis was also analyzed in the course of this thesis. The results also suggest that considerable progress can be achieved in terms of daylight and solar potential, simply by reorganizing the layout of building blocks without reducing the amount of usable floor area. For all that, extensive covering of the site is not generally preferable because it reduces the daylight availability and solar potential on the building façades. Nevertheless, the roof surfaces do remain an important source of usable surface for thermal solar and BiPV applications.

Hypothesis 3: ***The Contemporary City of Three Million Inhabitants would not offer the expected quality of solar exposure claimed by Le Corbusier at that earlier time.***

Hypothesis 3 was proved by comparing the daylighting performance and solar potential of Le Corbusier's *Contemporary City* with two classical Parisian urban blocks. The rational and systematic urban plan designed by Le Corbusier, is not an effective design option for either density or daylighting performance. Indeed, the more random traditional pattern showed a comparable daylighting potential and possibly higher urban density. Relying on health regulations and without any scientific basis, Le Corbusier's plan was simply too radical a reform of the urban fabric of the French capital.

To claim that this doctoral thesis includes all the aspects of urban design and building shapes would be pretentious. "*Indeed, in this complex system which is the city, everything has an influence on everything: economic logic, the logic of property, financial logic, the logic of regulations, technological and behavioural logic are constantly interreacting*" (Allain 2004). The same urban design could be suitable for a given location and not for another, because of the different neighbourhood constraints. It does not make sense to maximize the buildings performance in terms of daylighting and solar potential, if afterwards we are going to place it in non appropriate location. As Goethe said of Christopher Marlowe's *Dr Faustus*: "*Wie gross ist alles angelegt?*". Far more pertinent to this research one could do no better than to ponder again the phrase by Prof. Rémy Allain[66] who has brought so much knowledge to all those who have chosen the town as their preoccupation : "*One has to realize that the urban form is not easily grasped*".

5.2 Future Outlook

This study could be extended in various ways. In addition to the computer analyses related to the solar potential of buildings, it could be extended in order to include geographic and temporal sectors in Canada, China, Danemark, Germany, Italy, Japan, Russia, USA, Spain, etc.

It would also be useful to compile a handbook/catalogue comprising all possible combinations of generic urban layouts with their impact in terms of daylighting and solar potential in a built environment. One essential requirement would be to model urban forms with an identical plot ratio in order to obtain comparable results. This study could also include a choice of "good and bad" examples of existing districts using the same methods of analysis used in the present research study. This catalogue would be of enormous value to urban planners and architects for the creation of housing estates or entire districts. It would also be interesting to extend this analysis to other representative regions located at different latitudes to provide more detailed knowledge in planning solar cities.

Moreover, it would be important to include in this study a Summer daylighting analysis of urban zones in order to examine overheating risks. The problem of overheating is especially relevant today and resolving it would avoid using air conditioning in certain buildings. It would be invaluable in creating

[66] Prof. Rémy Allain, RESO (Rennes - Espaces et Sociétés), UMR CNRS 6590. Allain, R. (2004). La morphologie urbaine. Paris, Armand Colin/SEJER.

districts which would limit overheating risks. In fact, if urban shapes strongly influence the daylighting of buildings during the Winter period, this impact is lower in the Summer period for our latitudes.

To return to the simulations, a precise positioning of the windows on the external building envelopes would be of great interest. Analysis of this kind would allow us to consider the windows of the envelope and thereby provide an estimation of the amount façade openings as well as contributions to solar gains.

No cast shadow can impede the utilisation of solar energy. Another possible approach would be to evaluate the direct shading effects of trees on buildings. A shading effect does not only affect buildings but also the interstitial spaces in-between them which are usually in semidarkness. An examination of the impact of built forms on exterior zones would considerably enhance this study.

To conclude an analysis of the so-called non-passive solar zones in buildings in order to avoid them as much as possible would also be of undeniable benefit to the solar performance of buildings. Spaces which are in the buildings' angles or on the inside buildings and which cannot sufficiently benefit from daylight, solar gains and natural ventilation must be avoided. One could also proceed to an in-depth study of buildings in relation to their compactness in order to increase the amount of floor area benefitting from daylight and passive solar energy.

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Curriculum Vitae

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Born on June 13, 1968
Swiss & Italian citizenships
Married, 1 child

Education

2010	**Ph.D. in Environment (EDEN), LESO-PB, ENAC, IIC, EPFL** Thesis title: "Optimisation of Urban Form by the Evaluation of the Solar Potential".
2001	**M.Sc. of Art in Architecture, EPFL** ("Diplôme d'architecte EPFL").
1993	**Bachelor of Art in Architecture**, **HES-Bernoise** ("Diplôme d'architecte HES").
1989	**Federal certificate of Architectural Draughtsman, CFPS, Sion** ("CFC, Certificat Fédéral de Capacité de dessinatrice en bâtiments").
1985	**Diploma of Secondary Education, Collège de Derborence, Conthey, Switzerland** Scientific orientation (niveau A).

Academic Awards

2004	**Performance bonus as a research assistant at LESO-PB, ENAC, IIC, EPFL**
2000	**Cantonal Bank of Vaud (BCV) Prize for an Architectural Project at EPFL, SAR** 4th year project for a parliament building for the City of Lausanne under the direction of Professor Giorgio Grassi, who had been invited by the EPFL. Giorgio Grassi is architect in Milan and Professor of the Architecture Department at the Politecnico in Milan, Italy.

Fellowship

2005 – 2006	**Swiss National Science Foundation (SNF) Fellowship** Granted to prospective researchers.

Professional Experience

2010 –	**Architect EPFL-HES, City of Pully, Town planning and Environment service, Switzerland**
2008 – 2009	**Architect EPFL-HES by CCHE Architecture SA, Lausanne, Switzerland** ▪ **Yverdon Gymnasium, CESSNOV:** Construction manager, management of refurbishment site for the asbestos decontamination phase and renovation of the faculty room (budget 3 millions).
2006 – 2008	**External Assistant SAR (Winter semester, 20%), EPFL, MAS "UE-M Space and Light"** **Dr Bernard Paule, lecturer**
2006 – 2007	**Architect EPFL-HES by Pont12 Architectes SA, Lausanne, Switzerland** ▪ **Tunnel-Riponne building blocks in Lausanne:** Construction manager, management of refurbishment sites in the rue du Tunnel 10-16 and the rue des Deux-Marchés 11- 15 (budget 7 millions). ▪ **Thermal energy calculation of various projects according to the SIA norm 380/1**
2005 – 2006	**Visiting Scholar at the Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge, UK, Prof. Koen Steemers** Participation in a research project financed by the British Academy: ▪ **"Sustainable Urban Spaces. A Case Study in Saõ Paulo, Brazil":** A theoretical comparison of built forms in order to investigate the diverse effects of the built-up density in São Paulo, plus evaluation of a range of urban blocks located in Luz and Barra Funa, two districts in the city centre of São Paulo in Brazil.
2001 – 2005	**Research Assistant, Solar Energy and Building Physics Laboratory (LESO-PB), IIC, ENAC, EPFL**, **Prof. Jean-Louis Scartezzini, Privat-docent Dr Jean-Bernard Gay** (**retired)** Participation in two research projects financed by the Swiss Federal Office of Energy (SFOE): ▪ **"SOLURBAN":** Evaluation of the solar potential in various urban environments (Basel, Lausanne and Geneva). Research project with the goal of promoting sustainable urban architecture and of allowing a better direct use of solar energy in the urban environment. ▪ **"Quartiers Durables"** (Sustainable districts): Research project devoted to the application of sustainable development and various strategies in the case of refurbishment or reconstruction. The aim of this study is to demonstrate why the social and economic issues affecting building refurbishment or demolition should be addressed before major refurbishment work is undertaken.

- **"DB GBF Areal competition":** Evaluation of the solar potential of projects submitted to the architectural competition of an industrial wasteland in Basel, Switzerland.

- **Licensed examiner for MAS "Indoor Environment Quality", EPFL**
  Prof. Claude-Alain Roulet (retired), now Lecturer EPFL

1999 – 2001	**Student Assistant, Theory and History of Architecture Laboratory (LTH2), IA, ENAC, EPFL Prof. Bruno Marchand** ▪ Participation in several research tasks and publications. ▪ Participation in staging two exhibitions.
1995 – 1996	**Architect HES by Jean-Pierre Perraudin, Architect EPFL-SIA, Sion, Switzerland** ▪ Various architectural competitions. ▪ Assistant to the project director for the building of a country mansion in Sion.
1990 – 1991	**Internship by Michel Waeber, Architect SIA, Barberêche, Fribourg, Switzerland** ▪ Project of the extension of the Art and History Museum of the City of Fribourg.
1985 – 1989	**Training program for Architectural Draughtsmanship by Esthi & Peter Schwendener, Architects EPFZ-SIA, Sion, Switzerland** ("Apprentissage de dessinatrice en bâtiments").

Independent architect activity

2010	**Métamorphose competition with Pont12 Architectes SA, Switzerland** ▪ Sustainable urban development, Lausanne, Switzerland. **Corsier competition with Anastasio Di Virgilio, Campobasso, Italy** ▪ Joint urban development between Maison Neuve and Prés Grange areas, Geneva, Switzerland.
2001	**Minergie house with thermal solar panels and eco-materials, Ardon, Switzerland** ▪ Project and construction.
1996	**Bavois competition** ▪ Motorway relay in Bavois, Vaud, Switzerland.

Consulting and Services

2005 – present	**Evaluation of the solar potential of various architectural projects/Evaluation of various architectural competitions using the SNARC method:** ▪ **DELAMA Devanthéry-Lamunière-Marchand Urbanisme, Geneva, Switzerland:** Various studies connected to the quality aspects of densification by elevation in the City of Geneva, Switzerland. ▪ **CAR Cambridge Architectural Research Ltd in Cambridge (UK), Prof. Koen Steemers:** Evaluation of the architectural competition Tower Works for the reclamation of an industrial wasteland in Leeds in England plus evaluation of a development project of the Eastern Quarry site in the United Kingdom. ▪ **Laboratory of Geographic Information Systems, LASIG, EPFL:** Study of several building blocks in the old town district of Geneva, Switzerland. ▪ **Prof. Claude-Alain Roulet (retired), Lecturer EPFL and Maire of Apples, Switzerland:** Evaluation of projects for the architectural competition at the Collège d'Apples, Switzerland. ▪ **Privat-Docent Dr Jean-Bernard Gay (retired), LESO-PB, EPFL:** Evaluation of projects submitted to the architectural competition for the extension of the Ethnographic Museum and the Institute of Ethnology of the City of Neuchâtel, Switzerland.
2007 – present	**Reviewer for "Solar Energy" journal**
2002 – 2005	**Member of the Teaching Commission SAR, ENAC, EPFL**

Computer skills

Software	ArchiCAD, AutoCad, PPF, RADIANCE, EPQR, LESOSAI, Photoshop, Illustrator, FrameMaker, InDesign, QuarkXpress, Filemaker, Microsoft Office, Endnote.

Languages

French	Native language
Italian	Fluent, spoken and written
English	Good, spoken and written
German	Good, spoken and written

Publications

Link	http://infoscience.epfl.ch/