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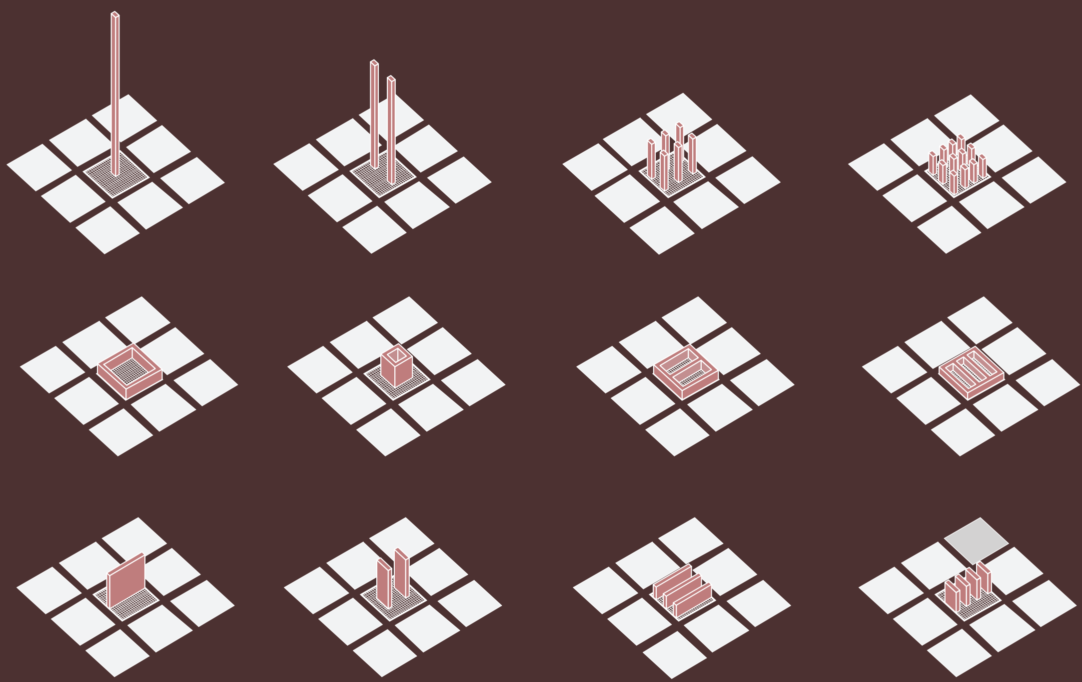
Building massing and performance:
A guideline for early-stage design analysing energy demand, daylighting, and solar potential



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Milan
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Master thesis presented to the Graduate Program in Building and Architectural Engineering of Politecnico di Milano as a prerequisite to obtain the master's degree in Building and Architectural Engineering.

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"Art without engineering is dreaming. Engineering without art is calculating."

(Steve K. Roberts)

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I am finishing this thesis full of hope that soon enough we will meet for a coffee at Piazza Leonardo da Vinci, in Milan.

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Abstract

The Building Sector is one of the responsible sectors for climate change, a consequence of population growth and the evolving forms of society's housing and living. Even though it contributes up to 30% of global annual GHG emissions and consumes up to 40% of all energy, it has a great potential for delivering significant and cost-effective mitigation measures. High-performance buildings can play a crucial role also in reducing energy use, by applying energy-saving strategies. To contribute to the growing knowledge on building massing at early-stage design, the goal of this research is to study building typologies and evaluate the resulting energy performance, to answer for environmental and regulations requirements, but considering at the same level of importance daylighting levels, which impacts greatly on several buildings aspects, such as its comfort and the electricity demand for lighting.

Case studies from towers, courtyards, and bars with the same floor-to-area ratio are analysed in regards to its daylighting conditions, solar potential, and energy demand, all the three indicators ranked equally. As the research finds some answers, the study is further detailed in order to reach a final answer and understand each typology's strengths and weaknesses. It will be proved that, for instance, high-rise towers have a high energy requirement while also a high solar production, which can be an interesting trade-off, considering the great daylight performance in the slender cases. Courtyards can be slightly limited in their daylight conditions while presenting a very low energy requirement. Bars seem to be the least performing typology among the three, presenting a considerably higher energy requirement with low solar capture and some daylighting limitations, mainly due to overshadowing. It is then proved that even if other passive strategies are applied on the envelope, the limitations from the massing decision follow along all the design process, and they must be carefully chosen at the early-stage to avoid resulting in poor building performance.

Keywords: Sustainable design; Energy efficient buildings; Daylight; Solar potential; Typology; Building massing; Early-stage design; Zero-energy buildings; Tower; Courtyard; Bar.

Abstract

Il settore edilizio rappresenta uno dei principali responsabili del cambiamento climatico, dovuto principalmente all'aumento della popolazione e all'evoluzione delle forme abitative e dell'abitare contemporaneo della società . Pur contribuendo al 30% delle emissioni annuali di gas serra e al 40% della domanda di consumo energetico mondiale, esso ha tuttavia grande potenziale nel fornire misure di attenuazione efficaci sotto il profilo dei costi. Gli edifici ad alte prestazioni possono infatti giocare un ruolo cruciale nella riduzione del consumo energetico tramite l'applicazione di politiche di risparmio. L'obiettivo di questo lavoro è quello di valutare le tipologie edilizie e i loro indici di prestazione energetica, per rispondere così ad esigenze di tipo ambientali e normativo, considerando allo stesso tempo i livelli di illuminazione diurna, capaci di influenzare diversi aspetti degli edifici, come il suo comfort o la domanda di elettricità.

Diverse tipologie edilizie, in particolare edifici a torre, a corte e in linea con pari indice FAR, verranno valutate in relazione a daylight, potenziale di energia solare e fabbisogno energetico. Affinando la ricerca, tale studio viene ulteriormente approfondito al fine di raggiungere ad una risposta finale, alla definizione di potenzialità e svantaggi di ciascuna tipologia. Verrà dimostrato ad esempio, che gli edifici a torre hanno un elevato fabbisogno energetico e al contempo un'elevata produzione solare; compromesso interessante, considerando le ottime prestazioni in termine di daylight. Gli edifici a corte risentono di limitazioni nelle loro condizioni di luce diurna pur avendo un fabbisogno energetico molto basso. Gli edifici in linea, invece, sembrano essere la tipologia meno efficiente tra le tre, presentando un fabbisogno energetico più elevato, scarsa capacità di captazione solare e limitazioni di luce naturale.

È dimostrato che, pur applicando strategie passive sull'involucro, i limiti derivanti dalla decisione delle volumetrie caratterizzino decisamente il processo di progettazione, e dunque devono essere scelti con cura nella fase iniziale per evitare scarse prestazioni dell'edificio.

Parole chiave: Progettazione sostenibile; Efficienza energetica degli edifici; Luce naturale, Potenziale solare; Tipologia; Volumetrie edilizie; Progettazione preliminare; Edifici a energia quasi zero; Edifici a torre; Edifici a corte; Edifici in linea.

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Introduction

Nowadays, it is not uncommon to watch the news or read papers on our daily routine talking about climate change developments. The changes in the average conditions of the planet - such as temperature rising, warming on the ocean, sea-level rise, glacial retreat, etc. - for a long period are a real concern for the present and the future of human life on Earth.

There is a current warming trend on the Earth's surface, which is of particular significance because most of it is extremely likely (greater than 95% probability) to be the result of human activity since the mid-20th century and proceeding at a rate that is unprecedented over decades to millennia.[32]

The main cause for these changes is attributed to the human expansion of the so-called "greenhouse effect". It is a well-known effect, originally a natural process that results in the warming of the Earth's surface. When the sun's energy reaches the Earth's atmosphere, some of it is reflected back to space and the rest is absorbed and re-radiated by greenhouse gases. The primary greenhouse gases (GHG) in Earth's atmosphere are water vapour (H2O), carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and ozone (O3). Without those gases, the average temperature of Earth's surface would be about −18 °C, rather than the present average of 15 °C. [33]

For a while now, it is widely accepted that human activities are contributing to climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that between 1970 and 2004, global greenhouse gas emissions due to human activities rose by 70 percent [34]. In the Fifth Assessment Report of IPCC, it is stated that the evidence for human influence on the climate system has grown since the IPCC AR4 and that emissions of CO2 from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010, with a similar percentage contribution for the increase during the period 2000 to 2010.

The rate of emissions growth is particularly concerning. If we look at the IPCC's high growth scenario, the GHG emissions could almost double by 2030 to reach 15.6 billion metric tons CO2 eqv. [2] . As Figure 1 shows, historically the majority of emissions were generated from North America, Western Europe, and the Eastern Europe, Caucasus, and Central Asia (EECCA) regions, but based on this scenario, the total emissions from developing countries will surpass these regions by 2030.

Ultimately, there is plenty of data widely available backing up the fact that climate change is real. Most experts agree that over the next few decades, the world will undergo potentially dangerous climate changes, which will have a significant impact on almost every aspect of our environment, economies and, societies.

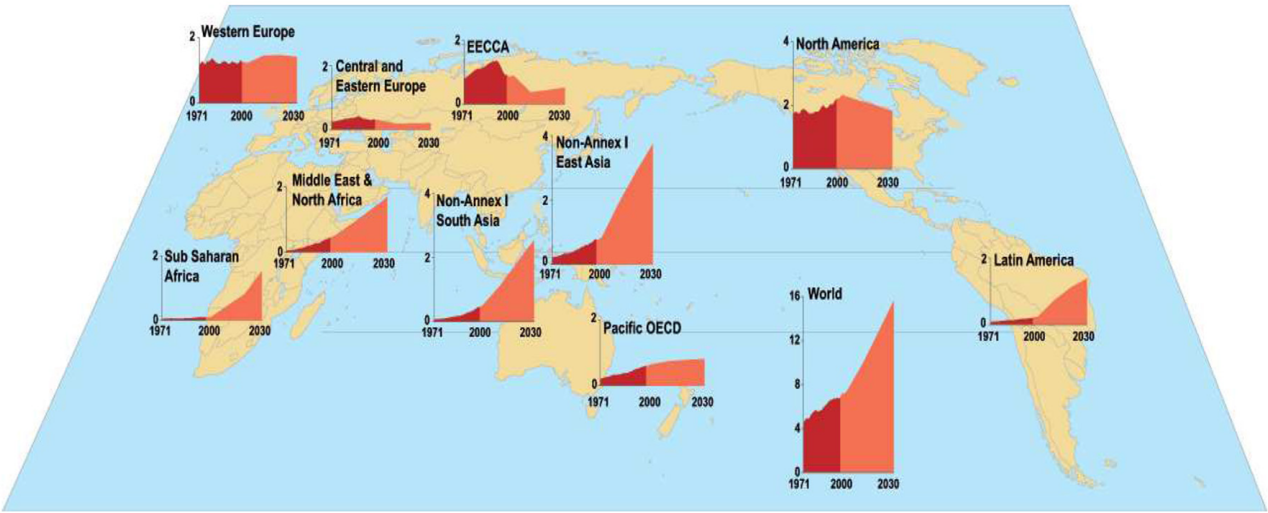


Figure 1: CO_2 emissions from buildings (including through the use of electricity) - IPCC high growth scenario. [2]

Notes

Dark red – historic emissions;

Light red – projections 2001–2030 data;

* 2000–2010 data adjusted to actual 2000 CO_2 emissions.

* EECCA = Countries of Eastern Europe, the Caucasus and Central Asia.

This research focuses on one responsible sector for climate change, a consequence of population growth, and the evolving forms of society's housing and living: the Building Sector. It is estimated that at present, buildings contribute as much as one-third of total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase.[2] The CO2 emissions, including through the use of electricity in buildings, are estimated to have grown at a rate of 2.5% per year for commercial buildings and 1.7% per year for residential buildings, between 1971 and 2004. [2]

Therefore, governments all over the world have been making policies aiming for improvements in new and old constructions and setting targets for greenhouse gas emissions reduction to be met. The matter must be addressed seriously, and the mitigation of greenhouse gas emissions from buildings must be the key element of every national climate change strategy.

Greenhouse gas emissions from buildings primarily arise from their consumption of fossil-fuel-based energy, both through the direct use of fossil fuels and through the use of electricity which has been generated from fossil fuels. Significant GHG emissions are also generated through construction materials, in particular insulation materials, and refrigeration and cooling systems.

Even though the building sector contributes up to 30% of global annual GHG emissions and consumes up to 40% of all energy [2], it has a great potential for delivering significant and cost-effective mitigation measures. High-performance buildings can play a crucial role also in reducing energy use, by applying energy-saving strategies such as enhancing the thermal performance of building envelopes, integrating low-grade energy sources, employing energy-efficient equipment, or improving the operation efficiency of HVAC systems, among others. It was reported that the heat gain/loss of the building envelope leads to approximately 20% and 50% of the cooling/heating load in buildings. Improving the thermal performance of the building envelope can reduce the heat gain or loss and potentially decrease the energy demand of buildings.

Furthermore, over the past few decades, great effort has been devoted by researchers, architects, and building designers to developing new approaches and techniques for improving the thermal and energy performance of external walls.

Besides developments in building technology and sustainability, great effort has also been made to improve building design in terms of quality and comfort for the end-user. In fact, if there is such a thing as a “perfect” building design, it probably would be a building that performs greatly in terms of sustainability and supplies not only the basic needs for the occupiers but also overcomes them. Of course, the definition of “perfect” can be abstract and it’s based on one’s personal opinion.

Comfort per se is a holistic experience, determined by the interaction of many environmental factors, its possibilities, and the ability of the occupant to determine and enjoy those options. It’s just a matter of looking where people spend their holidays to realize that the feeling of well-being is not prescribed by narrow environmental limits. [21]

However, if we pay attention, one could relate the state of comfort or discomfort inside buildings with some of the human senses. Acoustic comfort, related to our hearing capacity; Visual comfort, related to our sight; Thermal comfort, related to our touch/body sensation; and even “odour comfort” - after all, it implicates indoor air quality and also health conditions.

Thermal comfort is essentially related to the thermal balance between heat gains due to the metabolism of the body and heat losses from the body to the environment. [21] That’s the one and only reason why designers and engineers spend so much time working to improve building envelope and HVAC systems.

Visual comfort can be related to the view, but one could argue that the lighting conditions can impact greatly the sensation of indoor discomfort. Both too little and too much light result in eye strain and discomfort. That’s why designers should be aware of the importance of designing for daylight and also of an adequate artificially lighting strategy. Not only that, but visual comfort can include freedom from glare, freedom from veiling reflections, and particularly in the case of artificial lighting, colour rendering. Besides that, both daylighting and artificial lighting have an important role in expressing the architectural intentions of the building and hence may affect the pleasure and well-being of the occupants. Some attention, on that matter, must be paid to the windows, which usually have the dual function for visual comfort: they provide daylight and the views to outside. The association of these two factors in the occupant’s mind is positive - i.e. the limitations of daylight may be more readily accepted if the window provides pleasant views. [21]

All of that considered, a question is raised: how to tackle both sustainability and environmental issues as well as to succeed in all the comfort aspects in the building design? One sure thing is the latent need to build up knowledge on architectural moves considering the context of climate change and advance the knowledge in the area of energy-based form optimisation in the design of neighbourhoods and buildings [3].

This research is part of a broad collective effort to address these matters, to which there is a contribution from the work of undergraduate architectural students from the Design Studio "Solar Sculpting: Building Form and Energy" at Pratt Institute and the development of several master thesis from architectural engineering students at Politecnico di Milano. This wide research is also carried out in conjunction with Task 63: 'Solar Neighbourhood Planning' of the SHC (Solar Heating and Cooling Program, International Energy Agency), and its main objective is to explore passive measures related to the built form - and particularly the role of geometry - in improving thermal and visual comfort and potentially reducing energy needs in buildings. [3]

Therefore, the contribution from this research is the study of building mass and form, evaluating the energy performance, to answer for environmental and regulations requirements, while at the same time considering equally ranked in importance the daylighting levels, which impacts greatly on several buildings aspects, such as its comfort and the electricity demand for artificial lighting. Evidently, the energy requirement for heating, cooling and artificial lighting is an indicator of how far (and how frequently) the building is from comfortable thermal and visual conditions.

Together with reducing energy consumption, on-site energy generation has emerged over the past two decades as a decisive factor in addressing the depletion of natural resources and the environmental degradation associated with the use of fossil fuels [3]. Hence, an equally important research topic is related to the active solar potential of the building envelope and the role of solar radiation on external surfaces (both vertical and horizontal) to produce hot water and electricity from the sun. Thus, along with energy use and daylighting conditions, the research evaluates the solar potential and its variation according to the typology, combining all the factors in the seek for optimal balanced performance.

Literature Review

When starting this research, some fundamental concepts required remembering and reviewing, to allow the study to be built on a strong conceptual basis as the research questions were raised from challenges faced every day by architects and engineers. Here, a summary of previous literature is reviewed for every aspect that was studied, from the basics to similar studies on building form, daylighting, energy and, solar potential.

In the book “Energy and Environment in Architecture: A technical design guide” [21], Baker and Steemers raise the continuous dilemma between the professions that shape the building sector and reassure the trend of making informed decisions right at the beginning of the design:

> *“A view prevails that the architectural process tends to be isolated from the analytical support of the engineering and building science professions. Rather, the latter provides support in a reactive way accepting the basic concept and enabling it to be realized. However, there is growing evidence that the environmental performance of buildings is determined, to a considerable extent, at the conceptual stage.”*
>
> [21]

One of the first aspects to be covered about the environmental performance and how to evaluate it, was to study in detail the energy performance requirements and indicators, explained in the publication “Building and Climate Change: Summary for Decision-Makers” [2], by the Sustainable United Nations (UNEP) in 2009.

It covers the indicators that are used to set requirements for energy performance, according to the area of space covered, for example in heating / cooling a space or lighting demand, and should be adjusted according to location, usage, and so on. The energy performance indicators are useful to compare the energy efficiency against one building to another or one location to another, even though many countries still do not have agreed on methodologies or indicators to do so.

This is very important, as the energy performance requirements are an essential component of any greenhouse gas mitigation strategy. These policies, the publication [2] states, should be established at national and, where appropriate, the regional and municipal levels. On the examples of how energy performance requirements are used, they list the building codes (which have been found to be one of the most effective and cost-effective policies in reducing GHG emissions both from existing and new buildings), building commissioning (the assessment of whether a building’s system has been designed, installed and are working in accordance with the initial intents) and the self-regulation and fine-tuning of energy use (assessment of the energy performance indicators during operational phase).

Another key point in this publication is that they show that there is a vast array of policy options available for each of the main policy targets. The policy target is essentially the objective used to select the most appropriate policy for the carbon emissions scenario of a country's building sector. On that, the publication establishes:

> *"The five major policy objectives, or targets, for reducing greenhouse gas emissions from buildings are:*
>
> *Target 1: Increase the energy efficiency of new and existing buildings (both the physical envelope and the operational aspects such as energy systems for heating, ventilation, and other appliances);*
>
> *Target 2: Increase the energy efficiency of appliances (white goods, entertainment, personal computers and, telecommunication equipment);*
>
> *Target 3: Encourage energy and distribution companies to support emission reductions in the Building Sector;*
>
> *Target 4: Change attitudes and behaviour;*
>
> *Target 5: Substitute fossil fuels with renewable energies."* [2]

There also some definitions of the "environmentally-concerned" new ways of design that are interesting for the roots of this research. Because renewable technologies have become more affordable and way more flexible (building integrated photovoltaic systems, for instance), their applications in both new and existing buildings have grown significantly, resulting in the so-called "green buildings" or **"sustainable buildings"**, that can be defined as "*designs that combine design and technology, usually renewable energy systems, to meet the needs of the occupants with very low or even zero carbon emissions"* [2].

For example, **passive houses** are *"houses which maintain a comfortable interior climate without active heating and cooling systems. Their additional energy requirements may be completely covered using renewable energy sources."* [2]. Meanwhile, **zero-energy buildings** are *"buildings where energy provided by on-site renewable energy sources is equal to the energy used by the building. In addition, energy can be stored on-site, in batteries or thermal storage"* [2].

Other interesting projects taking place today are **energy-plus buildings** – *"buildings that produce more energy than they consume over a year. The extra energy is usually electricity, produced with solar cells, solar heating and, cooling, insulation as well as careful site selection and orientation."* [2].

In the results from the simulations and case studies, we will be able to conclude which kind of buildings we are dealing with. Of course, because here systems will be applied to maintain internal comfort, it is not the case of passive house, even though the effort is also in applying passive strategies to achieve energy savings. In the end, we will understand if early design stage decisions such as the massing can already define that the design will result in a "sustainable building", a "zero-energy building" or an "energy-plus buildings".

Having passed some fundamental definitions and concepts, it must be told that this research was born to give a certain continuity to another two previous studies, by the colleagues Pietro Pavesi in his MSc thesis work "A parametric design workflow applied to a responsive curtain wall system for daylight optimization of an existing building" [13] and Daniele Compagnoni, Michele Pozzi and Benedetta Ravicchio in their MSc thesis work "Chameleon: Shaping Visual Comfort. - A parametric tool for façade form-finding in the early design phase" [14]

Pavesi studied a form-finding process focused on the façade shape. The driver is the indoor visual comfort and energy efficiency of the system. It establishes a design methodology and a script to guide the search for the best performing combination of shapes and materials, caring for comfort equally both for daylighting and energy savings. In the article named "Use of 3D tessellation in curtain wall facades to improve visual comfort and energy production in buildings" [5], which was originated from his thesis work, with the help of Prof. Gabriele Masera, Prof. Simone Giostra, and Prof. Marco Pesenti, they reassure the need for passive strategies taken at the early design stage to answer for environmental targets, which brings out *"a new architectural language - one that reconnects form to performance, where formal features visually inform the users on the flows of energy and materials taking place in the building."* [5]

His study aimed was to investigate the potential of folded façade geometries alone to deliver the desired daylight target while also increasing the solar potential for energy generation, as compared to a flat surface curtain wall. In this study, the same principle was followed, whereas starting from the assumption that the shape indeed affects building performance, only that here the changes start in a broader spectrum, changing the typology and building massing instead of the façade. One could say that an ideal output or following study could be matching the results found in this research and the results from Pavesi's work by applying the best performing typology and massing to an optimized façade shape. His study employs metrics for daylight indicators based on LEED requirements, using spatial daylight autonomy and annual solar exposure, which will also be evaluated in this research.

The outputs of his investigation of various folding configurations for the building envelope show that the 3-dimensional combination of opaque and transparent panels can indeed deliver much better performances, in terms of visual comfort, compared to a flat base case. The study shows, anyway, that geometric manipulation of the envelope offers a promising new design opportunity that is particularly relevant for mid-to-high-rise construction located in dense urban areas, where the building's shape, layout, and orientation are often determined by site constraints and legislation alone.

Aligned with the above-mentioned study is the work of Compagnoni, Pozzi, and Ravicchio [14]. They follow the same pattern of studying the optimization on the building envelope shape evaluating daylight and energy but their approach is to make a plugin for Grasshopper, named Chameleon, that can perform this optimization process in a more uniform way, that could be applied for several projects and not bespoke for only one case.

In this project, as already mentioned, it was decided to change the level of optimization from only the façade but seeking to optimize for energy and daylight performance at the very beginning of the process, when the designer is deciding the building geometry. On that matter, the study developed by Sattrup and Stromann, named "Building typologies in northern European cities: daylight, solar access, and building energy use" [4] is very much in accordance with this research's intent. Their study analyses the potential of passive solar energy daylight and their impact on the total energy performance of typical urban typologies in northern Europe, using Copenhagen, Denmark, as a reference.

> *"How does urban form and density, as expressed in different building typologies, affect energy use and daylight? Architects and planners should ask themselves this question at the very beginning of the design process, and the answer is a matter of great importance because once a typology has been decided, its basic form and structure are likely to remain relatively unchanged during the building's life cycle.*
>
> *The effects of building typologies are long term. If we think of entire districts as being characterized by certain prevalent typologies, it is crucial that we understand the properties of those typologies when developing design guidelines for better, more energy-efficient cities with generous daylight availability."*

They point out the so far it is available a great amount of literature about building design, but surprisingly not so much about the effects of massing, density and urban form on a low-energy building. They published in 2013, and perhaps now, in 2020, we still have this lack of abundant publications. This is one of the reasons for this study, which hopefully will contribute with information and validated results to build upon the field literature and knowledge.

Some initial assumptions are raised in [4] based on experience: *"Dense urban building patterns might be expected to increase heating requirements and decrease cooling requirements because of restricted solar access and reduced solar gains. With regard to artificial lighting, compact urban geometries restrict daylight, too, though daylight is considerably more complex than solar access".*

The previous statement is demonstrated in Figure 2. They use plot ratio as a parameter to define urban density. It is the total floor area / plot area and it is expressed in percentage as the common denominator for the patterns studied. However, the initial assumptions should, of course, be verified and not be seen as absolute truth. For instance, *"if we look at the factors again, we can say that more compact urban design should reduce heat losses due to reduced surface area and more shared wall space. Increased density and a decreased surface-to-floor-area ratio can be expected to increase the need for cooling, as will any increase in the need for artificial lighting."*. [4]

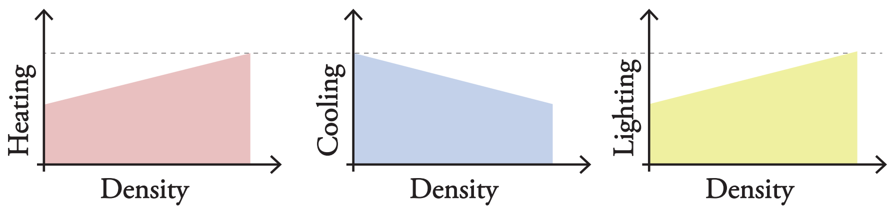


Figure 2: Energy required per square meter of floor space for space heating, cooling, and artificial light. [4]

This study approach is very interesting due to the similarity with the one proposed for this work. They compared a Courtyard block (Type A), an Indented Block (Type B), a Perimeter Block (Type C), a Bar-code Block (Type D), a Slab block (Type E) and a Tower block (Type F), shown in Figure 3. According to their findings, courtyards present the highest density and lowest energy use when compared to the other typologies. The energy consumption between the types B, C, D and E is quite small, between +2% and +8%. The tower block, Type F, has significantly higher energy consumption (16% higher than Type A, which correlates with the compactness of the surface-to-floor-area ratios of the different types).

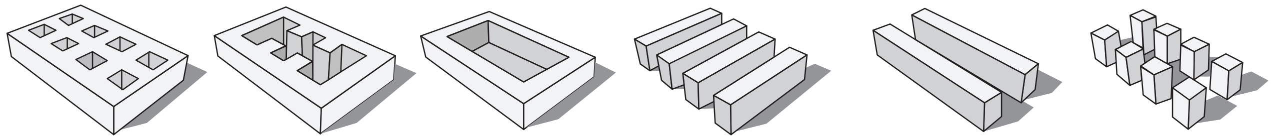


Figure 3: Six traditional urban building type patterns. Figure adapted from [4]

> *"Generally, energy consumption increases as the density of the urban building type pattern decreases, but the big jump in energy performance is achieved when additive urban forms are used instead of detached building types.*
>
> *The dominant factor in total energy consumption is heating. This is partly due to Copenhagen's low mean temperature, which is 8.2°C (compared with London's, which is 10.2°and New York City's, which is 12.4°C), which necessitates more energy for heating to achieve thermal comfort."* [4]

Regarding the daylight conditions, the courtyard (Type A) has the lowest passive solar gain and, in contrast, the towers (Type F) have the optimal daylight performance. Moreover, it was concluded that with well-insulated building façades, increased urban density and compactness will not necessarily lead to further energy-use reductions, which is evidence that the design should in fact design also for daylight and solar access rather than focusing on energy use alone.

Therefore, having analysed both traditional and contemporary typologies, the final results show that the impact of choosing a specific typology *"may affect up to 16% of the total energy performance and up to 48% of the daylight autonomy in buildings at similar urban densities"* [4], which is proof that the definition of the building geometry is a key factor affecting energy consumption and daylight levels.

Another popular publication that studies the relationships between built forms, density and solar potential is the article named "Urban form, density and solar potential", by Cheng, Steemers, Montavon and Compagnon [20]. They simulated eighteen generic models, each one representing a particular combination of built form and density but applying a level of randomness either in the horizontal pattern and/or in the vertical one. They evaluated three design criteria, applied in the climate of São Paulo, in Brazil: (i) openness at ground level, which is highly related to pedestrian comfort; (ii) daylight availability on the building façade, which indicates the daylight performance in buildings and (iii) PV potential on the building envelope, which represents a significant portion of renewable energy application at the urban scale.

Among the studied cases, they had the samples organized into four distribution patterns. They are organized by combining different horizontal and vertical layouts, either uniform or random. Denoted by the expression (**H**orizontal layout, **V**ertical layout), the result of the categories are: (uniform, uniform), (uniform, random), (random, uniform) and (random, random), and they can be seen in the following Figure 4, extracted from their paper:

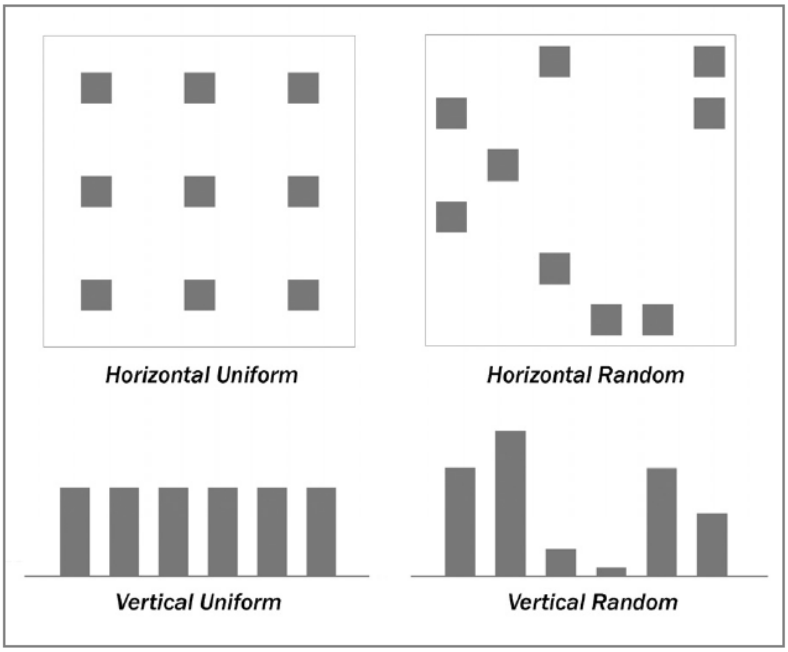


Figure 4: Horizontal and vertical urban layouts. [4]

The parametric analysis was carried out to reveal the interrelation between randomness, plot ratio and site coverage in order to provide educated information for designing towards the increase of solar potential in cities.

The results are firstly evaluated in terms of the sky view factor. It is *"a measure of the openness of a surface: a SVF of 1 means an unobstructed view of the sky and a SVF of 0 means a completely obstructed view of the sky"* [20]. They found that the improvements with (random, random) setting are significant when compared to (uniform, uniform), the increments are 56%, 112% and 173% respectively for low, medium and high plot ratio. The findings also suggest that random arrangement is more beneficial in high-density settings than low-density settings.

Afterwards, the results were evaluated in terms of daylight availability (DA) on the building facade, which is defined by:

$$DA = \frac{\text{global illuminance on building façade resulting from sunlight, skylight and reflected light}}{\text{global illuminance on an unobstructed horizontal plane}}$$

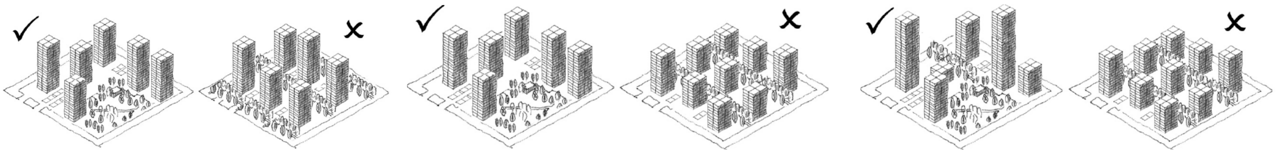
The findings are that, for a given built form, the average daylight availability on building façade decreases with increasing plot ratio and site coverage. These results are expected giving that increasing built density simply by adding more blocks or building higher would create more obstructions and thus reduce the access of daylight on building façades. The results show that, at a low plot ratio, the effect of horizontal randomness seems to be negligible; nevertheless, its importance is noticeable at a high plot ratio. On the other hand, the effect of vertical randomness is significant in all classes of plot ratio.

Subsequently, the solar potential for photovoltaic systems (PV) has been examined in the parametric study. The present research has been based on their methodology and adapted the thresholds to suit the adopted climate and found results. They defined the values based on technical limitations as well as economic aspects, and their assumptions are:

> *PV POTENTIAL = % of building envelope which receives an amount of solar radiation higher or equal to the set thresholds*
>
> *PV application thresholds = 800 kWh/m^2 for building façade*
> *1000 kWh/m^2 for roof*

The results suggest that high site coverage is favourable as it provides an extensive roof area which is a major source of high-level solar radiation. However, in such high coverage layout, the random vertical layout is disadvantageous as it creates overshadowing of roof area which in turn, undermines the solar availability on the roof surface. Contrarily, in low site coverage development, a random vertical layout is preferable. This is because in low site coverage layout, the availability of roof surface is relatively limited and building façade becomes the major surface for PV application. The random vertical layout allows better solar access on the façade, therefore results in higher solar potential. Horizontal randomness, on the other hand, does not affect the results very much.

Altogether, a random layout seems to be more beneficial. Horizontal randomness is more influential than vertical randomness when evaluating ground openness. Vertical randomness is important in all cases. Moreover, for both SVF ground and DA facade, randomness is more beneficial in high-density setting than in low-density setting. Therefore, some conclusions can be drawn:



"For high density solar cities, one of the most important recommendations is randomness in horizontal layout"

"For arrangements with higher buildings, less site coverage and more open space are preferable than those with lower buildings and higher site coverage"

"Vertical randomness is preferable. To make this happen, planning regulations on building height would have to be made more flexible"

Figure 5: Recommendations for designing solar cities. [20]

> *"After all, the key message of this paper is that the intention for densification and the concept of sustainability are not mutually exclusive. Given proper urban design and layout, compact cities can be a respectable solution to rapid urbanization and urban regeneration."* [20]

It should be noted, however, that one possible limitation of the study this study is that it is based on the average annual sky conditions of São Paulo, which is of low geographic latitude (23.5° S). It would be interesting to apply the same concept in another location to understand if the results would be the same, but perhaps some comparison can be made afterwards with the results obtained in this study as well, giving that the location is quite different.

Now, going back to the first book mentioned in this chapter, some lessons learned are also to be highlighted here, based on these two publications: "Energy and environment in architecture: a technical design guide", by Baker and Steemers [21] and "Energy consumption and urban texture", by Ratti, Baker and Steemers [22].

One of the first points to be raised is some data regarding Daylight Factor, metric that will be applied in this research and will be further detailed in "Metrics" on page 42. In [21] it is shown that in a 3-meters high room, at a distance greater than 6m from the window (or twice the ceiling height), the DF on the work plane will fall to typically less than 1%, which will then fall outside the acceptable range of 2 to 5%. This then becomes a validated rule-of-thumb, meaning that *"if a building is deeper than 12m, the inner central zones, i.e. beyond 6m from either side, will need to be permanently artificially lit. Furthermore, the intermediate zone between 3m and 6m will be daylit for fewer hours than the outer zone. A double-height space will allow useful penetration up to 12m (assuming the window height is close to that of the wall), indicating that the penetration of daylight is dependent upon the ratio of room height to depth."* [21]

The book also introduces the LT Method (Lighting and thermal), which aims for a design to maximize the passive zones (perimeter zones) of the building and provide means of estimating the energy performance for different options. Therefore, the concept of passive and non-passive zones is defined, where passive zones can be daylit and naturally ventilated, which by consequence makes them zones admissible of suffering overheating by solar gains in summer but able to make use of solar gains for heating in winter. On the other hand, non-passive zones have to be artificially lit and ventilated and in many cases cooled.

These concepts are also commented in [22], a publication that explores the effects of urban texture on building energy consumption. In this paper, only parameters related to urban form are taken into account in order to answer the question: *"what shape should a building be to reduce heat losses?"*. To answer that question, the authors continue to explore the above-mentioned passive zone concept and the surface-to-volume *(the amount of exposed building envelope per unit volume)* indicator.

They highlight:

> *"Minimizing heat losses during the winter requires minimization of the surface-to-volume ratio; but this implies a reduction of the building envelope exposed to the outside environment, thus reducing the availability of daylight and sunlight and increasing energy consumption for artificial lighting, natural ventilation, etc."*
>
> (...)
>
> *The proportion of passive to non-passive areas in buildings provides an estimate of the potential to implement passive and low energy techniques. It should be noted, however, that this is only a potential: the perimeter zones of buildings can still be wastefully air-conditioned or artificially lit. In some cases, passive zones can consume more energy than non-passive zones, especially when excessive glazing ratios and untreated façades make them particularly vulnerable to overheating during the summer and to heat losses during the winter.* [22]

As we can see, there are two conflicting requirements for an ideal energy performance: reducing the building envelope, which is beneficial to heat losses, and increasing it, which is favourable to the availability of daylight and natural ventilation. The point now is to understand which one prevails and delivers the best final result, which is not one that it's like to have one simple answer. According to the authors, at very high latitudes (Copenhagen for example, has a latitude of 55.4 °N) where solar gains are scarce and temperatures harsh all year long, heat conservation strategies might well be prevalent over the collection of daylight and natural ventilation. In these cases, energy-efficient buildings should probably minimize the external envelope, while at low latitudes they might try to maximize them. [22] For this reason, the relative importance of the two requirements will be climate-dependent.

All of those concepts were learned and from now on, it is possible to apply the validated strategies and see if the simulations done for this research are in line or raise some questions from the previous findings. It was important to build up this knowledge to set some initial assumptions, such as the building envelope parameters, the solar radiation threshold for solar production, the best representative glazing ratio for a residential program, among other decisions that will be further detailed along with this research.

Objectives and Methodology

Considering the previously discussed environmental and comfort aspects, there is an increasing demand for sustainable design and green buildings, and in order to achieve it, the building performance has been having a greater influence on design decisions. Every aspect of building construction matters, some of them essential at the early design stage: the massing, placement in urban context, building geometry, envelope (not only the build-up but also the relationship between transparent x opaque), materials, and construction technology. Among those, one of the most important for the early design stage is the building form. It not only influences the aesthetics and functions of the building but also greatly affects a building's energy and daylighting performance. [7]

In fact, the relationship between urban morphology, building form and solar capture should be the design drivers at the urban scale, as it directly affects both daylight and energy production potential. This statement is based on the assumption that the potential for passive strategies at the individual building scale is largely affected by decisions at the urban scale. Geometric factors like orientation, plan floor depth, and aspect ratio (distance/height) of buildings can determine limits on the solar capture performance of any subsequent design alternative. Yet, possible consequences such as high solar gains or glare risk due to high illuminance levels can be dealt with at the building scale, taking advantage of strategies such as envelope insulation, fenestration pattern and shading devices that work to regulate heat transfer, daylighting and glare.

The research deals with the interaction between different building scales on the design process: firstly, the urban scale and the massing study of a residential typology neighbourhood; then, the building scale and possible environmental strategies, considering daylight conditions and energy use requirements and lastly the building envelope, which includes the implementation of active (PV and ST systems) and passive systems (WWR, shading devices, etc).

Thus, the aim of the research is essentially to match the three performance aspects that influence substantially the design output: <u>energy demand</u> (for heating, cooling, artificial lighting, appliances, etc), <u>daylight conditions,</u> and <u>solar potential</u> (the ability of an envelope to receive solar radiation and therefore present a potential to produce solar energy, either from photovoltaic or solar thermal systems).

As it was mentioned earlier, the energy performance of a building is strongly influenced by its level of solar exposure, which is affected by the climate, built context, and building morphological characteristics. [17] Since these are typically fixed at the early design phase, the goal is to help designers to make more informed decisions, giving that performance assessment methods based on solar considerations at the urban scale are essential to support early decision-making.

Particularly, factors affecting solar exposure can be divided into two main categories:

(i) site-specific parameters, such as climate and existing obstructions; and

(ii) design-specific parameters, such as building height and orientation.

While site-specific parameters are imposed by the project's inherent characteristics, [17] design-specific parameters are decisions that will ground the whole building design, and therefore it is quite important to get it right.

The research will study three building typologies: towers, courtyards and bars and compare them in terms of the three above-mentioned indicators, trying to understand if the building mass has indeed an impact on the building performance, and if so, which typology or building dimensions shows to be the most beneficial. The study starts with a broad evaluation of case studies, where some assumptions must be made to form a fair comparison, and then it is further detailed as some conclusions are taken.

Research questions:

- Urban form and massing can be determining factors at the early stage design process to influence the building energy performance?

- Is it possible to identify an optimal building typology that stands out from the others by performing better in terms of energy demand, daylighting comfort, and energy production (solar potential)?

- Besides building typology, what are other measures that the designer can take at early design stage do to improve the building performance?

- After building geometry is defined, how the facade further development and the enhancement of envelope features can impact the 3 main indicators for the building performance (energy demand, daylighting and solar potential)?

Method:

This study is a collaboration between Politecnico di Milano, in Milan - Italy, and Pratt Institute, in New York - USA. It started from the results obtained from the architecture students in the course "Solar Sculpting: Building Form and Energy", at the Undergraduate Architecture Program at Pratt, taught by Prof. Arch. Simone Giostra and Prof. Arch. Lawrence Blough. They experienced several different design outputs with variable energy and daylight results, and that's the origin of the questionings that led to this research.

Therefore, for this study, it was applied the same climate data as they used in the course: the weather in New York, and, more specifically, data measured at La Guardia Airport. This location falls under the Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Climate Zone 4A. [36]

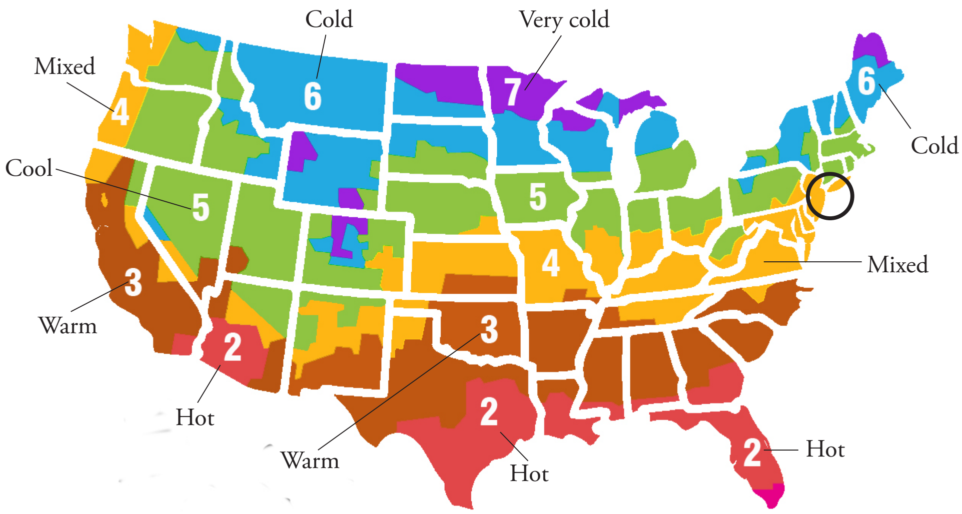


Figure 6: Climate zones - ASHRAE [36]

Climate Zone 4A is defined as "mixed – humid". This classification is for regions that receive more than 50 cm of annual precipitation, has approximately 5400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 7°C during the winter months.

Moreover, for this research three typologies will initially be analysed and then compared following the 3 main indicators already discussed: energy demand, daylighting and solar potential, with some assumptions to make them reasonably comparable. While generic, the models were structured to represent the most important geometric factors that regulate the development of the building performance. Therefore, all the cases studies have the same Floor-to-Area Ratio (FAR), equal to 3. This indicator is widely used in the field literature, and it represents the ratio of a building's total floor area (gross floor area) to the size of the piece of land upon which it is built.

$$FAR = \frac{\text{gross floor area}}{\text{area of the plot}}$$

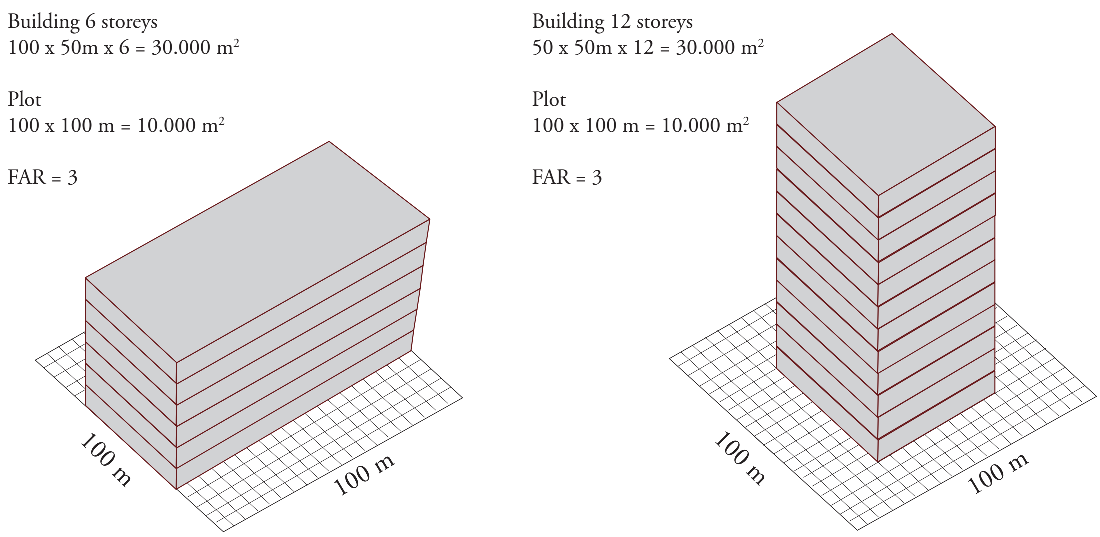


Figure 7: FAR comparison - understanding the effect of having the same FAR in different building geometries. [Source: the author]

The study applies a parametric approach [2] for buildings with a residential program. Following, there are some other considerations about the procedure and the decisions taken during the process:

Plot

The block in this study is a regular 100x100 m, which was chosen to simplify sub-sequent subdivisions and the adjustment of the three typologies to it. It was divided into a grid of 5x5m, allowing for different dimensions and distributions over the plot.

Simulation Context

The surroundings of the building and the urban pattern can play a significant role for the energy and especially daylight simulations. They also play an important role because they can be obstacles that will cause overshadow on the studied building. Therefore, each simulation model is located in an analytical field in the centre of a fictional context. This fictional context changes every time because it mirrors the behaviour of the studied building form, and those surroundings will cast shadow and reflect light onto the model.

In between the centre block and the context, a street width was simulated accordingly to the average of the streets in New York. The street width is 20 meters, which is equivalent to a street composed of two traffic lanes, one public transportation lane, bicycle lanes and pedestrian sidewalks. Figure 8 gives an idea of how the set up is seen from the top for each typology:

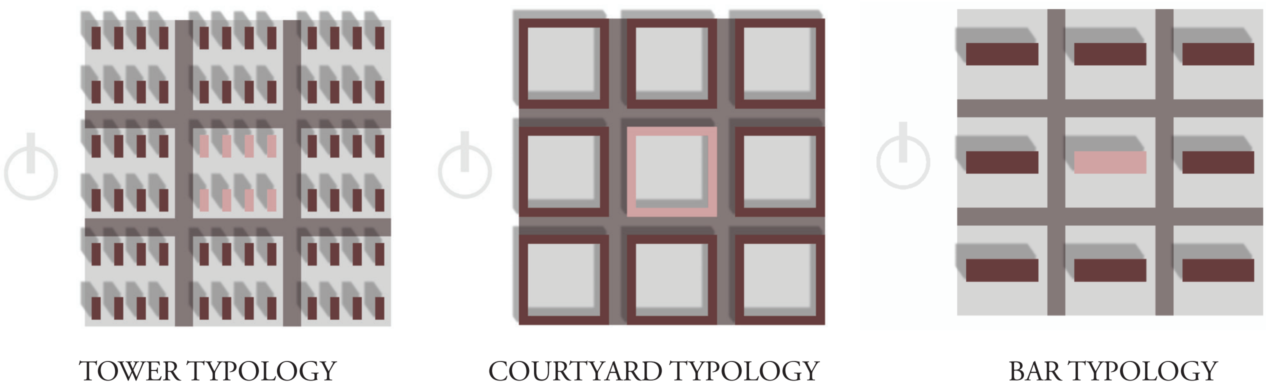


Figure 8: Plot area in the centre block, with the studied building in light red. Context blocks surrounding it and the buildings working as surrounding urban fabric in light red. [Source: the author]

Building typologies

A generic building is defined to represent each of the three studied typologies. There are constraints for each typology in order to adapt it to the plot, but the guidelines that rule the 3D model are essentially the same.

Towers

Vertical buildings that are placed according to X and Y axis of the plot, with the following arrangements (X,Y): 1x1, 1x2, 1x3, 1x4, 2x1, 2x2, 2x3, 2x4, 3x1, 3x2, 3x3, 3x4, 4x1, 4x2, and 4x3. Besides the organization, they also vary in size from 10, 15, 20 and 15 m. The smallest plan floor area is 10x15m (or 15x10m) and the largest is 25x25m. This arrangement is better understood when looking at Figure 9:

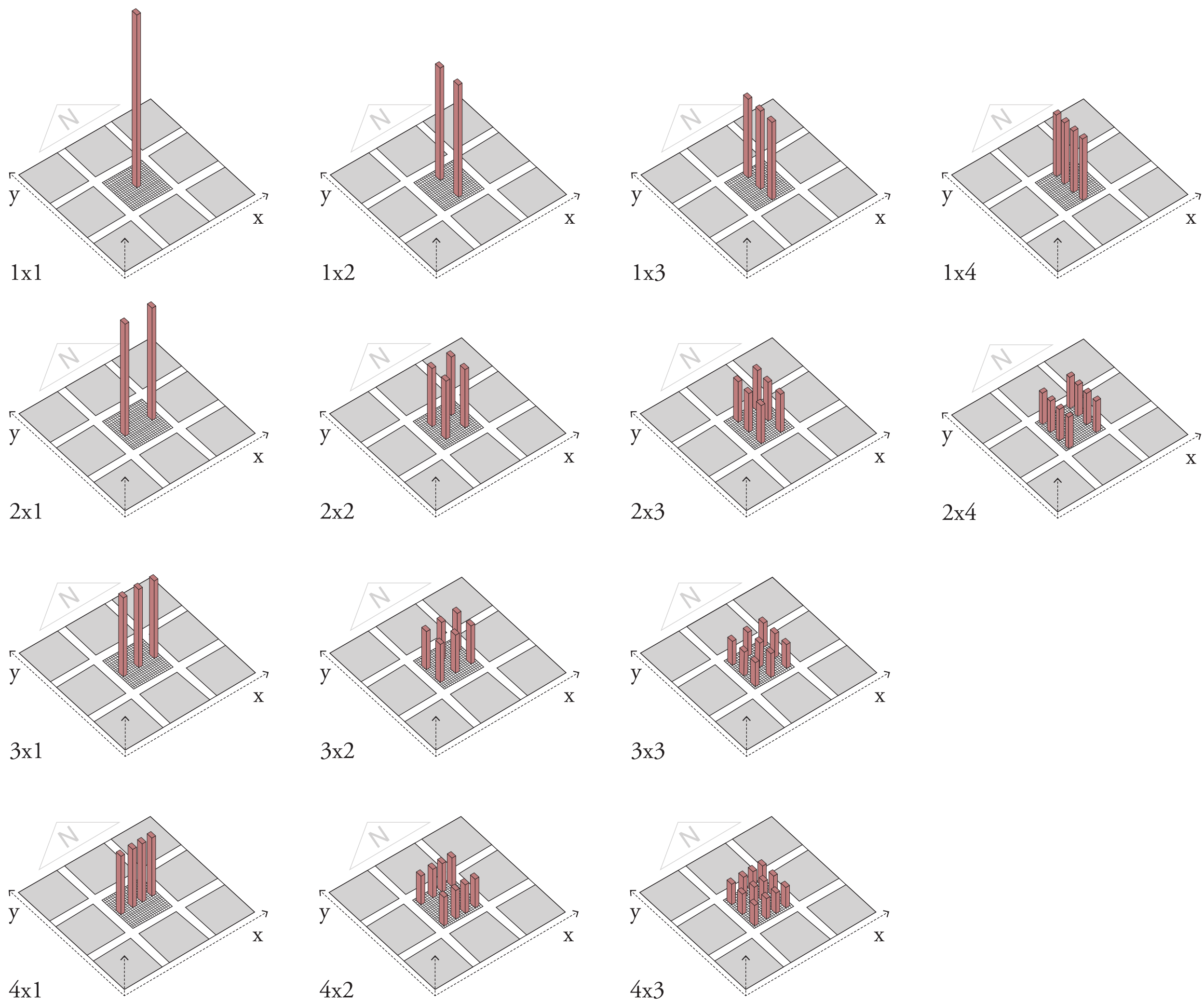


Figure 9: Example of tower arrangement for the case of 10x15 m or 15x10m dimension. [Source: the author]

The case shown in the previous Figure 9, 10x15 along with 15x10, is the smallest considered plan floor area, taking into consideration the indoor spatial constraints for a residential building. It was chosen to show here due to the fact that this dimension is able to fit in all the distribution possibilities. If we consider, for instance, the 25x25m case is only possible until the cases with 2 towers in one axis (1x1, 1x2, 2x1, 2x2), giving that another constraint applied to all the cases is that the minimum distance between one building and another is 17,5m.

Still from Figure 9, the reader can have a visual idea of the previously mentioned fixed FAR. This means that all the cases will have the same square footage. What will vary to comply with the FAR = 3 is the number of floors. That is, in the case with only one tower, the building will have twice the floors than in the case with 2 towers (and same dimensions), and so on.

The following table lists the possible dimension combinations, bearing in mind that not all of them are possible in all of the distribution combinations.

Table 1: Simulated tower cases within the 100x100 m plot possibilities

	1x1	1x2	1x3	1x4	2x1	2x2	2x3	2x4	3x1	3x2	3x3	3x4	4x1	4x2	4x3
10x15	●	●	●		●	●	●		●	●	●		●	●	●
10x20	●	●	●		●	●	●		●	●	●		●	●	●
10x25	●	●			●	●			●	●			●	●	
15x10	●	●	●	●	●	●	●	●	●	●	●	●			
15x15	●	●	●		●	●	●		●	●	●				
15x20	●	●	●		●	●	●		●	●	●				
15x25	●	●			●	●			●	●					
20x10	●	●	●	●	●	●	●	●	●	●	●	●			
20x15	●	●	●		●	●	●		●	●	●				
20x20	●	●	●		●	●	●		●	●	●				
20x25	●	●			●	●			●	●					
25x10	●	●	●	●	●	●	●	●							
25x15	●	●	●		●	●	●								
25x20	●	●	●		●	●	●								
25x25	●	●			●	●									

[Source: the author]

Courtyards

Building following the shape of the plot, surrounding an inner open space. The distribution options analysed are (i) no internal division with variable inner patio dimension according to the building depth (or, in other words, the external boundary of the building is fixed), (ii) no internal division with a variable dimension of the setback from the plot boundary (or, in other words, the inner patio dimension is fixed and the building will be further away from the street), (iii) 1 division of the inner patio oriented E/W, (iv) 1 division of the inner patio oriented N/S, (v) 2 divisions of the inner patio oriented E/W, and (vi) or 2 divisions of the inner patio oriented N/S.

For clarity, it should be noted that the nomenclature E/W or N/S corresponds to the longer axis of the vision. That is, when the courtyard building has one division E/W, it means that the wing is oriented with the longer dimension pointing east and west (the façades will face north and south). The opposite is also valid, of course. To have a visual understanding of this, see Figure 10.

Besides the distribution cases, the buildings also vary in depth. Following the adopted methodology, the depths vary from 10m, 15m, 20m until 25m.

While for the case of towers the combination between distribution and dimension created 128 cases, in the case of courtyards the number of case studies is quite limited for the 100x100 m plot. In Figure 10 it is possible to see the 16 cases developed combining the distribution and the dimensions previously explained.

Once again, the FAR = 3 is respected which results in buildings with different height and equal square footage. In this typology, as it happened with the previous one, the plot area also presents some constraints and not all the combinations are possible. Table 2 presents the combinations simulated, respecting the minimum distance between constructions of 17.5 m.

Table 2: Simulated courtyard cases within the 100x100 m plot possibilities

	NO DIV Variable courtyard	NO DIV Variable sidewalk	1 DIV E/W	1 DIV N/S	2 DIV E/W	2 DIV N/S
depth 10 m	●	●	●	●	●	●
depth 15 m	●	●	●	●		
depth 20 m	●	●	●	●		
depth 25m	●	●				

[Source: the author]

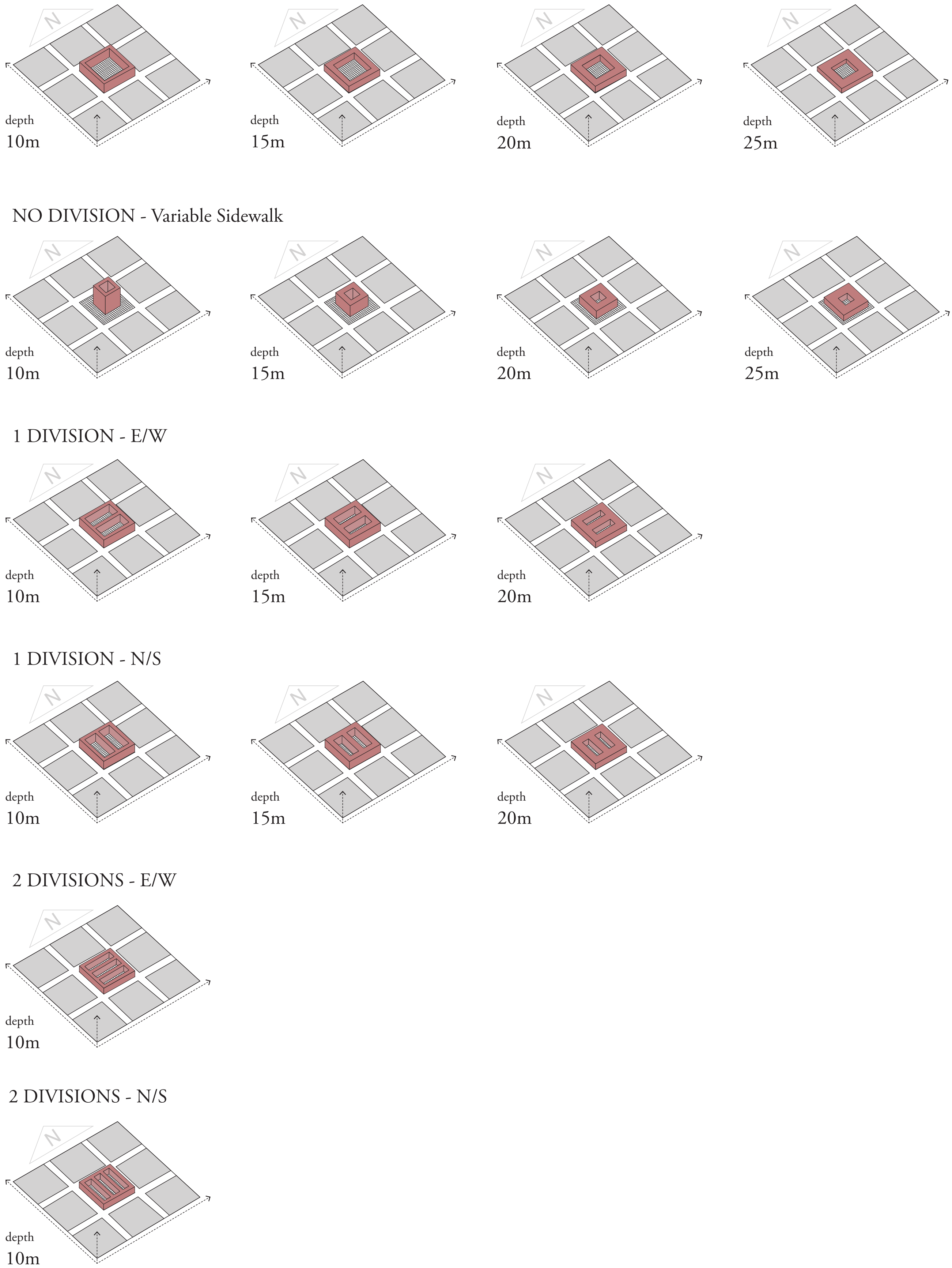


Figure 10: Study cases analysed representing courtyard buildings. [Source: the author]

Bars

Horizontal buildings that present two façades significantly wider than the other two are in this research named bars. Following the methodology, it was simulated all the possible scenarios to fit the 100x100m plot. For the case of bars, it was decided to organize the distribution with two parameters: the number of buildings and their orientation. The set up will have up to 4 buildings side by side, and as it was done for the courtyard cases, the orientation is named after the orientation where the longer axis is pointing. Therefore, cases E/W will have the longer façades facing north and south and cases N/S will have the longer façade facing east and west.

After the distribution logic explained, it's the time for the dimensions: the buildings vary in width and length in a different magnitude, in order to form the desired geometry. In width, the dimensions follow the pattern of the 5 meters grid, which means it will go from 10 to 15, to 20 and then to 25m as maximum. In terms of length, the bars start with 40 m, in a step of 10m, which means going to 50m, then 60, 70, 80, 90 and finally 100m. This latter case, with 100m, it's the case where the longer façades are as wide as the plot side dimension.

The following figures show all the combinations for the cases of 10x40m, the minimum length, and for 10x100m, the maximum length, where the distribution can better be understood.

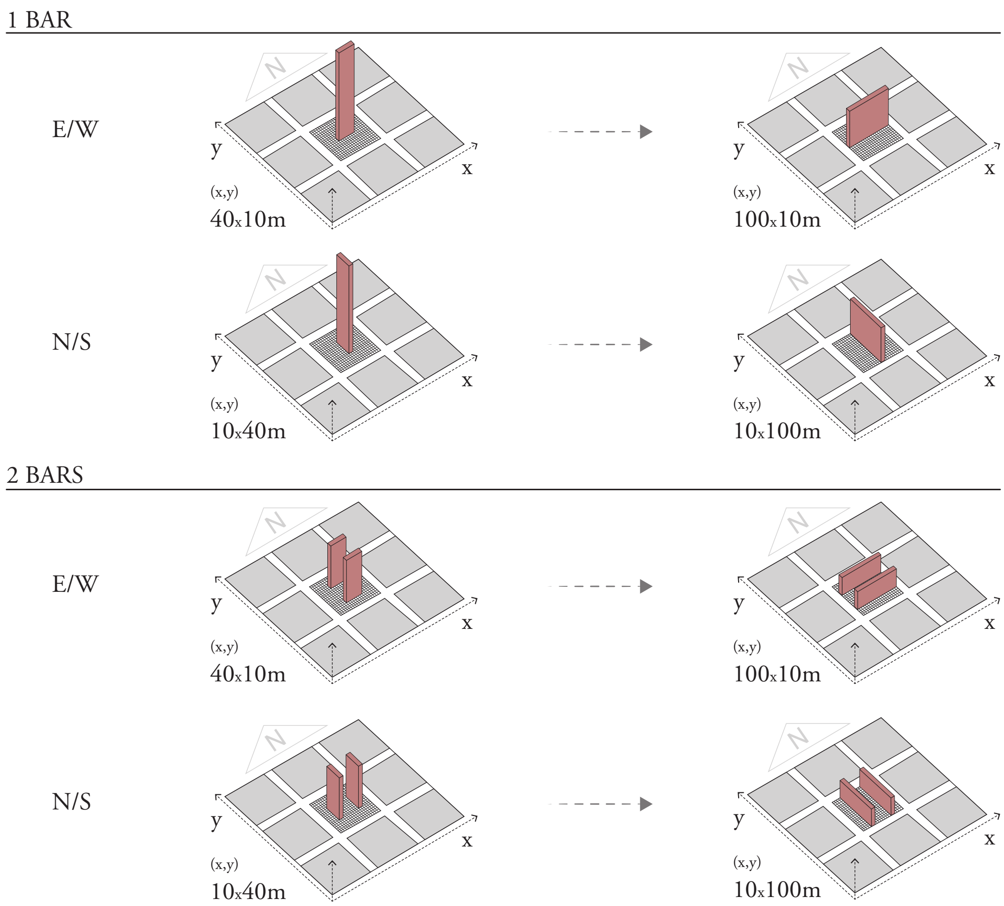


Figure 11: Representation of all the distribution combinations for bar typology using 10x40 m (and 40x10m) as example - Part 01. [Source: the author]

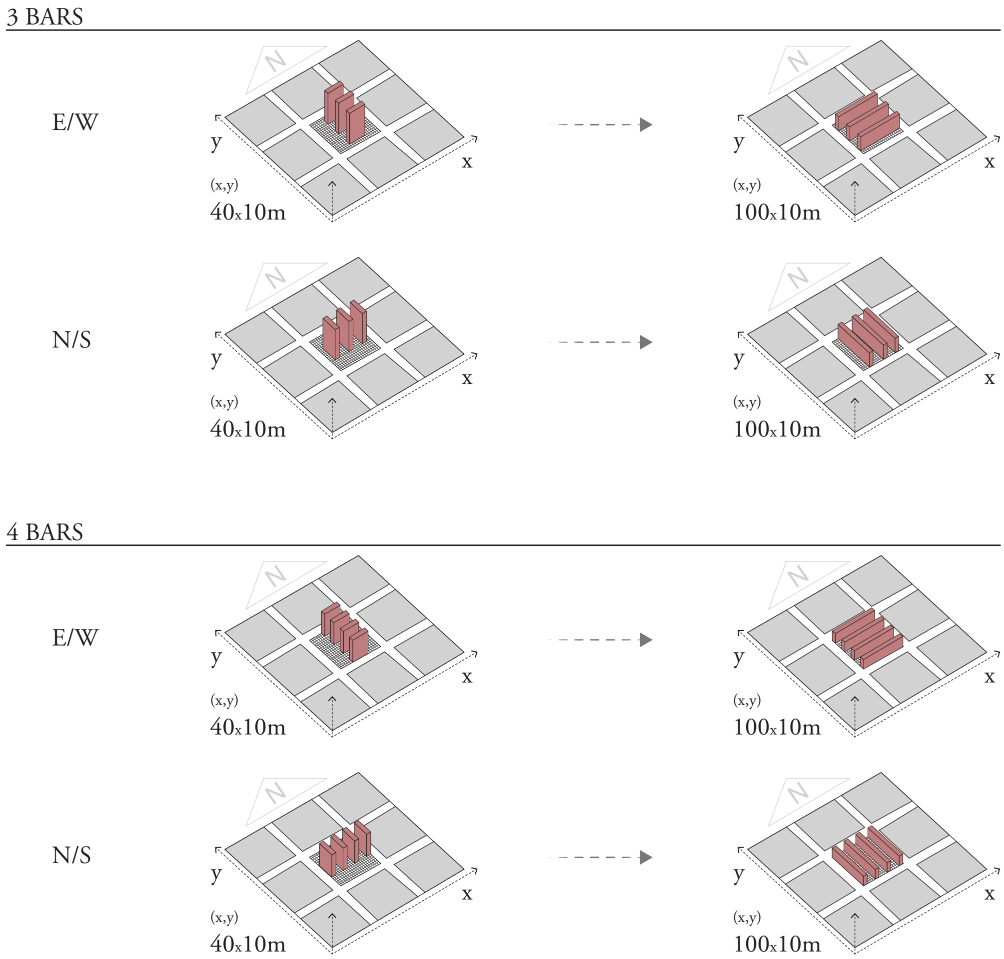


Figure 12: Representation of all the distribution combinations for bar typology using 10x40 m (and 40x10m) as example - Part 02. [Source: the author]

The cases shown above were chosen as representative because in the 10m width buildings it is possible to have 1, 2, 3 and 4 buildings along the 100m, respecting the previously mentioned minimum distance between buildings. However, as it happened for the cases of tower and courtyard, not all the possibilities were able to fit inside the studied plot. Following after the cases with 10m width, the 15 m and 20 m ones can only happen until the cases with 3 bars. The 25m width buildings only happen until the cases with 2 bars.

All the simulated combinations are shown in the following table:

Table 3: Simulated courtyard cases within the 100x100 m plot possibilities

(width, length)	1 BAR E/W	2 BARS E/W	3 BARS E/W	4 BARS E/W	1 BAR N/S	2 BARS N/S	3 BARS N/S	4 BARS N/S
10x40	•	•	•	•	•	•	•	•
10x50	•	•	•	•	•	•	•	•
10x60	•	•	•	•	•	•	•	•
10x60	•	•	•	•	•	•	•	•
10x70	•	•	•	•	•	•	•	•
10x80	•	•	•	•	•	•	•	•
10x90	•	•	•	•	•	•	•	•
10x100	•	•	•	•	•	•	•	•
15x40	•	•	•		•	•	•	
15x50	•	•	•		•	•	•	
15x60	•	•	•		•	•	•	
15x70	•	•	•		•	•	•	
15x80	•	•	•		•	•	•	
15x90	•	•	•		•	•	•	
15x100	•	•	•		•	•	•	
20x40	•	•	•		•	•	•	
20x50	•	•	•		•	•	•	
20x60	•	•	•		•	•	•	
20x70	•	•	•		•	•	•	
20x80	•	•	•		•	•	•	
20x90	•	•	•		•	•	•	
20x100	•	•	•		•	•	•	
25x40	•	•			•	•		
25x50	•	•			•	•		
25x60	•	•			•	•		
25x70	•	•			•	•		
25x80	•	•			•	•		
25x90	•	•			•	•		
25x100	•	•			•	•		

[Source: the author]

<u>Building properties</u>

The model buildings are insulated and have the following thermal characteristics:

Table 4: Fixed simulation parameters for all the cases

External walls	Roof	Floors	Glazing unit
U-value (SI) 0.38 W/m²K	U-value (SI) 0.28 W/m²K	U-value (SI) 0.15 W/m²K	U-value (SI) 1.9 W/m²K SHGC 0.4
R-value (IP) 14.78 h.ft²F°/Btu	R-value (IP) 20 h.ft²F°/Btu	R-value (IP) 35 h.ft²F°/Btu	R-value (IP) 2.85 h.ft²F°/Btu

[Source: the author]

Those values are part of the "construction library" in the simulation software, and they are selected according to the Energy Modeling Standard, in this case ASHRAE 90.1-2004. In the standard, the recommendation of values is according to the climate zone (4A), surface type and building program (in this case, residential). The values reported in Table 4 show the U-Value in the International System of Units because that's the system applied in all the calculation and results. However, it was important to show here also the R-Values in the Imperial System of Units because those are the values found in ASHRAE publications.

Furthermore, two other key aspects are assumed fixed for the sake of the comparison: all the case studies and simulations were done considering a <u>residential program</u> and a <u>fixed glazing ratio of 0.3</u>. The glazing ratio establishes the proportion of glazing to opaque surface in a wall. Because we are dealing with the residential program, the ratio of 0.3 is what is typically found in residential buildings [4] - if this number is high, the result is almost a totally transparent envelope, as shown in Figure 13.

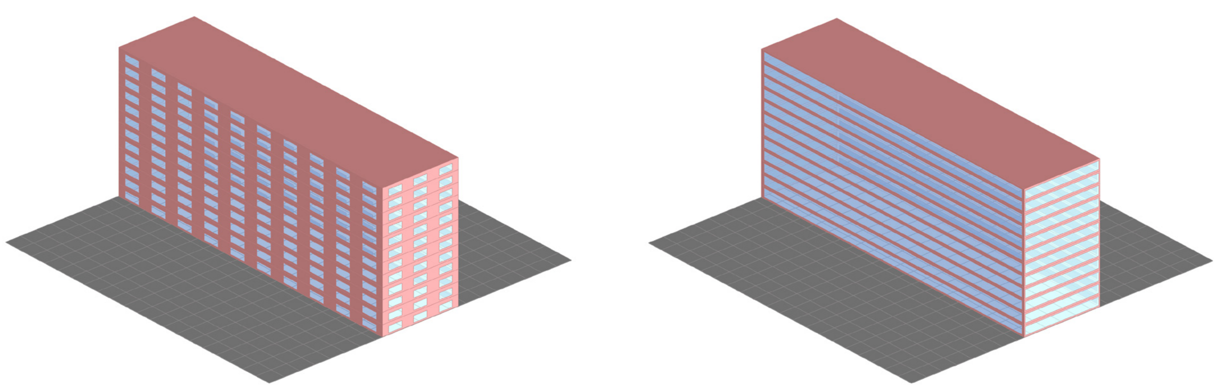


Figure 13: Comparison between a glazing ratio of 0.3 (figure on the left) and 0.7 (figure on the right) [Source: the author]

Considering all of those parameters, the problem was how to simulate all of the conditions in a practical yet accurate way. The goal is to find the best performing case study, with low-energy consumption, high solar energy production and good daylight levels [2]. Therefore, the adopted procedure and the software required are illustrated in Figure 14:

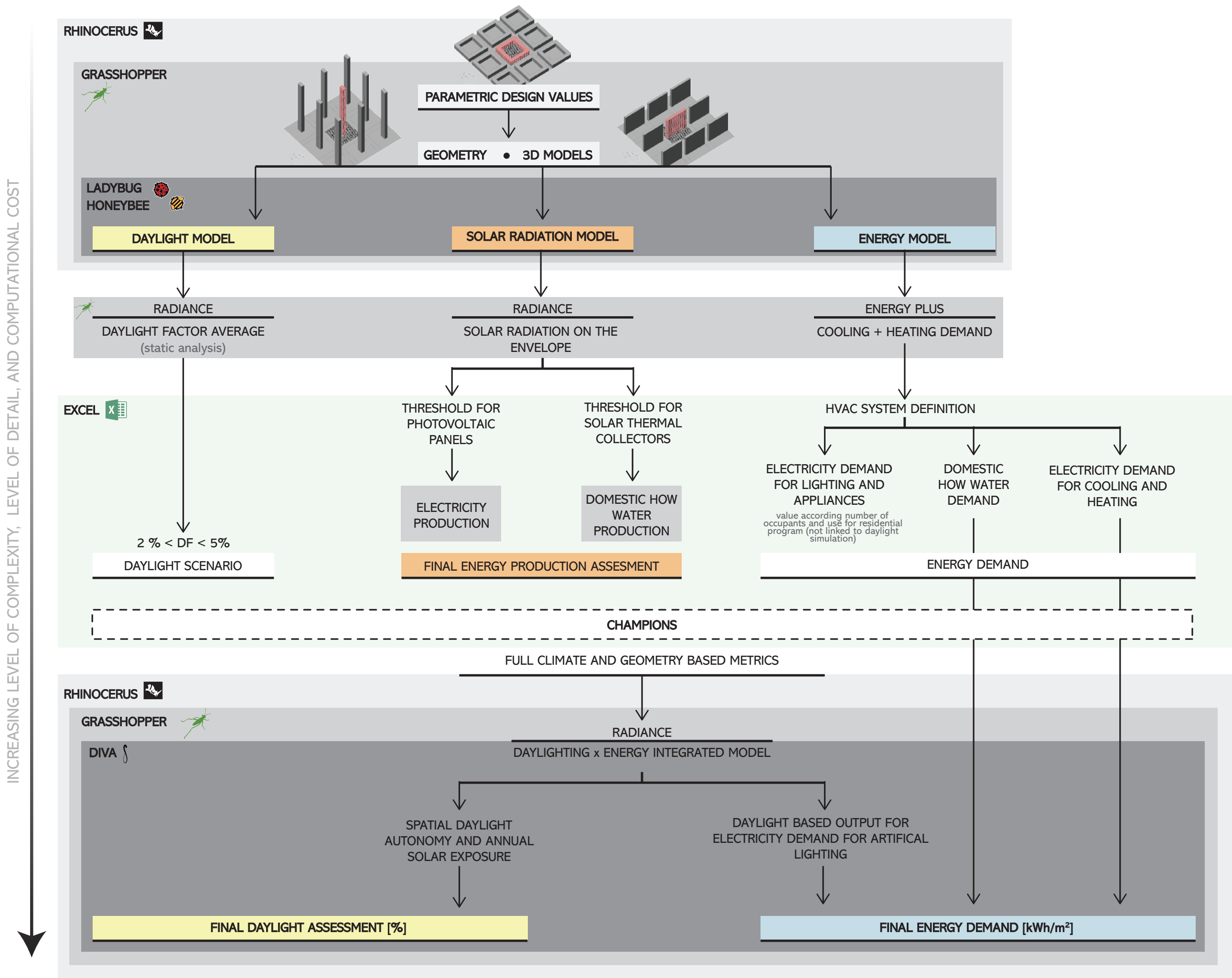


Figure 14: Daylighting x Radiation x Energy process and tools [Source: the author]

There are four main steps in this approach. The first step is to identify design variables to be examined and to build a parametric design model. The second step is the development of daylight, solar radiation and energy model. The third step is to draw some conclusions and identify the best performing cases, in order to further detail the simulation on the so-called "champions". This is a strategy adopted to overcome some limitations with computational power and time-consuming simulations.

The fourth step is the integrated daylighting and energy simulation. The integrated lighting and energy simulation means that the lighting energy savings from daylighting are fully considered in the energy simulation. To achieve energy savings from daylighting, it is necessary to install a lighting control system in the building. Lighting controls can adjust the level of electric light to complement the illumination provided by daylight or turn off the light when daylight illuminance is adequate. In building performance simulation, the process is similar. [7] A daylighting simulation is required first to calculate the illuminance at the lighting sensor positions for every hour in a year, and electrical light would be turned off or dimmed according to the daylight illuminance. Then a year-long lighting schedule is generated. This schedule will be valid also for the energy output of demand for artificial lighting. This procedure will be further detailed in Chapter 2.

With that, the study will be able to obtain more accurate values for the most performing cases and understand if the values obtained with the full climate data are in accordance with the values obtained in step two.

Metrics

According to what was introduced previously, it should be highlighted that one key aspect of this research is the three main building performance indicators: energy demand, energy production and daylighting conditions, which are ranked equally. To evaluate those aspects and make a fair comparison among case studies, it is important to understand what are the metrics available for each indicator and select the appropriate ones for each stage of the study. They are described here.

Energy demand

Energy demand for buildings has increased significantly in recent years, mainly due to the rapid development of urbanization, economic development, people's incomes and living standards, which cause an increased demand for building services and comfort levels. Moreover, recently people have spent more time inside buildings, which assures that the upward trend in energy demand will continue in the future. That's basically the reason why designers and engineers have been making so much effort to improve energy efficiency in buildings, as it is a prime objective for energy policy at regional, national and international levels.

This study starts with the energy demand being evaluated in terms of annual heating and cooling thermal requirements to achieve comfort temperature for all the year. This is applied in Chapter 01, and the unit is kWh/m^2. Later in the research, this demand is converted from thermal to electricity demand when the HVAC assumptions are introduced, which makes it possible to combine the HVAC consumption with the electricity required for artificial lighting and appliances. This is the energy demand presented in Chapter 02 when discussing the "Champions", or the best performing case studies. Moreover, for this stage, the unit remains kWh/m^2.

Solar potential (Energy production)

After discussing energy demand, it's time to take a look at energy production. To assess that, the solar radiation falling on the envelope is evaluated and, with that information, it is assumed that the façade and roof surfaces can receive photovoltaic cells to generate electricity and thermal collectors to provide domestic hot water, with the simplification that they will be parallel to the surface (vertical for the envelope and horizontal for the roof). This is named here as **solar potential**, which is explained following.

As we know, one of the main renewable energy resources applied in buildings is receiving energy from the sun [10]. Solar radiation falling on the envelope plays several crucial roles in building performance. A designer can take advantage of solar radiation using passive strategies such as heating the building using solar thermal energy. Furthermore, the visible portion of the energy received from the sun can impact the daylight performance in a building and offset lighting loads, which also alter cooling and heating loads.

Besides passive strategies, solar renewable energy can be utilized in building envelope using active technologies. Building-integrated photovoltaic is an example that uses solar energy to generate electricity and can be applied in the building envelope. The other application of solar energy in buildings is the solar hot water systems. Solar hot water systems can be integrated into the building design to collect the heat from the sun and deliver it for hot water usage. There is also the possibility of building-integrated solar thermal shading systems, that uses small-sized solar thermal panels as an application of utilizing solar energy to generate hot water while reducing solar heat gain and controlling glare.

Having all those possibilities, for this metric of solar potential the solar radiation falling on the opaque envelope is simulated and it is assumed to receive active technologies. Hence, the buildings are assumed to have all the facade, in all orientations, and the roof available to receive either photovoltaic panels or solar thermal collects. A threshold is defined to select the areas that will receive PV panels or ST collectors, adapting from the method used in [17].

> *Threshold on solar radiation falling on the envelope:*
>
> *- Surfaces that receive 200 to 400 kWh/m² over the year receive solar thermal collectors;*
>
> *- Surfaces that receive more than 400 kWh/m² over the year receive photovoltaic panel;*

It should also be noted that for Chapter 1, the first stage of the research, the numbers showed in solar potential is the total radiation falling on the envelope. This radiation will only be divided and have a system assigned afterwards when a selection occurs to understand the real compromise between the energy production and the energy demand. In the later stage, the efficiencies of 0.7 and 0.15 are applied to solar thermal collectors and photovoltaic panels, respectively, to find the effective domestic hot water production from the first and the electricity production from the latter.

On-site energy production is considered an important component in many environmentally conscious projects [11]]. Therefore the attempt here is to identify the potential of taking advantage of solar radiation at an early stage. Of course, other measures can be taken to further improve the capture of solar radiation, such as tilting the PV panels that for this research are considered parallel to the building facade. Some assumptions had to be made for the sake of simplicity and comparison between one case and another, hoping that this metric will give an idea of how well the case will perform with possibilities to perform even better. Building-integrated active technologies such as the panels on the façade are important to be evaluated, as roof surface represents a smaller portion of the total envelope area in taller buildings, [5] façades can offer new opportunities for integration of solar panels.

Daylighting

The drive towards sustainable, low-energy buildings has increased the need for simple, yet accurate methods to evaluate whether a "daylit" building meets minimum standards for energy and human comfort performance. [26] Daylight levels impact greatly on those two fundamental aspects, as it describes the act of lighting the interior of a building with daylight [25]. With an adequate design, it is possible to enhance visual comfort conditions for building occupants and to reduce the overall energy use of the building. To do that, careful considerations must be taken when choosing building massing, facade orientation and layout.

There are several metrics used to account for the quality of daylight indoors. They can be divided into static and dynamic metrics. The static metrics, where the most used one is Daylight Factor, is calculated using a single-point-in-time approach, not accounting for all the influences on daylight illumination levels nor the variation over time. In the effort to improve these limitations, the dynamic daylight performance metrics were afterwards introduced. They are based on time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events [24].

Both static and dynamic metrics will be utilized along with this research, therefore the most important ones are here explained. However, it should be noted that the adopted metrics for each stage of the research are then highlighted in each chapter.

STATIC METRICS

Daylight Factor

The daylight factor is a common parameter to characterize the daylight situation at a point in a building. It is defined as a ratio [25]:

$$DF = \frac{\text{Indoor illuminance at a point in a building}}{\text{Outdoor horizontal illuminance under a CIE overcast sky}}$$

This metric enjoys considerable popularity since it is an intuitive quantity that can be measured and/or calculated either based on calculation tables or more refined simulation methods.

The concept of using an illuminance ratio to quantify the amount of daylight in buildings has been around at least since 1909 when Waldram published a measurement technique [24] based on the approach detailed in [29]. The original motive for using ratios rather than absolute values was to avoid the difficulty of having to deal with “frequent and often severe fluctuations in the intensity of daylight” [29]. Initially, sky factors were used that quantify the contribution of direct light from the sky-dome to a point in a building. Over time the sky factor evolved into the daylight factor, as light reflected from external obstructions, light losses through glazings, and internal reflectance were added as well. In 1949 the reference sky changed from a uniform to what is now an International Commission on Illumination (CIE) overcast sky [30]. The luminance of the CIE standard overcast sky is rotationally symmetrical about the vertical axis, i.e. about the zenith. And, of course, there is no sun. Thus for a given building design, the predicted DF is insensitive to either the building orientation (due to the symmetry of the sky) or the intended locale (since it is simply a ratio) [26].

Due to the variation of the illumination from the sky, it is not useful to describe the daylighting in a building in units of illuminance. Rather, when using DF, the daylighting performance of a building is described in terms of percentage. The idea is to assume an outside illuminance of around 10.000 lux under an overcast sky, and then the minimum requirement for the room is an average of 500 lux, [23] which makes the 2% that composes the minimum threshold for the acceptable DF value. The higher the DF, the more natural light is available in the room, however, a maximum acceptable value is defined as 5%, composing the comfort range of good DF levels from 2% to 5%.

The daylight factor is, therefore, able to measure the subjective daylight quality in a room and it is often used due to computational limits to perform a dynamic climate-based simulation, which can be quite time-consuming. Daylight factors vary for different building designs and accordingly have the capacity to influence design choices. Some parameters that affect DF are the building geometry, surrounding landscape and buildings, as well as surface properties (colour, diffuseness, specularity, transmittance, reflectance) [24]. Some say that the reference overcast sky is the worst-case sky condition and therefore any other sky will lead to more daylight in the space.

Some limitations of this metric are that it does not considers season, time of day, direct solar ingress, variable sky conditions, building orientation, or building location. Therefore the recommendations based on DF are the same for all the facade orientations and building locations. It must be noted that when evaluating glare or developing glare prevention strategies, DF cannot be of guidance and another metric should be applied in parallel.

Nevertheless, the daylight factor is widely used and provides a feeling of how “bright“ or “dark“ the interior of a given building is. Even though it does not even include the contribution of the sunlight, only including the skylight [26], the daylight factor is a measure of relative illumination within a space compared to that of a standardized overcast sky condition which results in DF being a crude proxy for actual daylight illumination. Since it is based on a single sky condition, its credibility to judge the overall daylight situation in a given building is intrinsically limited.

DYNAMIC METRICS

This section describes dynamic daylight performance metrics as an alternative to the daylight factor-based approaches described in the previous section. Dynamic performance metrics are said to *"have the ability to capture the 'architectural' dimension of daylighting, even though it is not suggested that these metrics can predict holistic 'good' daylighting"* [24].

The holistic scenario for comfortable daylighting should be a combination of the good level of daylighting metrics and the building form that satisfies occupant needs by keeping them comfortable, and, at the same time, overall electric lighting loads should be low and solar gains controlled. Those are results from different interventions on the levels of building architecture, engineering systems, facade engineering, interior design and furniture, among others.

Furthermore, below there are some of the metrics that contribute to this goal explained, in order to make an informed decision on which ones should be applied to this study.

Daylight Autonomy (DA)

The definition of daylight autonomy is "the percentage of the year when a minimum illuminance threshold is met by daylight alone". According to the normative that originated it, the term is a function of daylight factor and minimum required illuminance level. But, in contrast to DF, daylight autonomy considers all the sky conditions throughout the year.

The minimum illuminance level corresponds to the minimum physical lighting requirement which has to be maintained at all times so that a certain task can be carried out safely and without tiring the occupant [25]. Therefore, it is measured at the level of the work plane [24].

The main advantage of the daylight autonomy over the daylight factor is that it takes facade orientation and user occupancy profiles into account and considers all possible sky conditions throughout the year. It is therefore a holistic approach [25] to describe the annual daylight availability at a workplace. On the other hand, it can only be calculated using computer simulations.

Spatial Daylight Autonomy (sDA)

In 2001, Reinhart and Walkenhorst redefined *daylight autonomy* at a sensor as "the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone" [24]. In later publications, the concept of daylight autonomy was further refined by combining it with a manual blind control model that predicts the status of movable shading devices at all time steps in the year. This fine-tuning of the previous concept of daylight autonomy generated the widely used Spatial Daylight Autonomy.

It examines "whether a space receives enough daylight during standard operating hours (8 a.m. to 6 p.m.) on an annual basis using hourly illuminance grids on the horizontal work plane." [25]

In lieu of collecting a year's worth of data in the field, sDA is calculated virtually through computational simulation with precise parameters. It references a local climate file — such as an EnergyPlus data file — to run hourly illuminance maps in the lighting software packages, and incorporates an algorithm to approximate manual operation of window blinds.

Floor areas, or grid points, in the building model that achieve 300 lux for at least half of the analysis hours count as meeting the daylighting threshold. As a result, sDA values can range from zero to 100 percent of the floor area in question.

> **sDa > 75% ⟶** preferred by occupants; that is, occupants would be able to work comfortably there without the use of any electric lights, and find the daylight levels to be sufficient. *(2 points in LEED evaluation)*
>
> **55% < sDA < 74% ⟶** "nominally accepted" space by the occupants. *(1 point in LEED evaluation)*
>
> **sDa < 54% ⟶** not acceptable

Hence, the goal is to achieve sDA values of 75 percent or higher in regularly occupied spaces, such as an open-plan office or a residential living room, and at least 55 percent in areas where some daylight is important.

Useful Daylight Illuminance (UDI)

UDI follows the same trend as it is a dynamic daylight performance measure that is also based on work plane illuminances. It aims to determine how "useful" are the daylight levels for the occupant and when.

The difference from DA is that there is a suggested range of acceptability, which was founded on reported occupant preferences in daylit spaces [24] and are presented here:

> *UDI < 100 lux ⟶ underlit*
>
> *100 lux < UDI < 2,000 lux ⟶ comfort range*
>
> *UDI > 2,000 lux ⟶ overlit*

Hence, these metrics determine that visual comfort in the workplace is not achieved when it's too dark (<100lux) or when it's too bright (>2,000lux), but in between those values. The upper threshold is there to detect possible visual and/or thermal discomfort, with probable overheating due to solar gains or glare effect due to the sunlight.

Annual Sunlight Exposure (ASE)

This metric is meant to complement sDA evaluation, identifying if there is excessive sunlight in a space, which will present a high potential for glare and solar heat gains. While ASE is a crude proxy for glare phenomena, it measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures, so it is technically not a glare metric.

It is defined as "the percentage of floor area that receives at least 1,000 lux for at least 250 annual occupied hours" [13] Hence, the values range from 0 to 100% (of floor area), with the latter suggesting that the entire floor area of the space in question exceeds the simulated value of 1,000 lux for at least 250 hours per year. Thus, to reduce the potential for glare and thermal stress, designers should aim for low or zero ASE values [37].

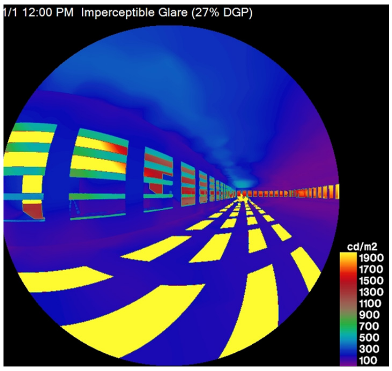
In the publication LM-83, by the Illuminating Engineering Society (IES) named "Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)" it is stated that spaces with ASE values higher than 10% will likely result in visual discomfort.

Daylight Glare Probability (DGP)

Daylight Glare Probability (DGP) is a metric for evaluating glare which improves the correlation with user assessments. It was developed by Jan Wienold at the Fraunhofer Institute for Solar Energy Systems in Freilurg, Germany. This metric represents the "percentage of people disturbed due to the level of the vertical eye illuminance". It usually is shown with fish-eye images that recognize the glare areas and the software already classifies it according to the following thresholds:

> DGP < 0.35 ⟶ *imperceptible*
>
> *0.34 < DGP < 0.4* ⟶ *perceptible*
>
> *0.39 < DGP 0.45* ⟶ *disturbing*
>
> *DGP > 0.455* ⟶ *intolerable*

Examples of one way that DGP is presented can be seen in Figure 15.



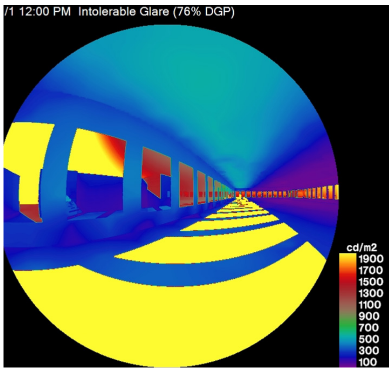


Figure 15: Examples of fish-eye images to evaluate glare. On the top, it is visible that the image on the left has intolerable glare (76% DGP) and the image on the right presents Imperceptible Glare (27% DGP). It is visible also that this effect happened, at this case, in the same room only by adding shading devices to the envelope. [Source: the author]

CHAPTER 01.

Massing and Performance

1.1. METHODOLOGY

At this first chapter of the research, it is explained step by step the procedures and decisions taken to simulate the energy performance and daylight conditions of the three studied typologies: towers, courtyards and bars. It is important to understand also some of the metrics explained before on page 42 are now selected, and with that, it is possible to understand the potential and also limitations of the results.

To have an overall view, the parametric modelling of the geometry depends on the Grasshopper software. Building performance simulation is performed via Ladybug and Honeybee plug-ins [9] which relies on Radiance and Daysim in daylighting simulation while uses EnergyPlus in energy simulation. After going over the procedure for simulating all the case studies and evaluating them in terms of the three main performance indicators, the outputs are compared firstly for each typology separately, to understand what are the parameters that really impact the performance individually and afterwards a comparison between the three typologies are performed to understand if choosing carefully the massing can in fact impact on the overall behaviour of the building.

1.1.1.MODELLING

The process begins in 3D modelling software Rhinoceros [7] and its parametric modelling plug-in Grasshopper. The building geometry is built with all the predetermined variables, whose values can be adjusted through sliders.

First of all the plot area of 100 x 100 m and a grid of 5 meters is built upon it. The studied plot area is in the centre of the study area, and the same block is copied towards each side to build up the context blocks. Those blocks will receive also a building equal to the case study, in order to account for overshadowing and all the effects of being inserted in the urban context. In Figure 16 the process is shown with the components and visualization from the software.

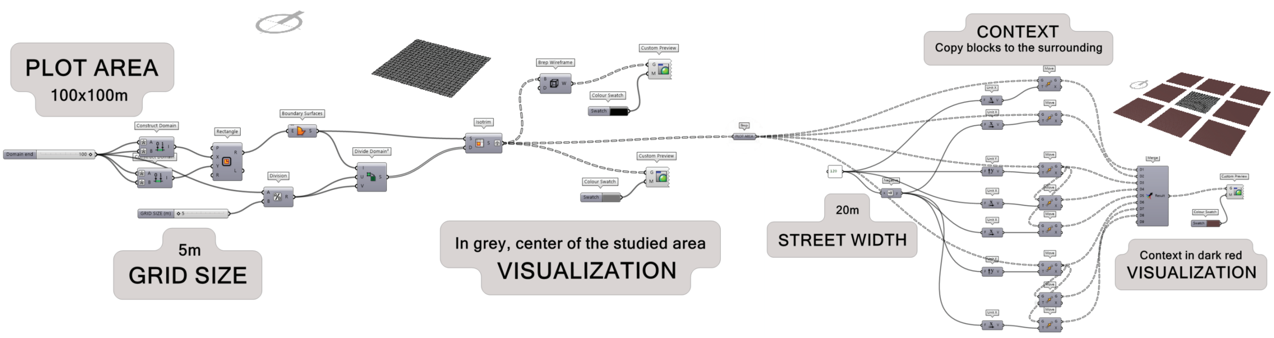


Figure 16: Script in Grasshopper for Rhino, showing the geometry modelling for the plot area and context. [Source: the author]

After that, the three typologies were modelled following the same logic. They were modelled inside Grasshopper to keep the file independent of the Rhino file, and then every single parameter can be adjusted in case the shape does not comply with the desired output. In Figure 17 (towers), Figure 18 (courtyards) and Figure 19 (bars), the procedure is explained with the image from the script and components and with the outputs of the main steps.

For the case of towers, the iterations are done using dimension for X axis and dimension for Y axis (both going from 10 until 25m with 5 meter-step). Those two sliders are input into the Colibri component to perform the iteration between all the possible combinations and record the data. Colibri is an open-source project that it's part of TT Toolbox (by CORE Studio, 2017), which allows it to iterate the geometry parameters, and then aggregate the outputs from the energy and daylight simulations. This data is utilized to create visual plots and further analysis to understand the relationships between building performance and design variables.

Going on with the script, from the left to right, there are the dimension sliders, then the Colibri iterator, and then the ground plan floor originated from the combination. From there the FAR = 3 is set, applying some calculation components to define how many floors should the building have, with the plan floor area in question, to reach the amount of 30,000 m², which divided by the 100x100 m plot area will result in the above-mentioned floor to area ratio equal to 3. Having the result for the number of floor areas, it is multiplied by 3.5 meters, representing the height of one floor, which will result in the total height of the building. This number is utilized to extrude the ground plan floor towards the Z-axis (vertical).

In the figure corresponding to the towers, the geometry shown is the most basic one, the case with only one tower. This was chosen to display here because the goal is to understand the logic behind the modelling, even though it's quite simple. In the other cases, with a higher number of towers, it is just a matter of replicating the building and distributing it over the plot.

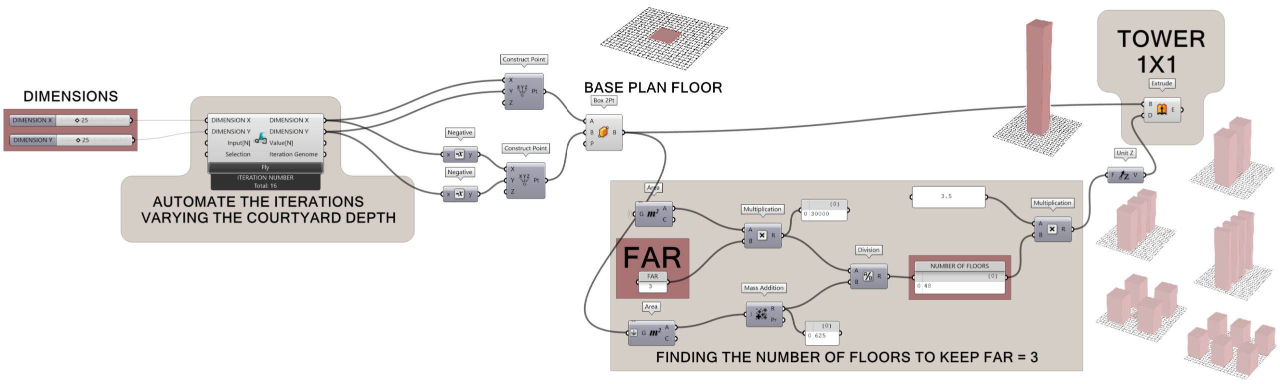


Figure 17: Script in Grasshopper for Rhino, showing the geometry modelling for the case of towers. [Source: the author]

In the case of courtyards, shown in Figure 18 the process is pretty much the same. However in this case the slides are not combining two dimensions as in the previous but only one that represents the building depth, since the perimeter is equal to all the cases. The depth varies from 10, 15, 20 and 25m. It is then used to form one wing of the building geometry, which is replicated and placed on the edges of the plot, leaving the inner part of the area free of construction. The same procedure with FAR = 3 is applied to discover how many floors each option requires to meet 30,0000 m^2, with the subsequent extrusion of the plan floor by that height. The case shown in the figure corresponding to courtyards is the basic one, where the building varies its depth at the inner edge, or, in other words, the variation reflects on increasing or decreasing the area of the inner patio. For the other cases, such as when it is divided into one or two more wings in the middle, it's just a matter of adapting this methodology.

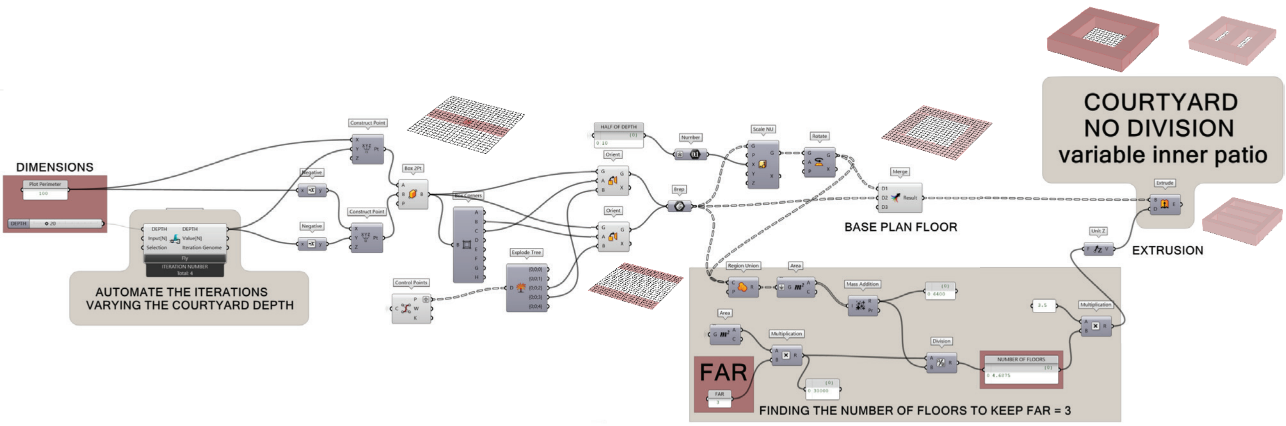


Figure 18: Script in Grasshopper for Rhino, showing the geometry modelling for the case of courtyards. [Source: the author]

Lastly, the script for the geometry of bars is shown in Figure 19, following the previously presented logic. The dimension parameters here are the bar length, that increases in 10m-steps from 40 to 100m, and the bar depth, that increases in 5-m step from 10 to 25m. The bar cases can vary in the number of buildings and orientation. For the first, adapting the procedure is quite simple because it's just replicating and distributing over the plot. For the latter, it is even simpler, because changing the orientation requires only a 90° rotation of the geometry.

In this last script representation, it is possible to see that useful information can be dynamically extracted. In this case, the envelope area (facade + roof) and the percentage of the occupied plot area were extracted and recorded with the excel files generated after the iterations. This is quite useful as it could be done manually but it is automatically done this way.

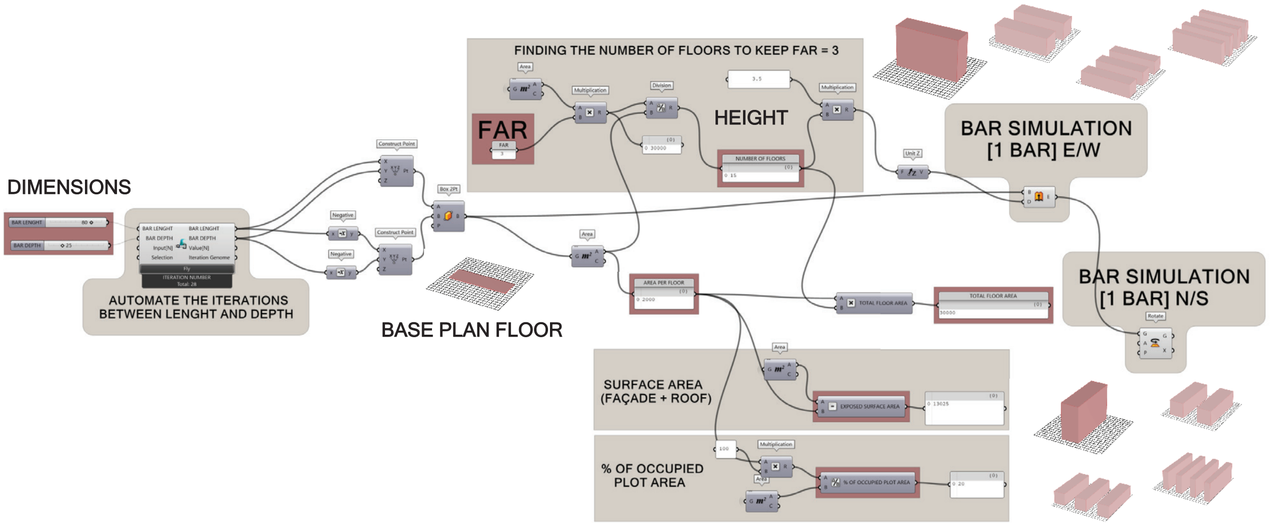


Figure 19: Script in Grasshopper for Rhino, showing the geometry modelling for the case of bars. [Source: the author]

After the geometries are modelled, the final case is plugged into the desired performance analysis, which is further detailed on the following topics.

1.1.2. BUILDING PERFORMANCE SIMULATION

Grasshopper plug-ins Ladybug and Honeybee [15] are dedicated to performing environmental analysis in a user-friendly approach. They provide here the functions of simulating solar radiation analysis, daylight and energy modelling. The free and open nature of the plug-ins democratizes environmental analysis tools, encouraging the advancement of environmentally-conscious designs.

The geometry requires some preparation in order to be connected to the components of any environmental simulation, either solar radiation, energy or daylight analysis. At this point of the script, firstly it is important that the surfaces are adjacent to other surfaces in the proper way to make sure the conductive heat flow is calculated correctly. Secondly, the floor height is defined and the building mass is automatically divided by the set number, which in this case is 3.5 m. Thirdly, the use of the building is chosen, in this case, residential, where the software will take several parameters that are defined by this kind of program, such as the people's occupancy that is discussed further in detail at the next topic. To finish the preparation of the zones, it is required to set the glazing ratio to create the transparent parts of the envelope. In this case, as already explained, the ratio is 0.3 for all the orientations. This process is demonstrated in the following Figure:

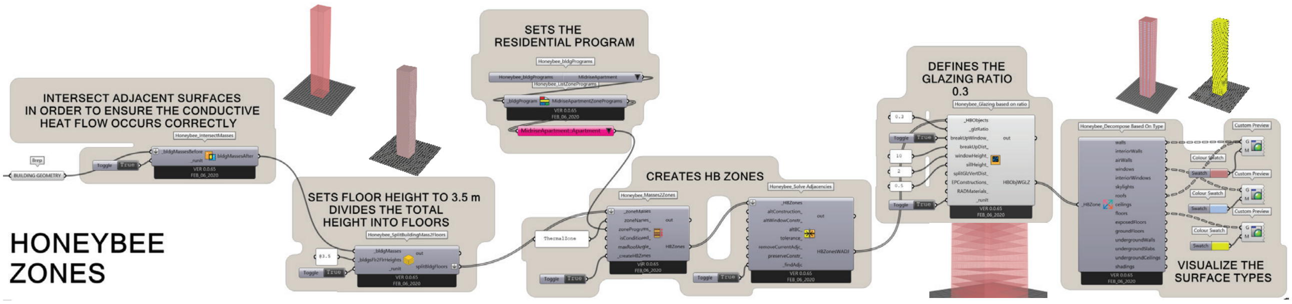


Figure 20: Script in Grasshopper for Rhino, using components from the Ladybug and Honeybee plug-in showing the preparation of the geometry for the environmental analysis. [Source: the author]

Besides the way to simulate, it is important to understand what kind of information is being extracted and if that's really the indicator that best suits the analysis requirements. Therefore, some studies were conducted to understand which building performance metrics are supposed to be "quality measures" for buildings with respect to their energy efficiency [24], and with respect to the intents of this research. Performance metrics can be used for comparative studies to guide building design or to benchmark a building against a pool of other buildings, and in the following topics, the reader can find some explanation over the available and applied metrics for this research.

1.1.2.1. ENERGY DEMAND PARAMETERS

In this first chapter, the energy demand is being evaluated in terms of annual heating and cooling thermal requirements to achieve comfort temperature for all the year. The unit is kWh/m^2. Later in the research, this thermal demand will be converted into electricity demand when the HVAC assumptions are introduced, but for this stage, it is yet analysed the thermal requirement.

The heating and cooling set-points were calculated with the adaptive comfort normative (ISO 17772:2017) and result in an overall average for the year in which for indoor temperatures lower than 20°C, the heating system is activated, and higher than 26°C, the cooling system is activated.

Another important parameter, that highlight reflects in the results for the energy demand is the occupancy schedule. It determines when the occupants are at home or when they are outside. The default schedule for the residential program in Honeybee is the one where the apartment is 100% occupied from 10 pm until 7 am. From 7 am to 8 am the occupancy is set at 85% and continues to drop until 10 am. From there until 4 pm the occupancy stays on 25% rate and then it starts to rise again. At 7 pm the occupancy reaches 87%, going up to 100% again at 10 pm. This pattern clearly represents the traditional family behaviour of staying at home during the night and leaving during the day for school or work. From 10 pm to 7 am, everyone is sleeping. Then they start to gradually exit until only 1 person in a family of 4 stays at home, for instance.

However, a life-changing event happened while this research was being developed. The world faced the COVID-19 pandemic, which changed and it is still changing, with yet unknown consequences for the future both in terms of health but also in the lifestyle and habits of the human race. This unforeseen tragic event caused people to sleep, work, play, study and exercise at home, which inevitably reflected in **where** people spent most of their time: at home. Moreover, there is a trend yet to be confirmed that the work-life will not go back to what it was before the pandemic. People realized that so many tasks can be done from home, where they can spend more time with their family and less time in commute and traffic.

Therefore, for this research, the occupancy schedule was adapted to assume people will be at home more often. Maybe they will go only two times a week to the office? Maybe the home office will be the official new work style? There are certainly a lot of advantages in life quality of at least taking a hybrid approach towards where the work or the study is done. For clarity, the schedule is here named as "Residential 2020".

It is a very simple approach, where one assumes 100% of the occupants will be at home from 6 pm until 9 am, and that 50% of the occupants will be at home from 9 am to 6 pm. This can be seen in the Figure showing the behaviour for one weekday in Of course it is not a very specific approach, but it was thought to approximate the time that people will spend exercising outdoors, going to supermarkets and everyday tasks outside of work or school and then also to approximate the fact that some days people will work a full day at home and some others they will go to the office.

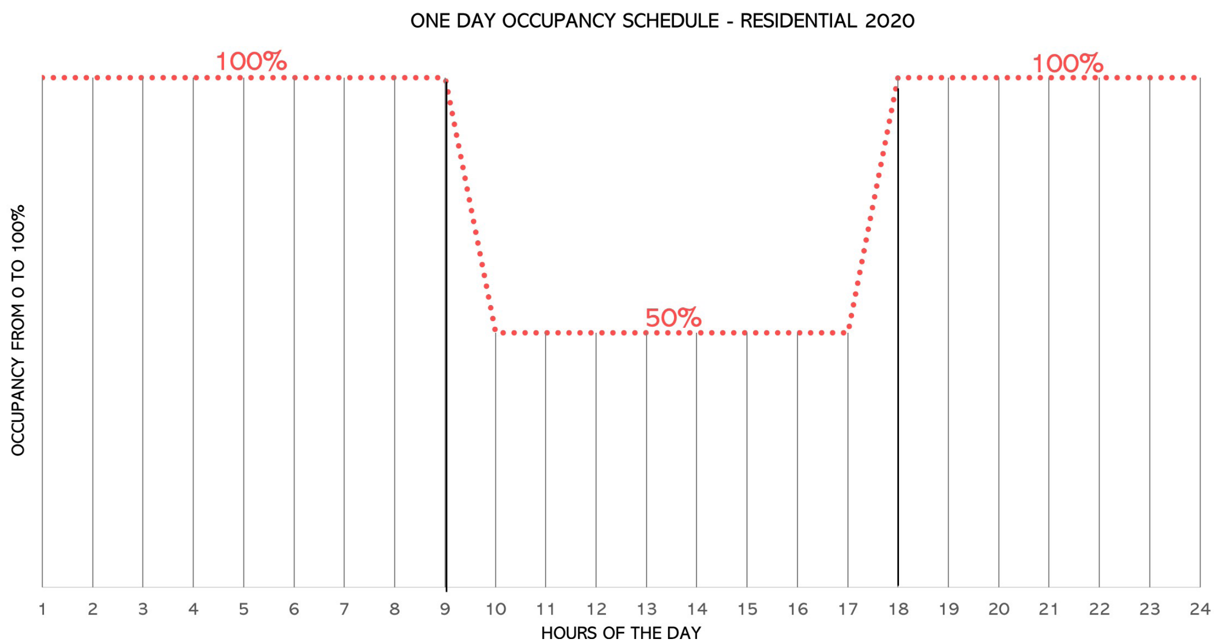


Figure 21: One weekday schedule for occupancy at the "Residential 2020" schedule. [Source: the author]

In the adapted schedule it was also assumed that during the weekends is assumed that everyone is at home 100% of the time. This is visible at the weekly occupancy schedule on the following Figure:

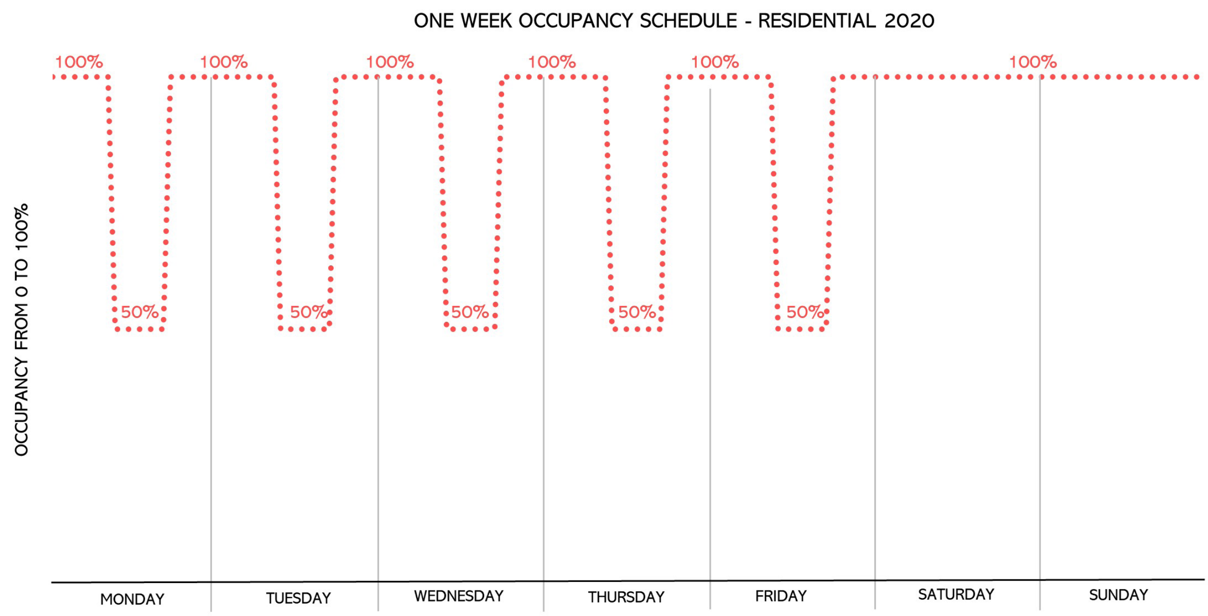


Figure 22: Full week schedule for occupancy at the "Residential 2020" schedule. [Source: the author]

After showing the detailed day and detailed week, in the following Figure, the annual scenario for the "Residential 2020" schedule is shown. There we will also see that from March to October the time difference due to the daylight saving time period is accounted for.

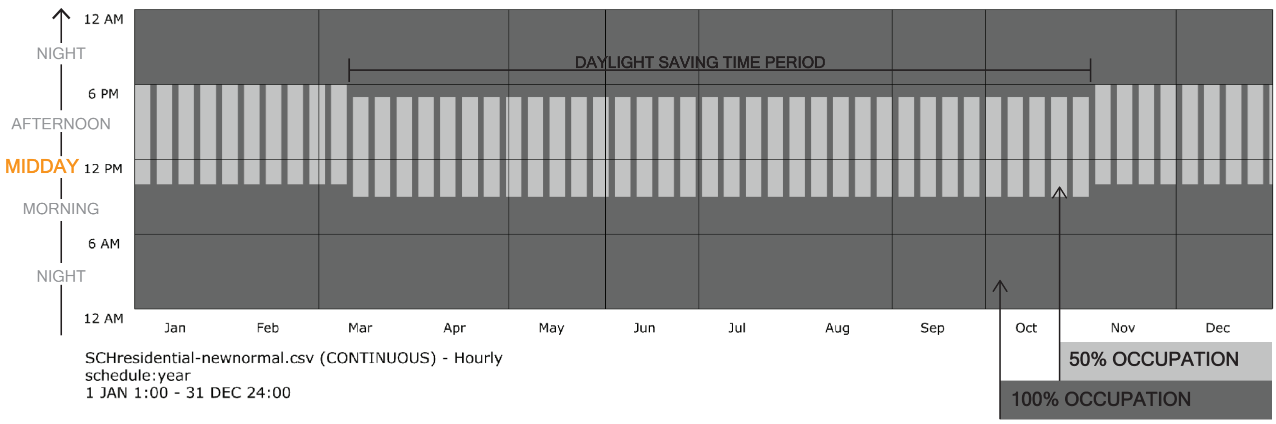


Figure 23: Full year schedule for occupancy at the "Residential 2020" schedule. [Source: the author]

In terms of how the schedule is built, the values for each hour of the day are written in an Excel file and then imported into Honeybee using the components shown below. In Figure 24 it is possible to see also the part in which the Honeybee Zones are modified to the new heating and cooling set-points, previously calculated, to 20 and 26 °C, respectively.

Besides the occupancy schedule, the residential program includes other parameters that are accounted for in the energy simulation. For example, in this stage of the simulation lighting and equipment loads are calculated from a stipulated value that answers for the domestic needs, and are in function of the floor area. This is important in order to be aware that, at this point, the lighting demand does not include the possible savings originated from daylight conditions due to the simulation being too time-consuming and requiring a high level of computer power - this will be studied further on, though, as the research increases the level of detail.

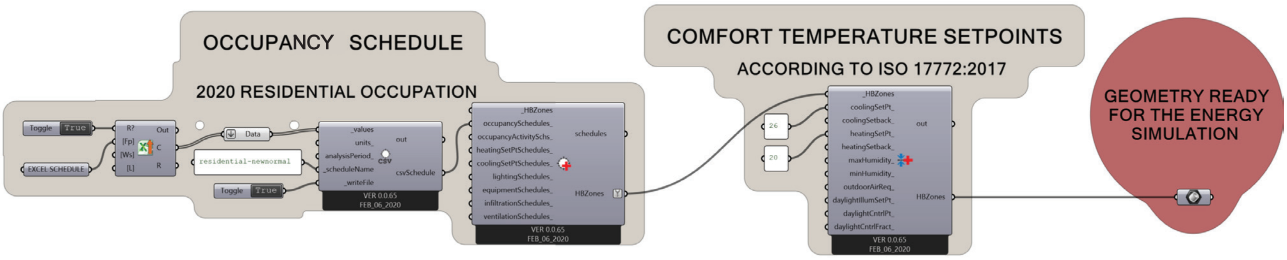


Figure 24: Script in Grasshopper for Rhino, showing the schedule import and the definition of the temperature set-points.. [Source: the author]

Other important parameters are:

Table 5: Parameters that affect energy simulation

Equipment Load [W/ m^2]	**3.875**	The demand for appliances per square meter. Typical values can range from 2 W/m^2 for just a laptop or two in the zone to 15 W/m^2 for an office filled with computers and appliances.
Lighting Density [W/ m^2]	**11.84**	The lighting load per square meter of floor. Typical values can range from 3 W/ m^2 for efficient LED bulbs to 15 W/ m^2 for incandescent heat lamps.
Number of People per Area [ppl/ m^2]	**0.0284**	The number of people per square meter at peak occupancy (100%). Typical values can range from 0.02 ppl/m^2 for a lightly occupied household to 0.05 ppl/m^2 for a tightly packed auditorium. To make it easier to understand this number, it should be noted that is the same of saying the building receives 1 occupant each 35 $m^{2.}$
Infiltration Rate [m^3/s $_{per}$ m^2 of facade @ 4Pa]	**0.000285**	The rate of outside air infiltration into the zone per square meter of exterior facade. ASHRAE recommends the following general infiltration rates based on the are of the facade exposed to the outdoors: 0.000071 - Passive house 0.0001 - Tight building 0.000285 - ASHRAE 90.1-2013 0.0003 - Average building 0.0005 - Leaky building

[Source: the author]

Another aspect that should be pointed out here and have a great impact on a building's energy performance is the envelope constructions and their thermal performances. They were already detailed in Table 4 on page 39, but it is worth reminding the thermal transmittance values and how they are selected:

External walls	Roof	Floors	Glazing unit
U-value = 0.38 W/m²K	U-value = 0.28 W/m²K	U-value = 0.15 W/m²K	U-value = 1.9 W/m²K SHGC = 0.4

The thermal transmittance values will determine how well-insulated the envelope is in relation to the percentage of energy that passes through it. If the number is low, it means the surface is well insulated and, on the contrary, a high number alerts a thermal deficiency of a construction. For this research, the values were selected by matching the weather data via an "epw" file, where it could be extracted the climate zone 4A and then call from the standard ASHRAE 90.1:2007 the constructions used for this scenario. In Figure 25 it is possible to see these steps in the script and understand where the values listed above can be found.

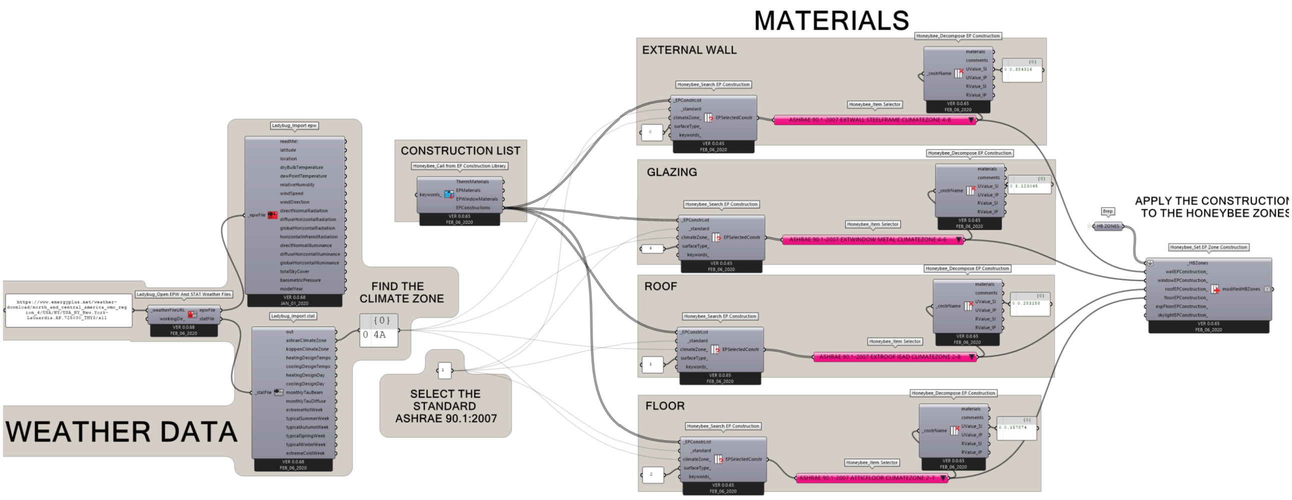


Figure 25: Script in Grasshopper for Rhino, showing the definition of construction materials and their respective U-Value. [Source: the author]

After all of those parameters defined, it is now time to look further in detail at the energy simulation itself.

1.1.2.2. ENERGY DEMAND SIMULATION

In the energy modelling process, parametric building geometry is connected to the parameters detailed in the previous topic and then connected to a Honeybee thermal zone component. The energy calculations were performed using the simulation tool Energy Plus. It exports HB Zones into an IDF file, and run them through the simulator. This program creates a fully integrated thermal model with a detailed hourly output of the selected variables. For this case, it was selected the "Zone Energy Use", which results in the heating, cooling, lighting and equipment energy demand.

Another important parameter is the shadow parameters, which sets how the component will run the solar distribution calculation. For this simulation, option 4 is chosen as it is the most accurate method. "Full interior and exterior with reflections" means that the simulation will perform the solar calculation in a manner that accounts for light bounces that happen both outside and inside the zones.

After waiting for the time for the simulation to run, it is possible to extract the outputs either by reading directly the hourly results or normalizing them by area. All this process is shown in Figure 26.

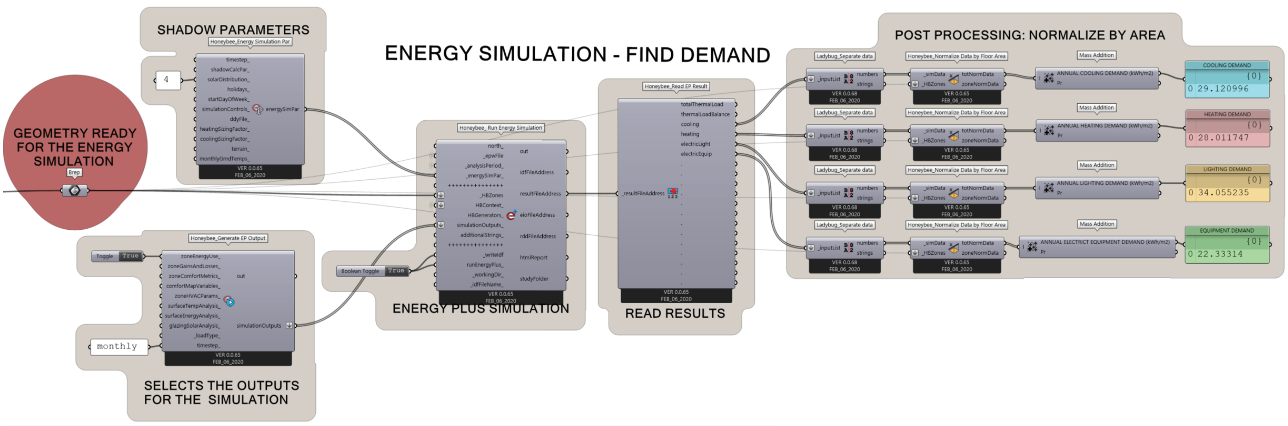


Figure 26: Script in Grasshopper for Rhino, showing the energy demand simulation and outputs. [Source: the author]

1.1.2.3. DAYLIGHT PARAMETERS

Having previously studied all the pros and cons of each metric detailed before, it was decided to apply the **Daylight Factor** for the first stage of this research, which is discussed here in Chapter 01. That is because when analysing the three typologies, towers, courtyards and bars, there are too many cases to simulate that would be too time-consuming and practically unfeasible. We have discussed that DF presents some limitations, like in regards to orientation, but the great advantage is that the simulation and computer power requirements are significantly lower. For this stage, it can be quite representative of the daylight scenario in each case studied.

Further on the research, in Chapter 02, where the study goes into more detail on some cases, it will be possible to apply dynamic climate-based metrics, but then the selected metrics will be explained in that chapter.

1.1.2.4. DAYLIGHT SIMULATION

The Daylight Factor simulation is done using Honeybee components linked to Radiance and Daysim. Radiance is a validated, physically-based backward ray-tracer that can simulate indoor illuminance and luminance distributions due to daylight for complex building geometries and a wide range of material surface properties for one sky condition at a time [25]. Daysim is a daylighting analysis software that uses the Radiance algorithms to efficiently calculate annual indoor illuminance/luminance profiles based on a weather climate file. These profiles can further be coupled with a stochastic user behaviour model to predict daylight performance indicators such as annual light exposure, daylight autonomy, and lighting energy use for different lighting and shading control strategies.

For this case, the geometry is plugged into the test points component, where it is defined the grid size for the sensors and the height that they will be. The simulations consider all the plan floors of all levels, with an analysis grid spaced 1 meter equally. The height is set to 0.8 meters to represent a work-plane height.

Afterwards, an important parameter is defined: the Radiance Parameters. They are responsible to distribute the light and its reflections according to the rendering options. The most accurate the simulations, the more time consuming they will be. Lastly, the simulation component is activated and the output is a DF percentage for each sensor of the room. They are then averaged and one average percentage of Daylight Factor is extracted. This process is shown also in the following Figure:

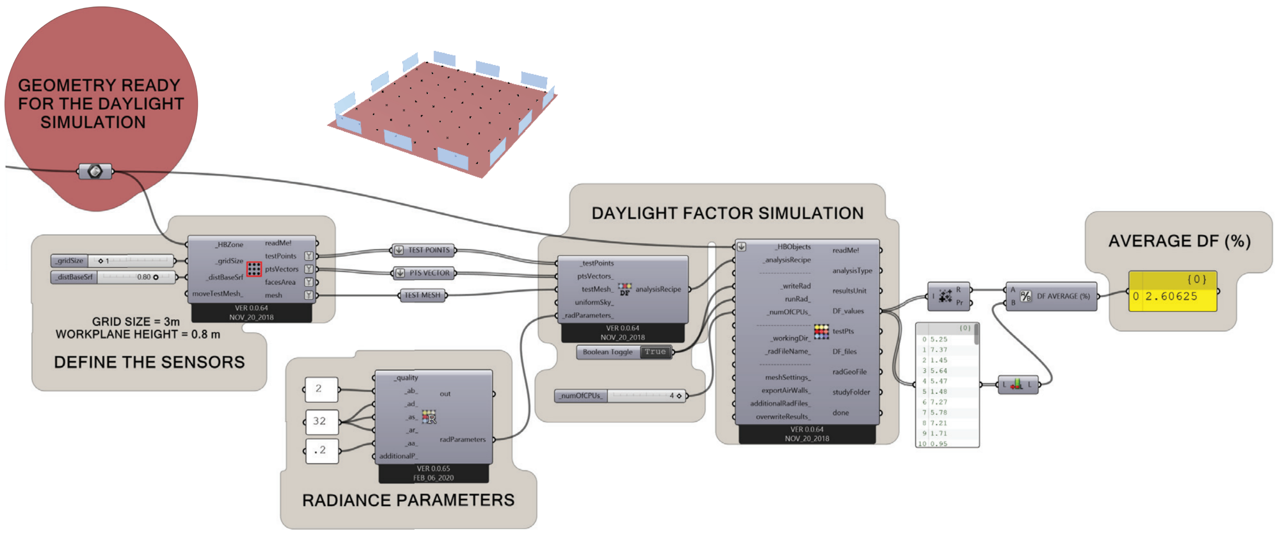


Figure 27: Script in Grasshopper for Rhino, showing the Daylight Factor simulation and outputs. [Source: the author]

Still, on the matter of the "rad" parameters, they are detailed in Table 6, below, which presents the overall scenario and meaning of the values that need to be defined and it gives some useful ranges for some Radiance 2.4 parameters. The "min" value gives the fastest, crudest rendering. It is not necessarily the smallest value numerically. The "fast" value gives a reasonably fast rendering. The "accur" value gives a reasonably accurate rendering. The "max" value gives the ultimate in accuracy. The numbers in bold are the ones selected to perform the simulations, always the same recurrent problem of limitations due to computer power and time.

Table 6: Radiance Parameters

Param	Description	Min	Fast	Accurate	Max	Notes
ab	ambient bounces	0	0	**2**	8	It is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.
ad	ambient divisions	0	**32**	512	4096	-
as	ambient super samples	0	**32**	256	1024	Super-samples are applied only to the ambient divisions which show a significant charge.
ar	ambient resolution	8	**32**	128	0	This number will determine the maximum density of ambient values used in interpolation. The maximum ambient value density is the scene times the ambient accuracy.
aa	ambient accuracy	.5	**.2**	.15	0	This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

[38]

1.1.2.5. SOLAR POTENTIAL PARAMETERS

Following the explanation done in the section for "Metrics" on page 42, solar potential represents the possibility of each case to receive solar radiation and make use of it with active strategies. Solar radiation will be used to produce electricity and domestic hot water, but, as in this Chapter it is presented yet the initial stage of the analysis, the solar potential is shown on the graphs as the amount of solar radiation falling on the envelope, not yet being divided according to its end use for production. The unit is kWh received on the entire building surface (all façade orientations plus roof surface) over one year.

1.1.2.6. SOLAR POTENTIAL SIMULATION

In order to measure as precisely as possible the irradiation on hypothetical buildings, it was chosen to use the well-known ray-tracing program RADIANCE, which conveniently simulates the energy flux arriving on any shape of shelter and can take into account the sky obstructions due to the surrounding landscape and associated reflections [16].

As it can be seen in Figure 29, firstly it is defined the analysis period (the entire year), the proper sky matrix and some other visualization parameters. Then the studied geometry is supplied to RADIANCE with a virtual geometrical model along with grid-points and normal vectors on each surface. The grid-points act like virtual watt-meters, measuring energy coming from the direction indicated by the normal vector. [16] The r-trace program (the tracing core of RADIANCE) computes the irradiation and writes the results for each grid-point to an output file. This procedure is shown in Figure 28.

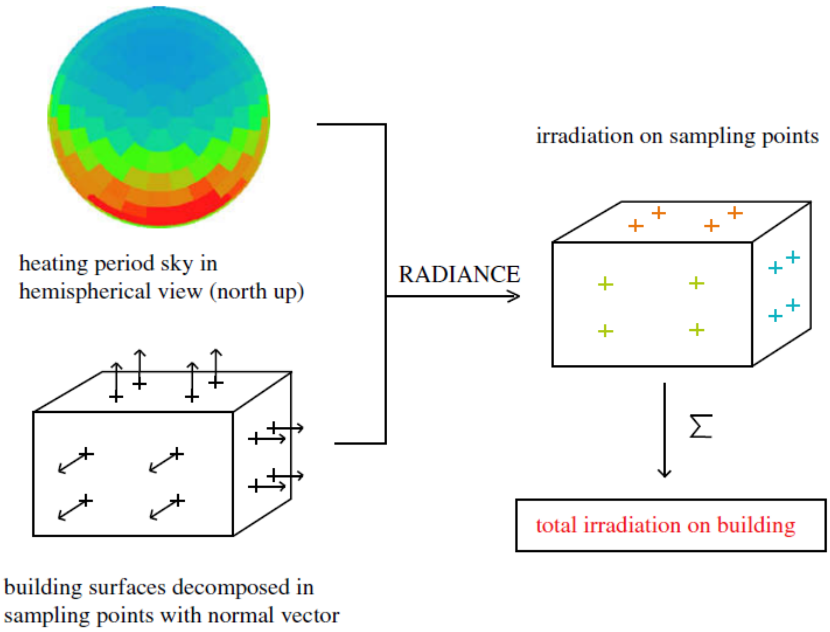


Figure 28: The irradiation calculation using RADIANCE [16]

The distribution of the grid-points on the building surfaces should be as uniform as possible and each grid-point centred on a small known area. The irradiation is then considered as constant on each small area, therefore, the number of points (and small areas) is adapted to the precision we want in the total irradiation calculation [16]. For the sake of this research, it was chosen calculation parameters that allow precise results in a reasonable computing time.

On this subject, the grid size is set to 1 meter. This represents the average size of a grid cell for the radiation analysis on the test surface. In order to choose this value, it must be considered that it should be smaller than the smallest dimension of the test geometry for meaningful results. As it was stated before, the smaller the grid size, the higher the resolution of the analysis and the longer the calculation will take.

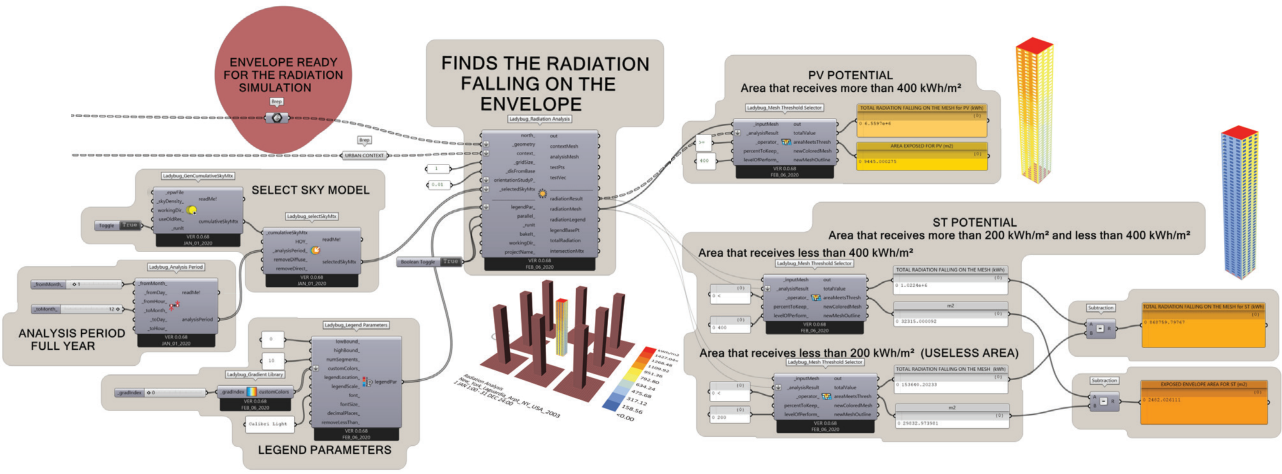


Figure 29: Script in Grasshopper for Rhino, showing the Solar Radiation simulation and outputs. [Source: the author]

This is all centred in the Radiation Analysis component, from the Ladybug plug-in, that allows for the calculation of radiation falling on the input geometry using the sky matrix. This type of radiation study is useful for building surfaces such as windows, where one can be interested in solar heat gain, or solar panels, where one can be interested in the energy that can be collected. Therefore, on the final right end of the script shown in Figure 29, some post-processing of the results is made to understand where are the areas of the envelope that receive more than 400 kWh/m^2, that will be dedicated to receiving PV panels and where are the areas that answer to the ST threshold, from 200 to 400 kWh/m^2. With that, we are able to understand how many square meters are going to be covered with solar active systems and also how much is the total useful radiation over the year.

1.2. TYPOLOGIES RESULTS

After explaining the methodology, cases studies for each typology, software, parameters used and metrics applied, the results are shown in the following graphs, divided by each typology. After the three typologies are deeply analysed, the comparison is made to finally understand if in fact there is a typology that stands out in terms of building performance in comparison.

1.2.1. TOWERS

For the tower typology, 128 cases were simulated and the overall scenario can be seen in Figure 30. Towards the right of the graph, in light yellow, there are the cases with only one tower (1x1), as the dots are placed more towards the left, the number of towers on the plot increase (aspect ratio), and this trend shows that Daylight Factor is decreasing. This is the effect of the Sky View Factor and its influence on the daylight factor because, as it was already discussed in "1.1.2.3. Daylight parameters" on page 61, the sky factor evolved into the daylight factor over time, as light reflected from external obstructions, light losses through glazings, and internal reflectance were considered.

The higher number of buildings means that more obstructions will happen and this is probably the factor affecting the Daylight Factor average. It should be noted that, even though Sky View Factor is a parameter that is used currently to support studies about urban-climate relationships, it is also valid to evaluate daylighting as it is indeed a precedent of the Daylight Factor. SVF is the ratio of the visible sky that can be seen from a location in the urban space to the whole sky-dome that contains both visible and obstructed sky. If SVF trends towards 0, it means an entirely obstructed sky, and if goes towards 1, a totally unobstructed one. Although it is not the metric in question, it is directly related to the contribution of direct light from the sky-dome and the presence or not of obstructions and it is clearly affecting the Daylight Factor.

Moreover, still looking at the Daylight Factor, the aspect ratio shows the horizontal trend from left to right, but there is also an easily observable vertical trend: Daylight Factor decreases as the plan floor becomes deeper and the buildings decrease their total height. This is in line with the rule-of-thumb for passive zones mentioned earlier in this research, where a maximum zone of 6 meters depth can receive good daylighting. If we look again at the graph, the "worst" cases in terms of daylighting, when DF decreases almost reaching the minimum acceptable threshold (2%), happen when the dimensions of the plan floor increases to 25m. This effect is attenuated a little when one of the dimensions is 20m.

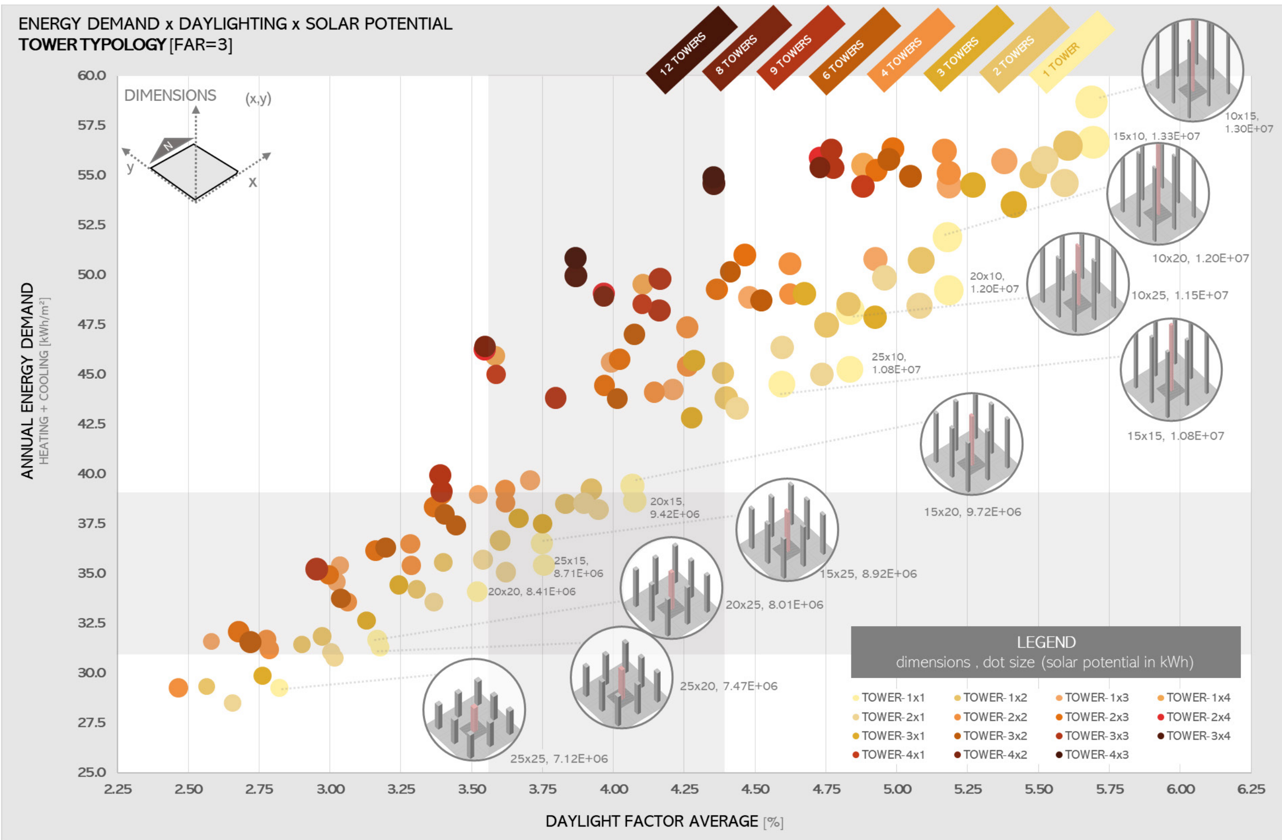


Figure 30: Overall scenario for TOWER typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

From the energy demand perspective, the same trend happens: as the plan floor increases dimensions and the building is lower, less energy is required per square meter for heating and cooling. On the contrary of daylight, however, the number of towers does not seem to influence a lot the energy demand, as we can find cases with the same energy demand with 8 or 2 towers. What do they have in common? The plan floor dimensions. In the table below there is a comparison between the same plan floor dimensions but in different distribution method, the first with 2 towers and the second with 8. Similar values of energy demand, with both presenting acceptable daylight factors and a huge difference in the number of floors.

Table 7: Comparison between two tower cases with same dimensions

10x15	Energy demand [kWh/m²]	Daylighting [%]	Solar potential [kWh]	Number of floors
1x2	56.52	5.60	11,972,651	100
4x2	55.41	4.73	8,508,500	25

[Source: the author]

The third metric in question, solar potential, is shown on the previous graph through the dot sizes. It represents the amount of useful radiation that the envelope receives over a year, expressed in kWh. In the overall graph it is visible that the buildings with higher potential to take advantage of solar radiation are the cases on the top of the graph: shallow plan floors and very tall buildings, but with high energy requirement as well. Further discussion on this metric follows when looking at Figure 33.

In order to have a better idea and comparison among the cases, it was decided to extract from the graph a horizontal and a vertical "slice". As it is highlighted in the grey in Figure 30, the two following graphs are a "zoom" to detail a little bit more the cases and their performance.

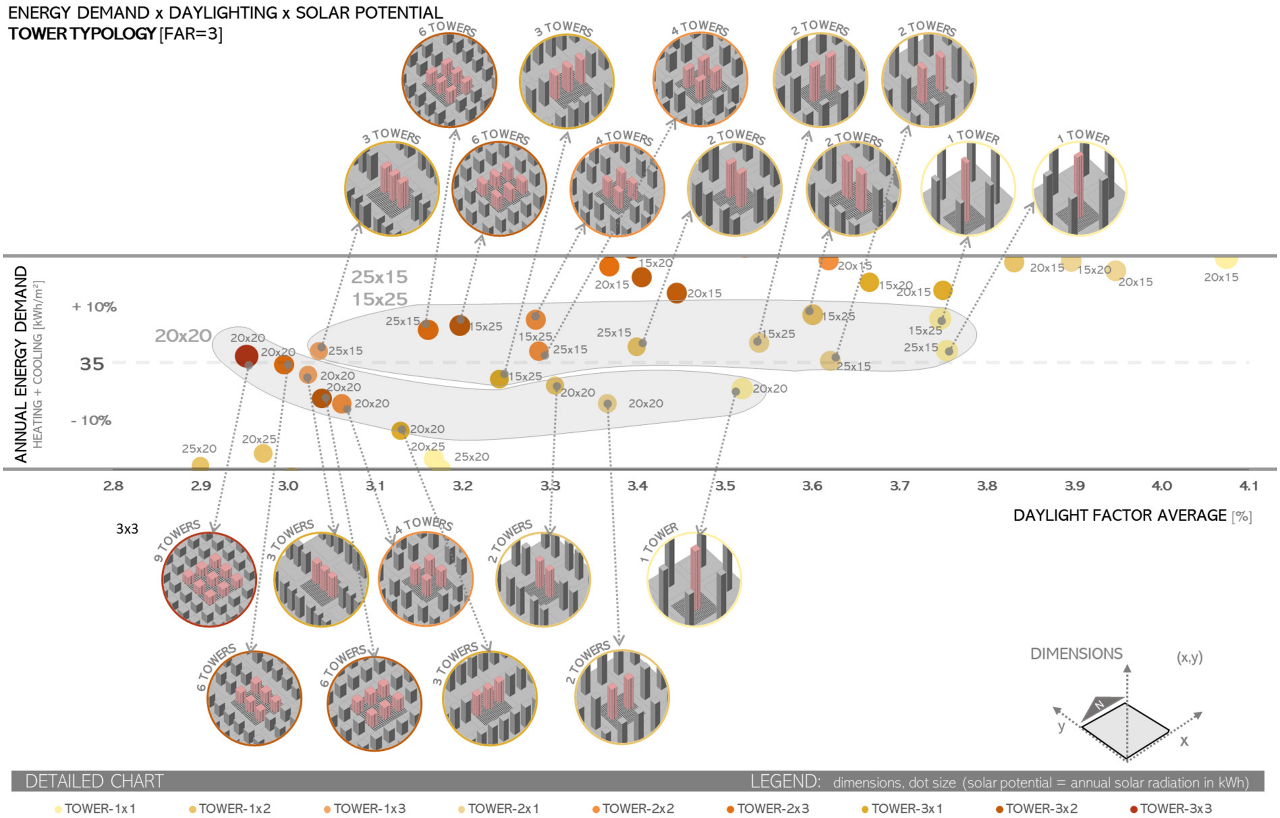


Figure 31: Horizontal detailed graph for TOWER typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

The detailed horizontal graph shown in Figure 31 was taken at 35 kWh/m², with tolerances of more or less 10%. This gives an idea of cases that have the same energy requirement but a pretty different Daylight Factor. The cases that pop up at this graph are the dimensions 25x15 and 15x25 at the upper part and the 20x20 at the bottom part of the 35 kWh/m² line.

From there it is visible that the cases with 6 and 9 towers, in 20x20 dimension, present the lowest values for DF, even though still inside the acceptable range. This is to say that by combining several obstructions, low height and deep buildings, the probability is high that when dynamic daylighting metrics are applied daylighting conditions will not be excellent, therefore those design moves must be carefully considered. Another interesting comparison to be made here is that even though DF does not account for orientation, the cases for 1, 2, 3 and 4 towers in the 15x25 and the 25x15 settings are not exactly the same both in energy demand and in DF. They are, however, pretty similar, with the bigger difference in DF being in the case of 2 towers: when the buildings are aligned along the axis east - west they present a higher DF than when aligned along the axis north - south. This is probably due to the position of obstruction towards the sky-dome.

The cases with higher DF are, once again, the 1 tower cases, that is because of the lack of obstructions but also because they are very tall buildings. This is showing that with the plan floor dimensions of 15x25 or 25x15 it is probably better to have one tall building than 4 middle-height towers: they will consume the same amount of energy for heating and cooling but the one-tower case will perform better in terms of daylight. They also present the same magnitude of solar potential, as it is visible from the similar size of the dots. It should be noted, however, that among the cases shown in the horizontal chart the solar potential variation goes from 6.9 .10^6 kWh (1x2, 25x20 - small dark yellow dot placed on the left of the graph but on the bottom edge, close to 2.9% of DF) to 9.47 .10^6 kWh (3x3, 20x20 - big red dot placed on the left of the graph, on top of the 35 kWh/m^2 dashed line). It is not an extreme change if the overall variation is compared: among all the cases for towers the solar potential variation ranges from 6.88 .10^6 kWh to 13.3 .10^6 kWh, but it's interesting to see the extremes presented in this chart because they are both on the same percentage for Daylight Factor (around 3% DF) and with the same energy demand.

Looking further on the detailed vertical section, it will be possible to compare how the plan floor and height affect the different dimensions, having the fixed parameter at 4 % of DF and evaluating the cases that fall under this range (considering 10% more and less) but vary significantly the energy demand.

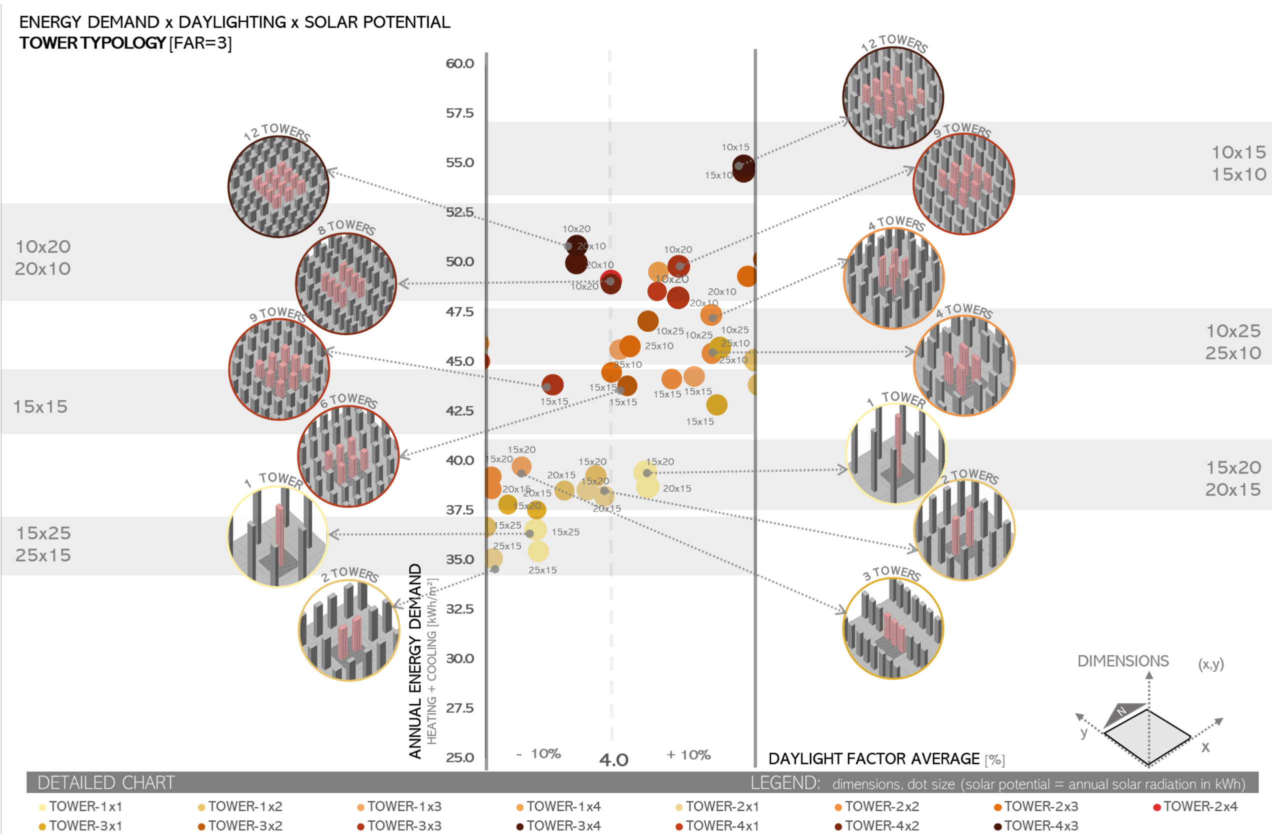


Figure 32: Vertical detailed graph for TOWER typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

From that comparison, it is possible to see that the highest energy demand per square meter for this DF threshold happens in the cases with a higher aspect ratio (more buildings) and, in consequence, low height ones, and shallow plan floors (10x15 and 15x10). As the dots become lighter towards the bottom of the graph, the aspect ratio and the plan floor depth increase. The case of 15x25 with 2 towers, for instance, presents an energy demand of 35.7 kWh/m², while the case of 10x15 with 12 towers presents an energy demand of 55 kWh/m². This is a difference of almost 20 kWh/m² just by changing the massing. The first building is 40-storeys high, while the latter 17.

Another observation is that the cases 15x15 are all equally performing: they have similar values for the three metrics evaluated, even though they vary in aspect ratio and height. This is confirmed by the following table where the values are described:

Table 8: Comparison between 15x15 cases from the detailed vertical section graph

15x15	Energy demand [kWh/m²]	Daylighting [%]	Solar potential [kWh]	Number of floors
9 towers (3x3)	43.86	3.80	8.77 .10⁶	15
6 towers (2x3)	44.47	3.97	8.37 .10⁶	22
6 towers (3x2)	43.80	4.01	8.25 .10⁶	22
4 towers (2x2)	44.13	4.14	8.42 .10⁶	33
3 towers (1x3)	44.27	4.21	8.45 .10⁶	44
3 towers (3x1)	42.84	4.28	8.63 .10⁶	44

[Source: the author]

Still on the graph for the detailed vertical section, in Figure 32, it should be noted that the solar potential varies even less than the graph showing the detailed horizontal section. Here, the variation goes from 7.8 $.10^6$ kWh (3x1, 20x15) to 9.72 $.10^6$ kWh (1x1, 15x20). This makes sense because the "cut" is made at the same Daylight Factor percentage, which confirms that here daylighting is aligned with the availability of solar radiation on the envelope.

Furthermore, another graph was made to try to understand better some trends for all the tower cases. In Figure 33 the same graph is presented as the first one with the overall scenario, but in this case the X-axis shows the solar potential and the dot size shows the Daylight Factor. As it was already mentioned, the overall variation happens from 6.8 $.10^6$ kWh to 13.3 $.10^6$ kWh. The trend found in the first overall graph of decreasing the energy demand as the plan floor increases dimensions still can be seen here, and the same horizontal trend of the cases with fewer towers being at the right and as the dots move towards the left they present the cases with more towers. This makes perfect sense as solar radiation is linked to daylight availability.

However, in the previous one, the trend lines were following a regular path for each distribution case, where the smallest plan floor was placed on the top right and the largest plan floor was placed on the bottom left (diagonal path). This one, on the other hand, the trend lines are not regular at all.

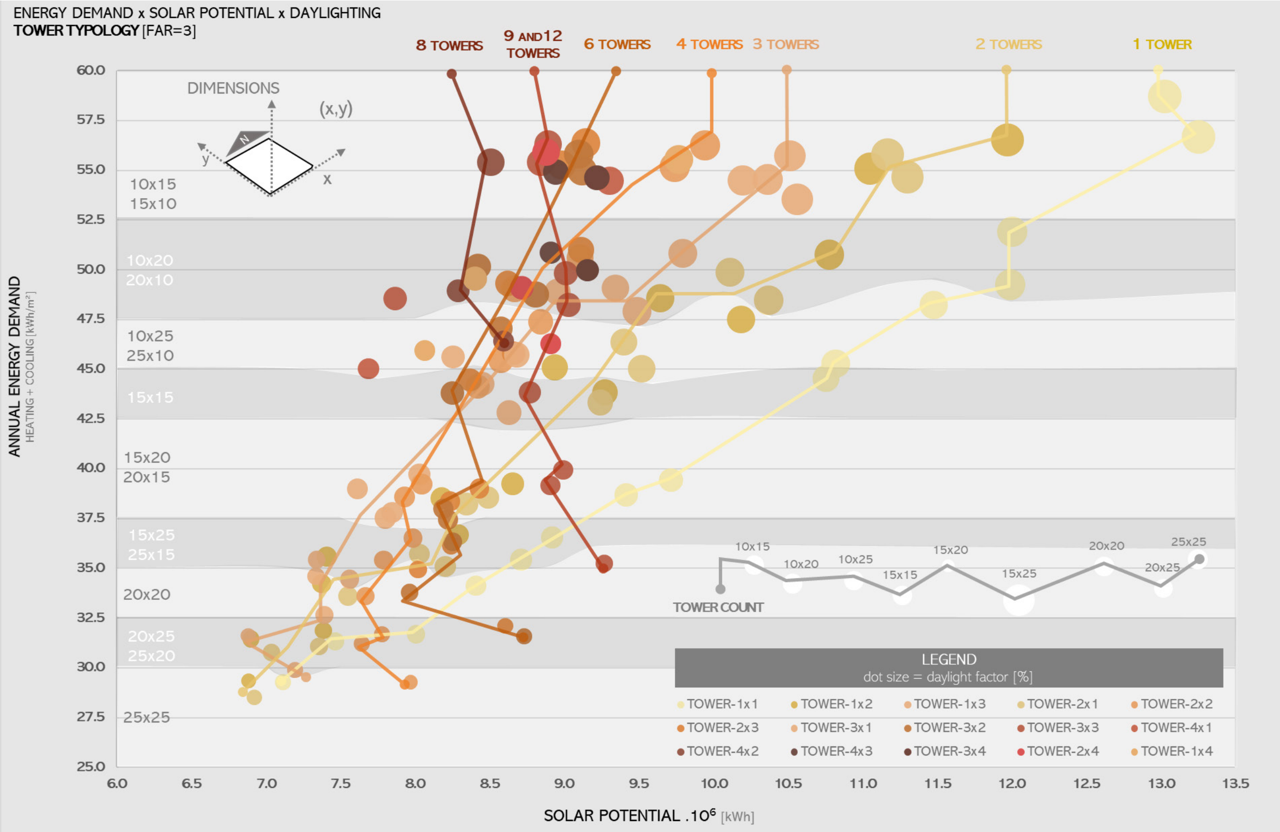


Figure 33: Overall scenario for TOWER typology in terms of Solar Potential (x), Annual energy demand for heating and cooling (y) and Daylighting (dot size). [Source: the author]

For the case of 1 tower, the trend line behaves similarly as in the diagonal trend (with some small inflections along the way, tough) seen in the previous graph. That is true also for cases with 2 and 3 towers (even though on the bottom left the lines for 2 and 3 towers intersects at some points). On the 4 towers trend line, it can be seen that it follows the diagonal path as the other ones until the cases of 15x20 and 20x15. At this point it goes down on a vertical path, meaning that it stops to significantly reduce the solar potential as the plan gets deeper. This fact can be seen in numbers in Table 9.

The same pattern of starting diagonally from the top right towards the bottom left with the inflection in the middle happens for the cases with 6 towers. The inflection, however, happens now from the cases 15x15. From that point towards the bottom, the line becomes vertical, with a final inflection on the opposite of the initial diagonal, from the 20x20 case to the 20x25 and 25x20. This final inflection means that the squared plan floor is presenting lower solar potential than the rectangular one.

Table 9: Comparison between 2x2 cases to show an inflection on the trend line for solar potential

4 towers (2x2)	Energy demand [kWh/m²]	Daylighting [%]	Solar potential [kWh]	Number of floors
10x20	50.59	4.62	**9.11 .10⁶**	38
10x25	47.39	4.26	**8.84 .10⁶**	30
15x15	44.13	4.14	**8.42 .10⁶**	33
15x20	39.24	3.62	**8.05 .10⁶**	25
15x25	36.52	3.28	**7.99 .10⁶**	20
20x20	33.60	3.06	**7.67 .10⁶**	19
20x25	31.71	2.78	**7.78 .10⁶**	15
25x25	29.28	2.47	**7.97 .10⁶**	12

[Source: the author]

For the cases with 8, 9 and 12 towers, the trend line is practically vertical. This happens because there are so many buildings and obstructions that the radiation on the façade is not a relevant factor anymore, but the number of roofs. Yet, it is visible that the façade, if open to receive solar radiation, can represent a significant increase in energy production. Cases with 1 tower and a tall building present the highest solar potential, yet the highest energy demand.

Still on the topic of understanding the trend lines, in Figure 34 it is possible to compare the first overall graph of Figure 30 but now showing only the trend lines with the trend lines shown in the graph of Figure 33, where the solar potential is shown in X-axis. Once again, it is visible the trend of the 1 tower cases on the very right and as it goes to the left, increasing the number of towers and as the lines go down, the cases increase the plan floor dimensions and therefore decrease the height.

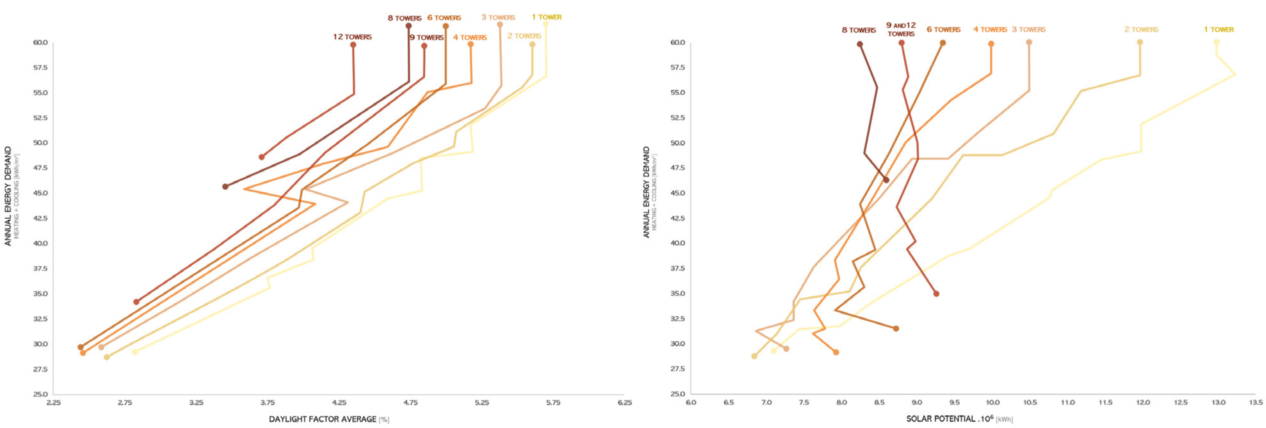


Figure 34: Comparison between trend lines for the for TOWER typology. On the left, the X axis show the Daylight Factor. On the right, the X axis shows the solar potential. Y axis shows the energy demand for heating and cooling in both images. [Source: the author]

1.2.2. COURTYARDS

The courtyard cases are more limited to fit inside the 100x100m, so only 16 cases are simulated for this typology. As explained before, the first obvious cases are the perimeter block, where then this divides into two possible scenarios: the first where the edge is fixed at the street side and then the inner patio varies dimension as the depth changes and the second where the inner patio dimension remains the same and the setback to the street varies. Those two are named: No division cases. That is because the following cases are dividing the inner patio in 2, when adding one central wing (1 Division), or dividing the inner patio in 3 patios, when adding two central wings (2 Divisions). Those cases are also simulated when the new wing axis is along east - west axis (EW cases) or when the new wing follows the north - south axis (NS).

In Figure 35 it is possible to compare all the cases and understand their performances:

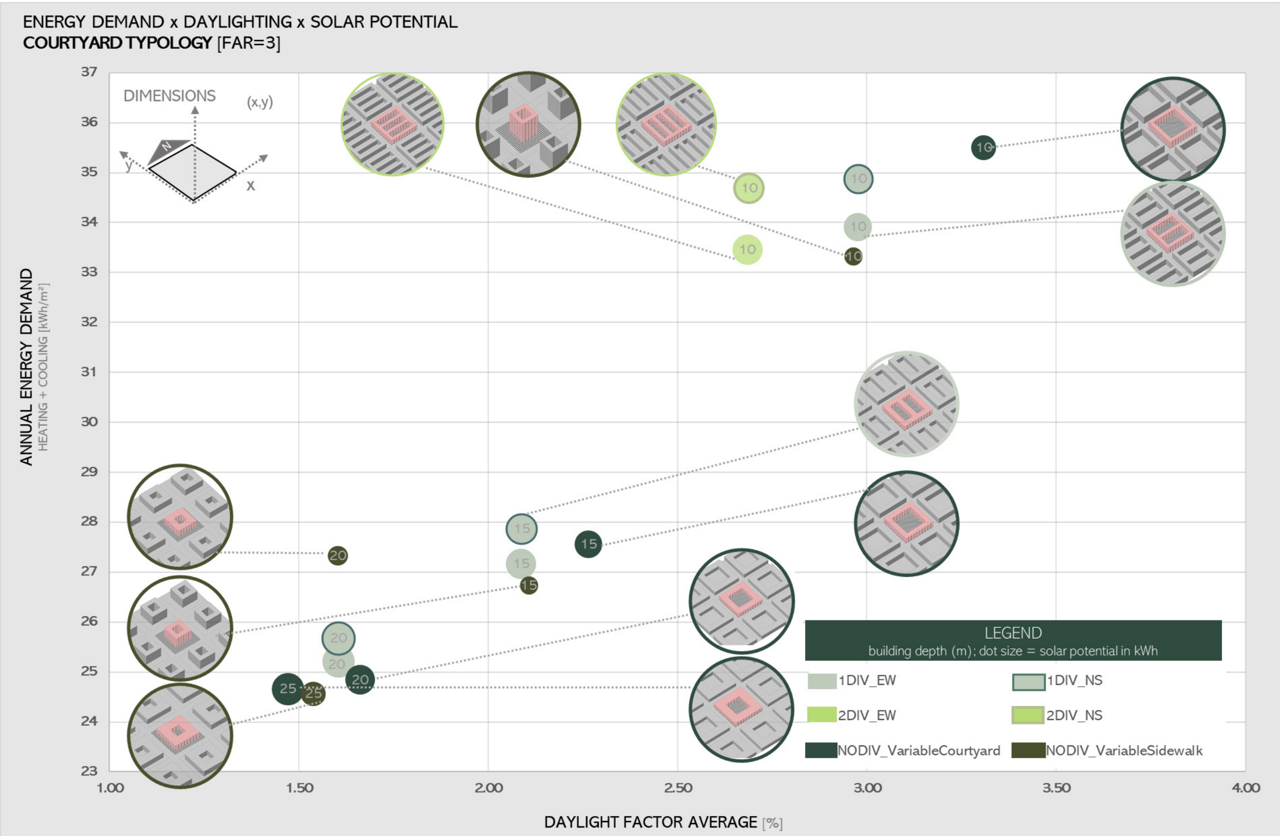


Figure 35: Overall scenario for COURTYARD typology in terms of Daylight Factor (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

At the centre of each dot it is visible the depth of the building. This indicator is the one with the most impact in the Daylight Factor and Energy use, with the composition of clusters of cases gathered by the depths that are clearly visible (10, 15, 20, and 25m).

The best performing cases in terms of daylight are the ones with depth a 10 and 15m. The cases with

1 division and 2 divisions have pretty similar results when comparing their orientation and daylight, but a small increase in the energy requirement in the cases where the intermediate wing is placed along the axis of N/S. It can be noted that the dot with a ring outside is placed vertically above the one without the ring.

When moving from 1 division to 2 divisions, there is almost no difference in the energy demand but a difference regarding DF percentage, where the cases with 2 divisions will obviously have a narrower inner patio. Comparing 10m depth cases, for 1 DIV EW it has a DF of 2.98 % while in 2 DIV EW it has a 2.68% DF. This means an 11% improvement in daylighting just by reorganizing the massing to have a greater inner patio. It should be remembered that all the cases present a FAR = 3, therefore have the same square footage. In this case, the 1 DIV building will be only one floor higher than the 2 DIV. (1 DIV EW 10m presents 7 floors and the 2 DIV one presents 6 floors).

Among the cases with no divisions, just the perimeter block, when comparing the one increasing the inner patio or the one increasing the sidewalk width, the first one performs much better. The small courtyard in the centre of the cases with increasing sidewalk width affects severely daylight performance.

Differently than for any other typology, here is visible a clear winner: 15m-deep cases have DF values comparable to the shallower cases (both 10m and 15m depth cases are above 2% DF), with a 30% increase of the energy use from 15m to 10m deep buildings.

On the graph shown in Figure 36, which presents Energy Demand x Solar Potential, the development of each case is highlighted, making it possible to trace trend lines as the depth changes. The cases with 10m depth present the highest energy demand, with 30% of difference to the following cases, the 15m depth. From the 20m to the 15m depth, it can be seen an increase in the energy demand of about 10%. And from 25m to 20m depth, there is an increase of only 4% - this is the effect of the depth not affecting so much anymore as the initial step.

At a first glance, the visible trend is that the deeper the building, the higher the solar potential. This is happening because probably the most important factor for the solar radiation capture here are the roofs, which increase their area once the building gets deeper. Because the building height is not so great, the tallest case having 19 floors, probably the façades do not contribute that much to the solar radiation capture.

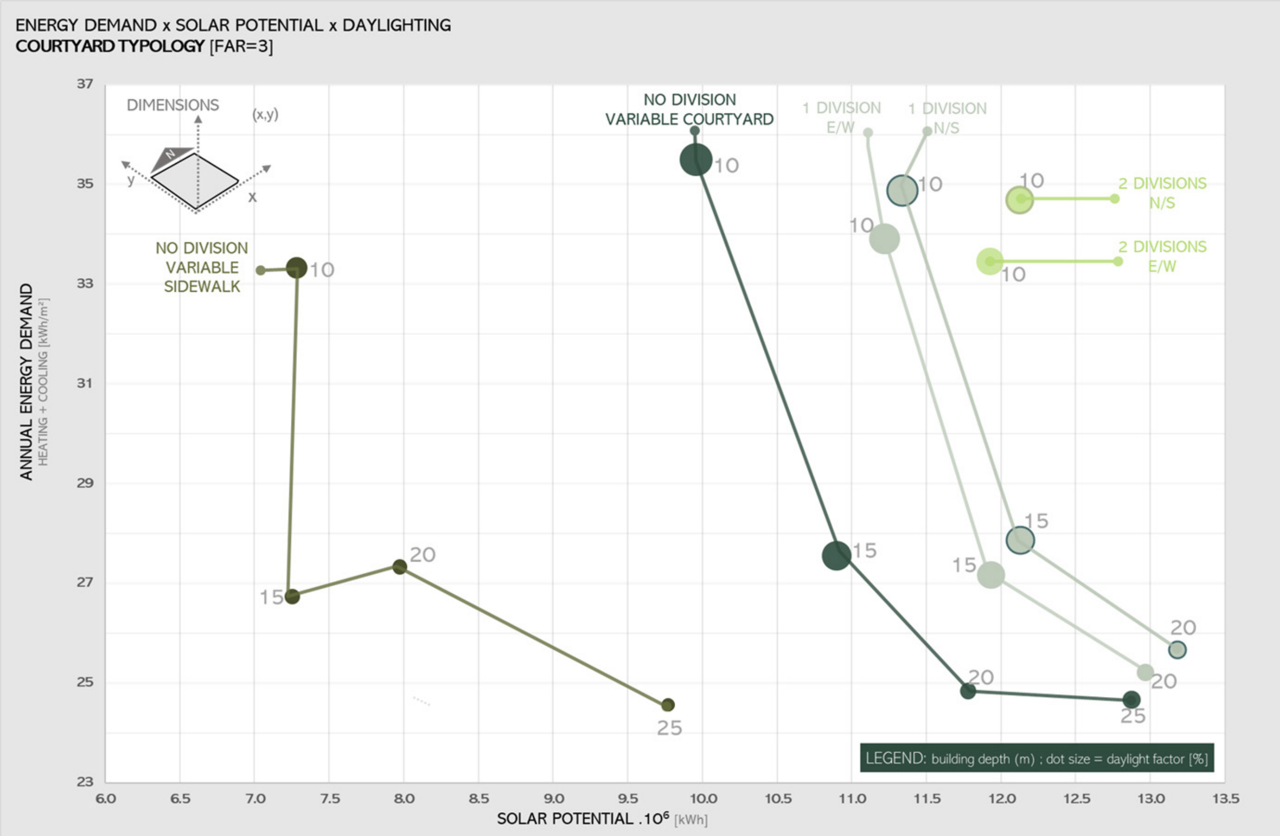


Figure 36: Overall scenario for COURTYARD typology in terms of Solar Potential (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

As mentioned before, the 15 m deep cases present to be the most beneficial considering the three metrics. Courtyard cases at this depth present low energy demand and a good solar potential, while still keeping the DF percentage inside the acceptable range.

1.2.3. BARS

For the typology of BARS, it was possible to simulate 168 cases according to different distributions and dimensions that fit in the 100x100m plot. The results are plotted in Figure 37. As it happened for the case of towers, the first initial visible trend is that the cases with fewer buildings (low aspect ratio) are placed on the far right of the graph and as the building count increases, the Daylight Factor decreases, resulting in the cases with 4 bars being at the far left of the graph.

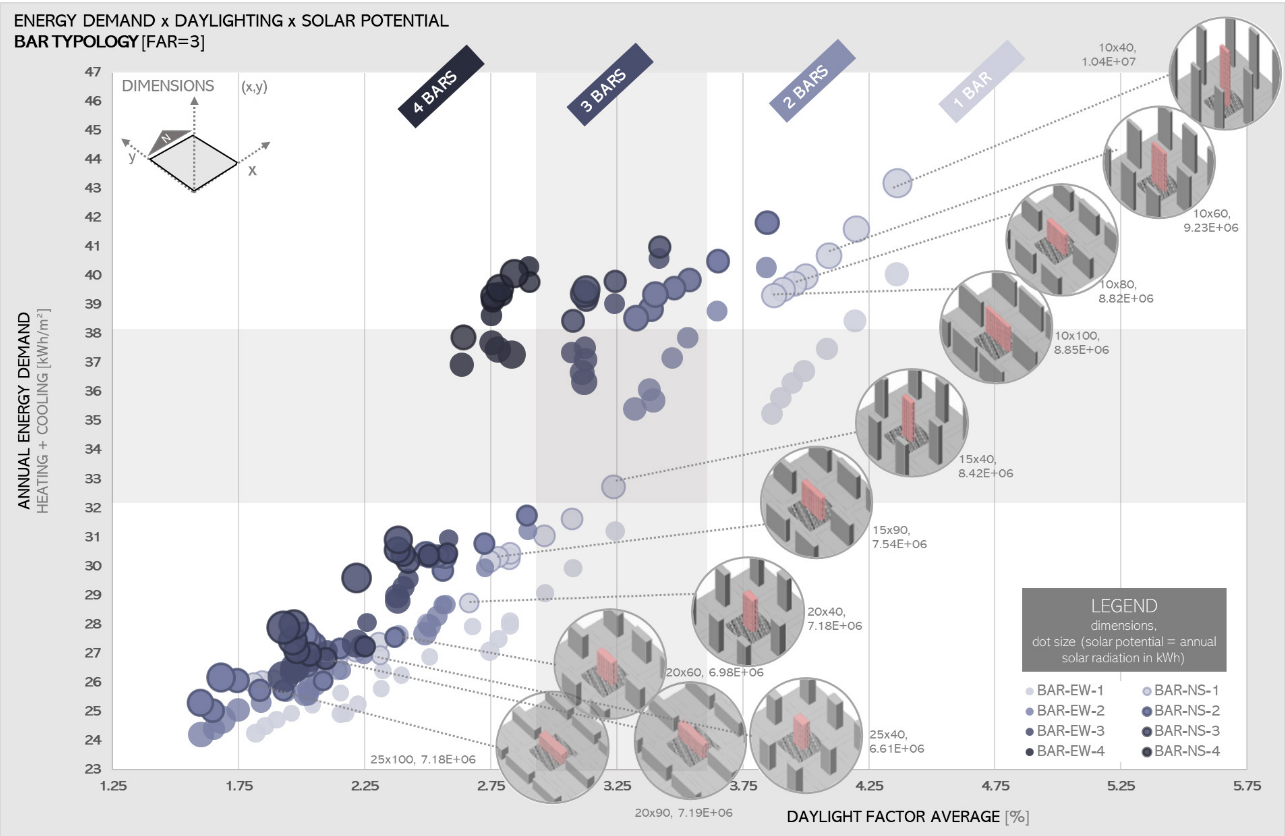


Figure 37: Overall scenario for BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

Variations in floor depth (compactness) and the number of buildings (aspect ratio) have both an impact on energy demand and daylighting. However, there are some differences. First of all, the graph largely confirms the assumption that daylight availability is heavily dependent on floor depth. Each 5-meter-step reducing the floor depth has an increasingly larger impact on Daylight Factor until it stabilizes, as can be seen with the values in Table 10. From 25m to 20m, there is a 20% increase in the DF percentage. From 20m to 15m, a 27 % increase and then from 15m to 10m, a bigger step, of 41% increase.

Table 10: Comparison between changes in floor depth for the 1 BAR E/W cases with length of 100m.

1 BAR E/W	Energy demand [kWh/m²]	Daylighting [%]	Solar potential [kWh]	Number of floors
100x10	35.27	**3.87**	$7.92\ .10^6$	38
100x15	27.09	**2.75**	$6.96\ .10^6$	30
100x20	24.97	**2.17**	$6.83\ .10^6$	30
100x25	24.26	**1.82**	$6.96\ .10^6$	33

[Source: the author]

Similarly, each step has an increasingly larger impact in increased energy use. From 25m to 20m, the increase is only 3%. From 20m to 15m, 8% increase. But finally from 15m to 10m, a 30% increase. Therefore, it seems that in shallower floors, energy requirement increases faster than the Daylight Factor. To go deep into the effect of the step in the depth, the following Figure can be enlightening:

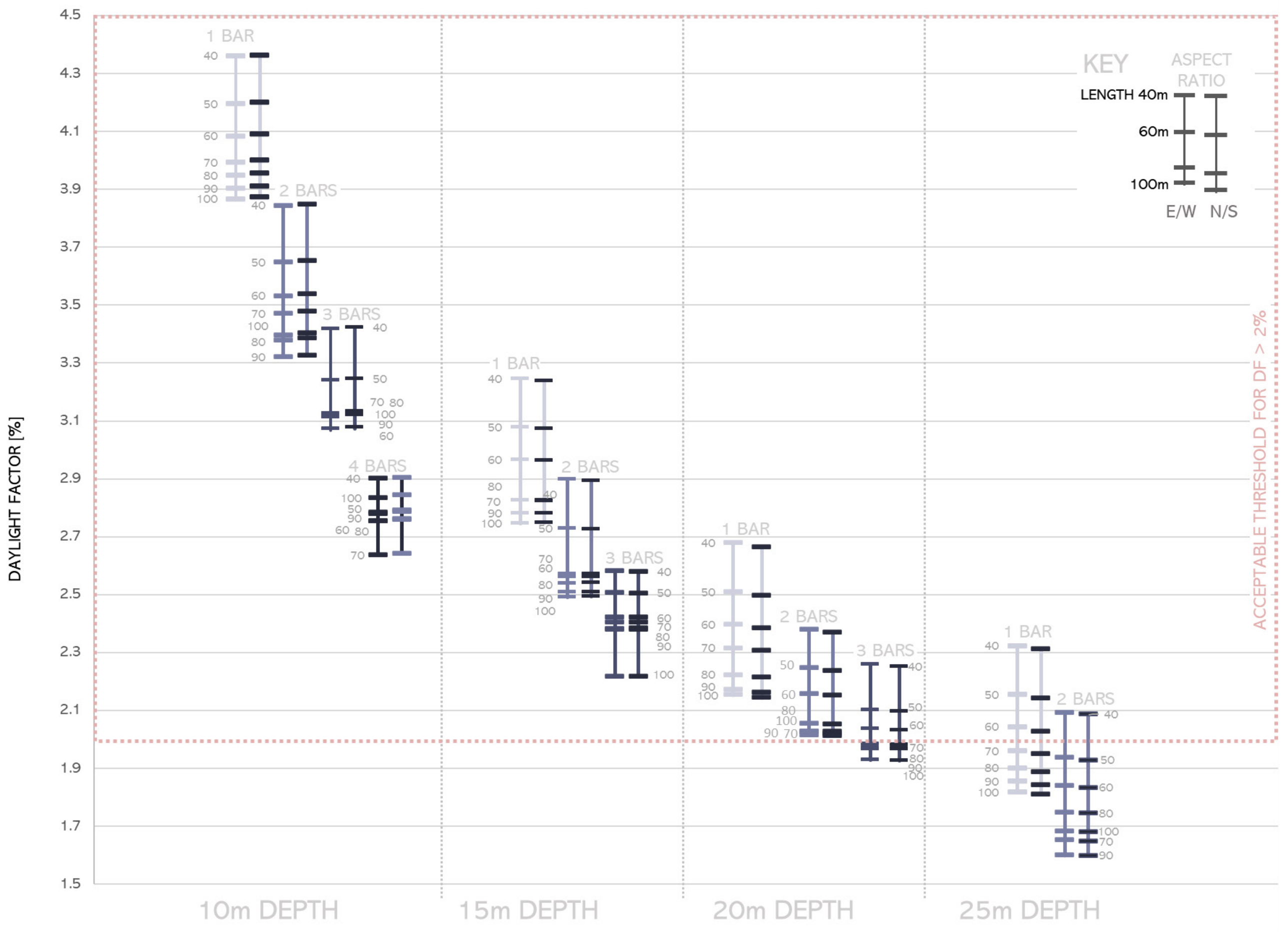


Figure 38: All the cases evaluated for BAR typology with the Daylight Factor average in the y-axis and the building depth in the x axis. [Source: the author]

It is now possible to visualize the step taken in the resulting DF average in relationship with the dimensions. Higher DF is presented in the 1 BAR cases for 10m depth and it is visible that some cases with 20 m and 25 m depth are outside the DF acceptable range. Furthermore, it can be seen that in all the cases the step from 40 m, to 50 m, to 60 m is way higher than the other longer dimensions. Moreover, it can be said that from the 70m depth until the 100m, in terms of daylighting the results are practically the same.

Let's take a look now only evaluating energy demand in the same way to understand how it behaves:

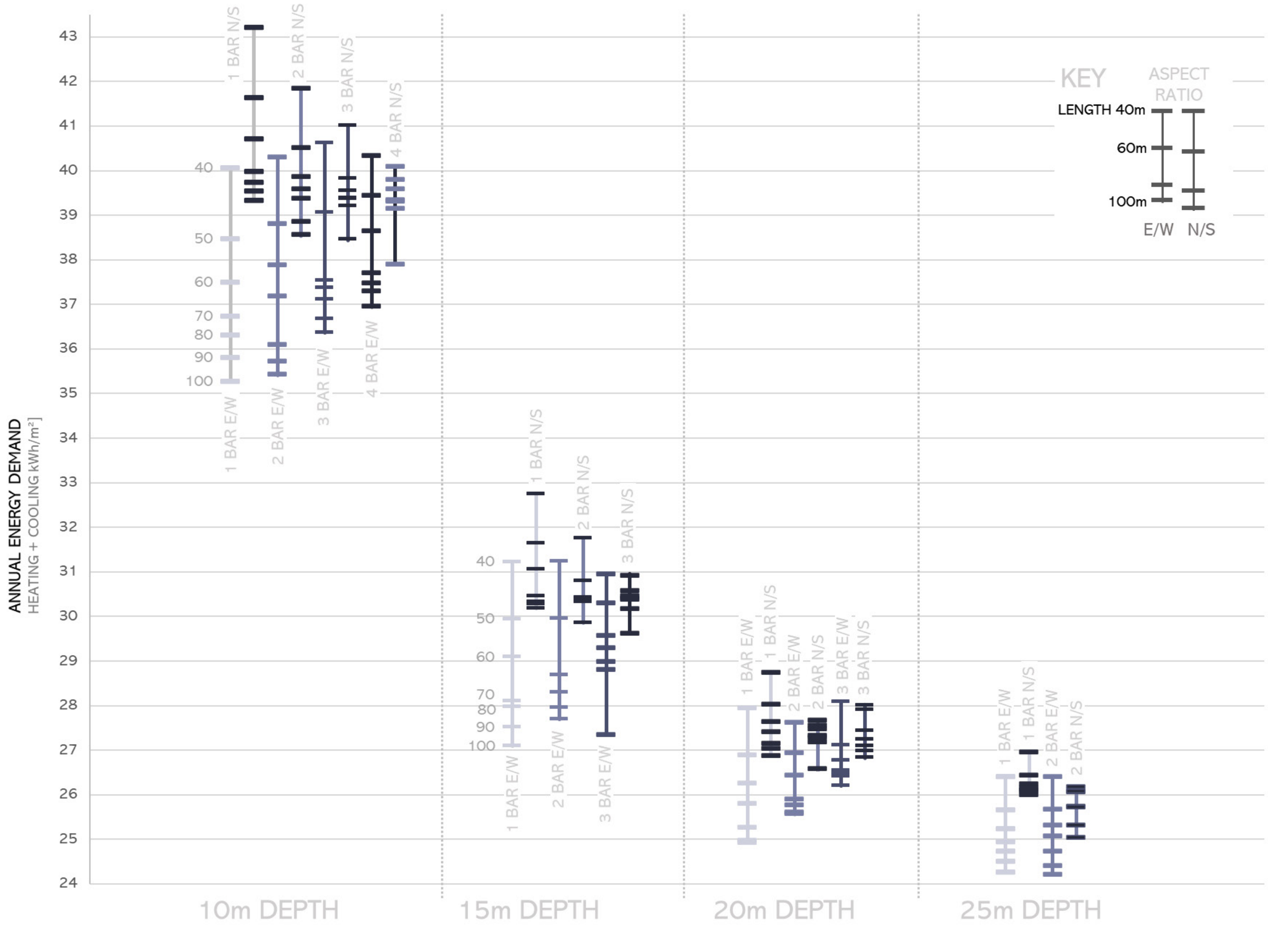


Figure 39: All the cases evaluated for BAR typology with the Energy Demand in the y-axis and the building depth in the x axis. [Source: the author]

On the matter of energy demand, on the opposite trend of daylight, the number of bars appears to have little impact on variations in energy use: 1 BAR E/W (40x10m) presents an energy requirement of 40.06 kWh/m², while the same dimension at 3 BAR E/W requires 40.61 kWh/m², only 1.4% higher than the first one. Therefore, energy use appears to be less sensitive to overshadowing and much more dependent on form factor (or compactness).

Even though the 10m depth was the best case for daylighting, it also presents the worst case for energy demand. The step to increase energy demand is again more effective from the 40m to 70m length, while from 70m up the energy demand ranges on about the same number. Some attention could be dragged to the cases of 4 BARS N/S with 10m depth, 3 BAR N/S with 15m depth, 2 BARS N/S with

20m depth and 2 BARS N/S with 25m depth, that do not present clearly the above-mentioned trend in the increase of the step but apparently only have a significant increase when they reach 100m length.

Another important aspect seen in the previous graph is the effect of orientation. It does not have a large impact on indicators, as the chosen daylight metric (Daylight Factor) does not consider orientation, climate or location. The differences between N/S and E/W will be more visible further in the analysis when the metrics are changed to sDA, a climate-based analysis that does consider the orientation. Besides that, it is visible that East / West bars oriented present a lower energy use as compared to North / South. Such difference decreases with more buildings on the plot— that is, the effect of orientation is mitigated by overshadowing.

Going back to daylighting aspects, it can be noticed that the floor depth has a larger impact on DF with fewer bars. For instance, let's look at the following two cases:

Table 11: Comparison between changes in floor depth for the 1 BAR E/W cases with length of 100m.

	BAR N/S	Energy demand [kWh/m²]	Daylighting [%]	Solar potential [kWh]
1 BAR	20x100	27.16	**1.64 2.16**	7.22 .10⁶
	10x100	39.33	**2.92 3.87**	8.85 .10⁶
2 BARS	20x100	27.66	**1.45 2.01**	9.17 .10⁶
	10x100	39.37	**2.36 3.40**	9.39 .10⁶
3 BARS	20x100	27.90	**1.34 1.93**	11.9 .10⁶
	10x100	39.55	**2.04 3.13**	10.3 .10⁶

[Source: the author]

For the dimensions above, the cases with 1 BAR present an 80% increase in the DF percentage just by changing 20m depth to 10m. For the 2 BARS, the daylighting increase is 70%. And for the 3 BARS, it drops to 62%. That means that with an increasing number of buildings on the same plot, reducing floor plates has a decreasing (or comparatively smaller) benefit on daylight availability. In short, buildings closer to each other reduce the amount of available daylight because of overshadowing, so that less daylight reaches each building in the first place, reducing the potential benefit of a shallow plate.

This confirms a long-held belief that overshadowing is of primary importance as compared to building footprint; that is: decisions taken at the urban scale in terms of aspect ratio may compromise any subsequent decision taken by the architect at the building scale. Solar radiation that has been compromised by adjacent buildings cannot be recaptured at the building scale— at least not by designing an appropriate footprint alone.

Crossing over energy demand and daylighting conclusions, looking again at Figure 37, it appears that decreasing floor depth, gains in DF decrease with the number of buildings, while the increase in energy use remains constant. That confirms that a shallow floor plate is worthwhile only with fewer (that is, further apart) buildings.

As it was done on the study on TOWERS, it was decided to take a horizontal and a vertical section to see more in detail the behaviour for the same energy requirement at the first, and the same daylight factor percentage, at the latter.

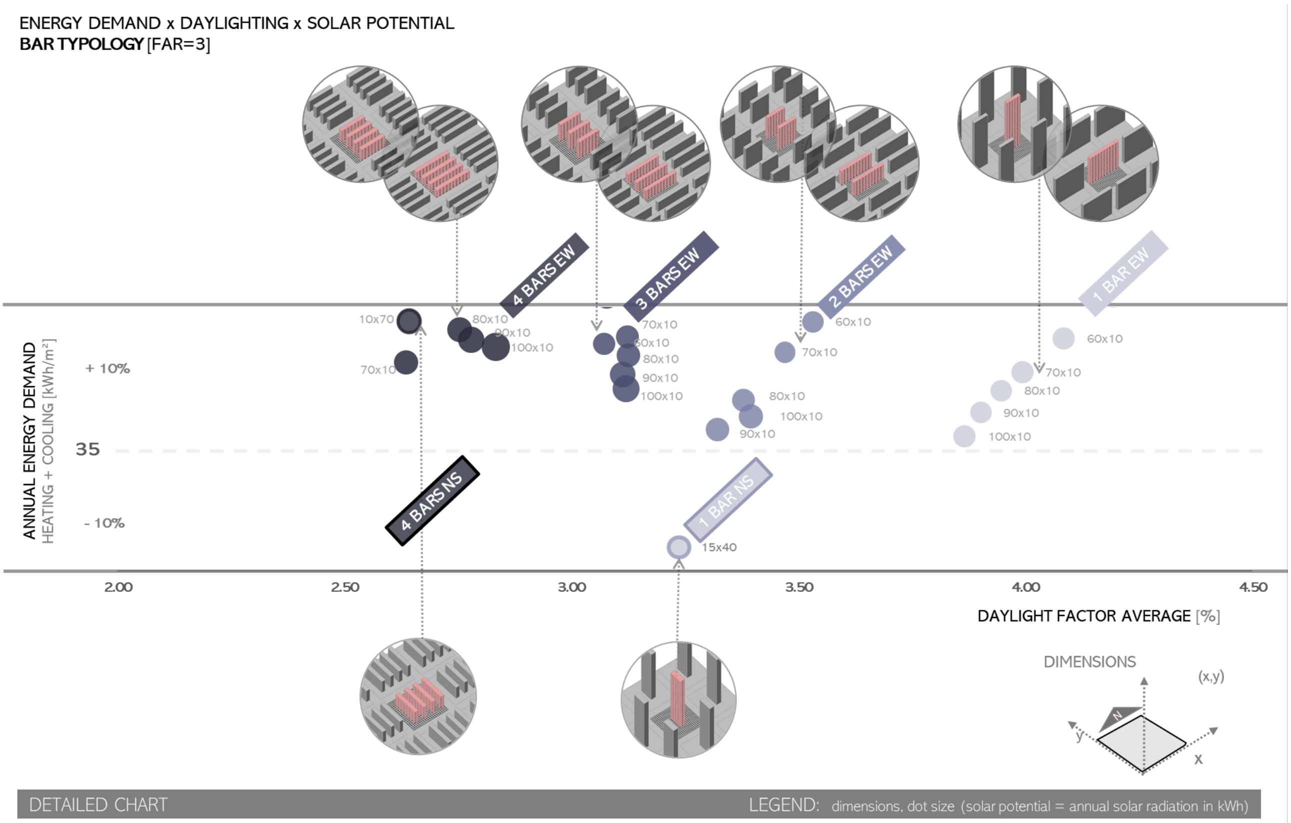


Figure 40: Horizontal detailed graph for BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

The cases that appear in the range of 35 kWh/m² (10% more or less) are the cases with a depth of 10m and the dimensions going from 60 to 100m. For the cases with 1 and 2 towers, there is a diagonal trend of increasing the plan floor area, decreasing the DF and the energy demand, as was mentioned earlier. For the cases with 3 bars, the trend line is not anymore diagonal but vertical, meaning that the effect of increasing the plan floor area from 60 to 100 meters will produce the same daylight conditions, with only the energy demand decreasing - this is in line as well with the overall behaviour mentioned before. For the cases with 4 bars, they behave pretty similarly both in DF and energy demand, meaning that the limitation of solar exposure of the façades caused by the number of buildings represents a steady performance no matter the plan floor dimension or orientation.

Now, in Figure 41, it is possible to analyse the vertical section, showing the cases with different energy demand for 3.25 Daylight Factor average (10% more or less). In this case, it is visible that the best performing is the 1 BAR cases (EW performing slightly better when compared to NS) with the 15m depth. It should be noted that these cases have more floors than the other with more buildings on the plot area.

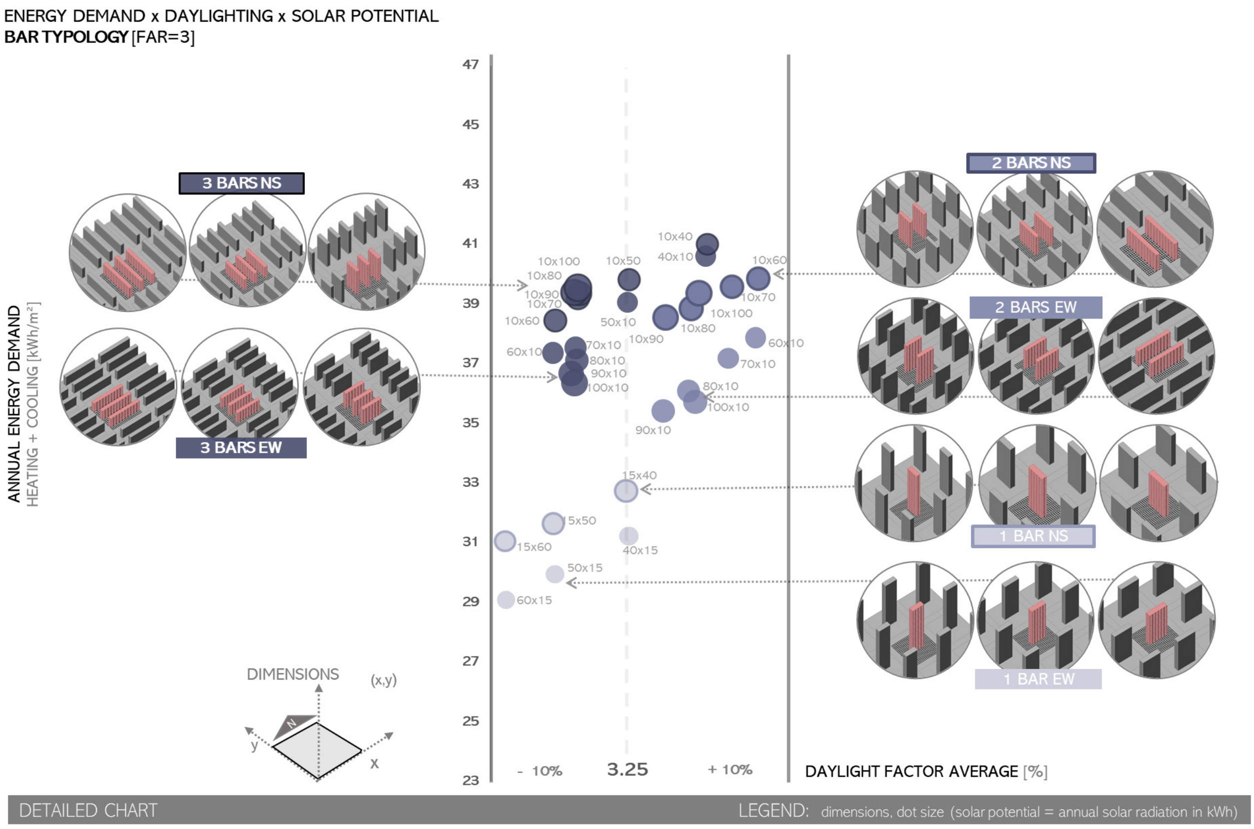


Figure 41: Vertical detailed graph for BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

Furthermore, if a trend line is drawn on the 1 BAR EW cases and on the 2 BARS EW, it can be roughly approximated that the energy demand variation amongst the different dimensions shown in this graph is about 10% from the top right of the diagonal to the bottom left of the imaginary trend line. The most energy demand cases here, the 3 BAR NS cases show a value of around 40 kWh/m², while the more efficient ones, 1 BAR EW, are ranging around 30 kWh/m², representing an increase of 35% in energy demand while presenting the same daylight performance. Only with that information, the designer can use massing for significant energy savings.

That being said, some attention should be drawn to the third metric that was not deeply discussed for the cases of bars so far. To illustrate the performance, the same overall graph was made, with all the bar cases, but changing the X-axis from Daylight Factor (that now is visible on the dot size) to Solar Potential.

Because the behaviours are not linear nor present a clear uniform trend, for the sake of clarity the cases were divided into East / West cases (Figure 42) and North / South (Figure 43).

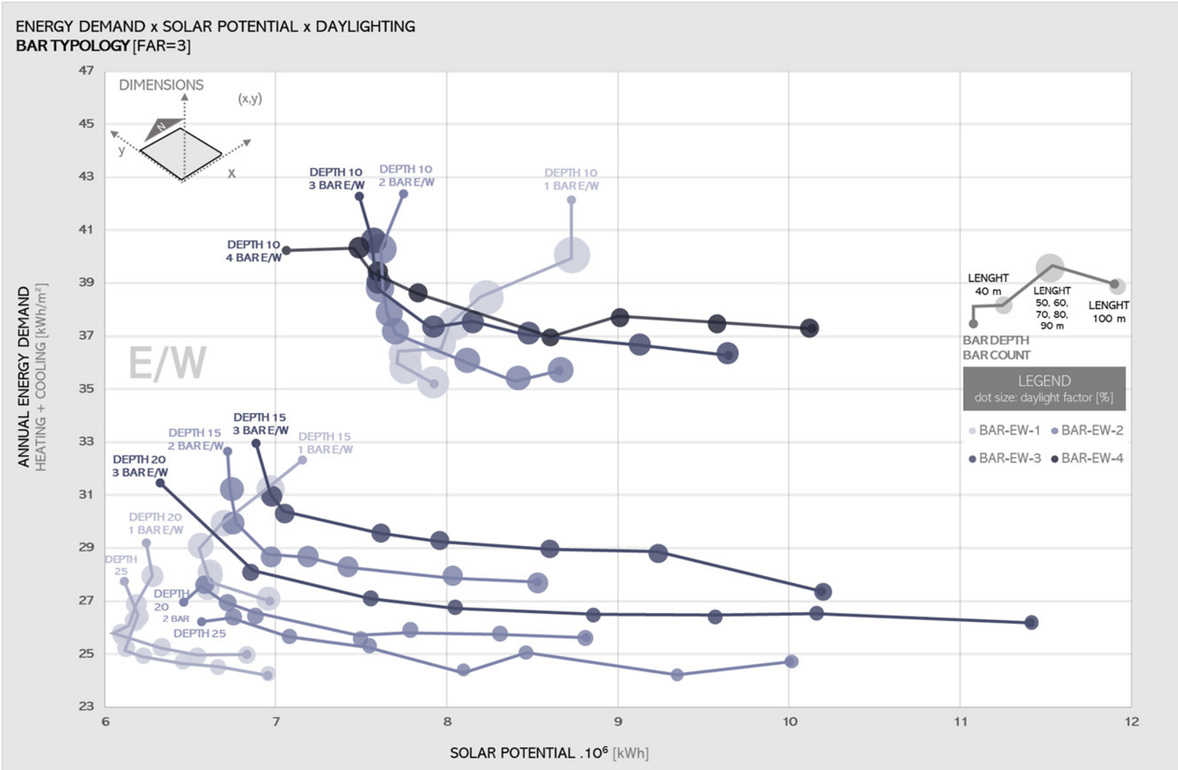


Figure 42: Overall scenario for BAR E/W typology in terms of Solar Potential (x), Annual energy demand for heating and cooling (y) and Daylighting (dot size). [Source: the author]

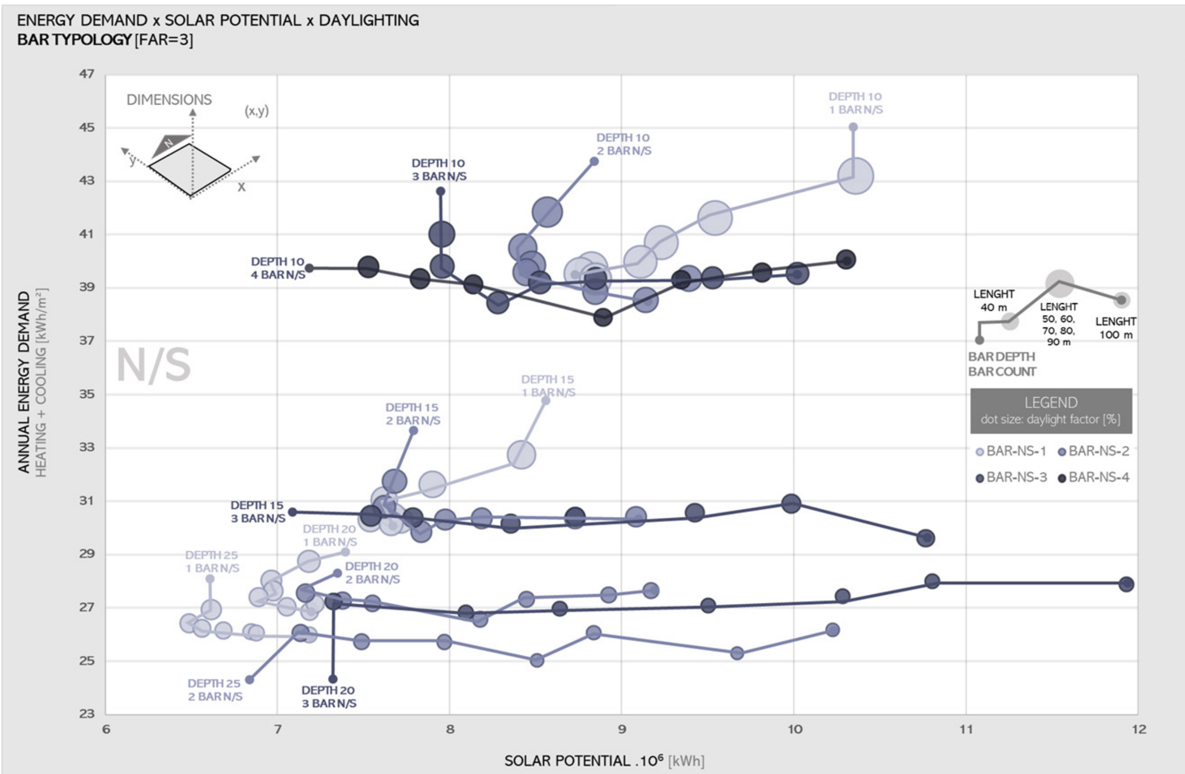


Figure 43: Overall scenario for BAR N/S typology in terms of Solar Potential (x), Annual energy demand for heating and cooling (y) and Daylighting (dot size). [Source: the author]

The predictable part is that slender and taller buildings have a good solar potential combined with good daylighting conditions, as the 10m cases on the top of the graph shows. However, the roof areas do play an important role in solar capture, therefore big plan floors with more buildings on the plot also present great solar potential. As a matter of fact, a "best case" could be highlighted in the solar potential graphs: the dot far on the right represents in both graphs the case of 3 BARS (E/W or N/S) in the 100x20m dimensions - and it has a quite low energy requirement for a high energy potential. However, its daylight factor is 1.93% (for both E/W and N/S), a value that is outside of the acceptable range. This case, in particular, is shown in Figure 44 in order to see that the low average of DF is probably due to the proximity of the buildings as well as its deep plan floor that goes in the opposite direction of the passive zones concept.

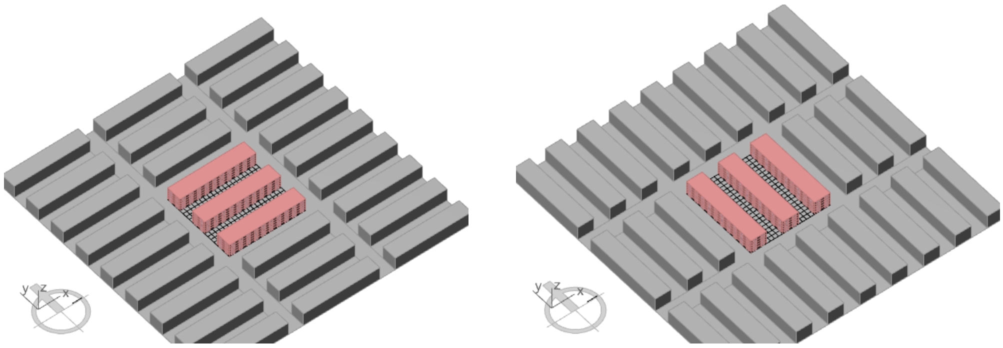


Figure 44: 3 BARS E/W on the left and N/S on the right, both in100x20m dimensions. [Source: the author]

As it's quite visible, it's hard to identify a logical trend, therefore some study was made on how the solar potential increases according to the number of bars and orientation. Orientation has a considerable effect on solar potential, with higher values for bars with the long axis oriented facing North and South This differential gets reduced by increasing the number of buildings, perhaps because the roof, less susceptible to overshadow, becomes the main source of solar potential in both orientations.

Table 12: Comparison between changes in solar potential because of orientation.

Solar potential [kWh]	1 BAR E/W	1 BAR N/S	Increase [%]
40x15	$6.97 .10^6$	$8.42 .10^6$	21%
50x15	$6.70 .10^6$	$7.90 .10^6$	18%
60x15	$6.56 .10^6$	$7.62 .10^6$	16%
70x15	$6.61 .10^6$	$7.72 .10^6$	17%
80x15	$6.62 .10^6$	$7.67 .10^6$	16%
90x15	$6.60 .10^6$	$7.54 .10^6$	14%
100x15	$6.96 .10^6$	$7.66 .10^6$	10%

[Source: the author]

Table 13: Comparison between changes in solar potential because of orientation.

Solar potential [kWh]	3 BAR E/W	3 BAR N/S	Increase [%]
40x15	$6.98 .10^6$	$7.54 .10^6$	8%
50x15	$7.05 .10^6$	$7.79 .10^6$	10%
60x15	$7.62 .10^6$	$8.35 .10^6$	9.5%
70x15	$7.96 .10^6$	$8.73 .10^6$	10%
80x15	$8.60 .10^6$	$9.42 .10^6$	9.5%
90x15	$9.24 .10^6$	$9.99 .10^6$	8%
100x15	$10.2 .10^6$	$10.8 .10^6$	6%

[Source: the author]

In Table 12 and Table 13 a comparison allows us to see what happens with the step of increasing the length of the building in both orientations and if the trend is the same when increasing the number of bars. In the first table, the comparison is with only one bar, and that proves the already stated fact that bars oriented along N/S receive more solar radiation than the same cases in E/W orientation. It can also be seen that the improvement is higher for shorter buildings (which are taller by consequence) than for the very long ones. On the second table, the same dimensions are analysed but with 3 bars. Still in this case the N/S performs better, but the increase is a lot lower than for the 1 BAR cases. It's interesting to see the trend of the increase in both tables as well. In the first table, the increase is high in the 40m length case, and it gradually decreases until the 100m length case that has the smallest difference between E/W and N/S. For the 3 BARS cases, it could almost make a parabola if looking at the increase in the numbers. The extreme cases, the shortest (40m) and the longest (100m) are the ones where E/W and N/S are more similar, with a low increase in solar potential from one to another, and the peak of increase happens on the 70m length case, with 10% difference.

This comparison from E/W to N/S can be made also in the trend lines extracted from the solar potential graphs shown previously. It is visible that there is not one rule for all the cases, but the line with the same depth and different orientation is always shifted to greater solar potential and also a higher energy demand. In Figure 45, the dashed lines represent the E/W cases while the continuous lines represent the N/S cases.

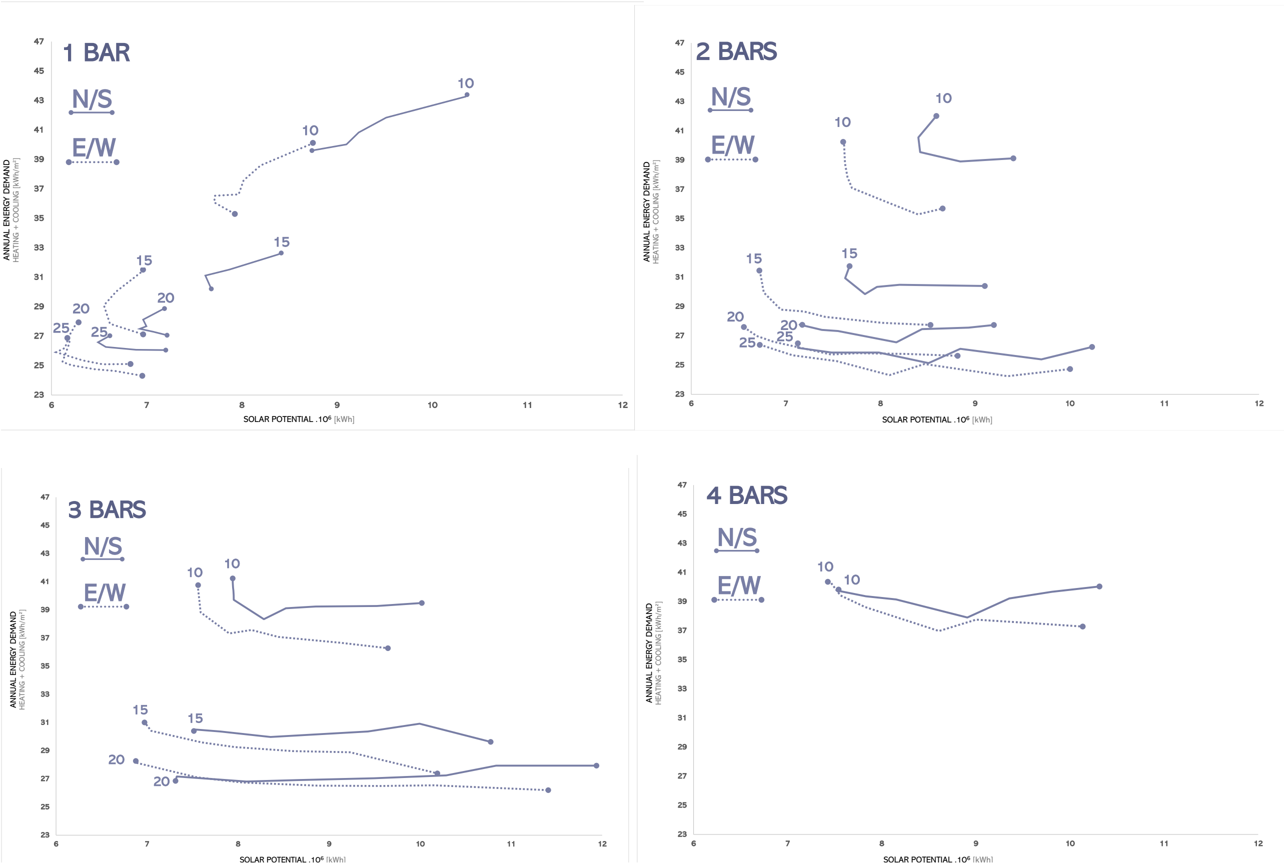


Figure 45: Trend lines extracted from the solar potential graphs to compare the behaviour between E/W and N/S, separated by number of bars.[Source: the author]

After having compared the number of buildings with the same floor depth, an interesting approach is to compare the same amount of buildings but different depths, as in Table 14:

Table 14: Comparison between changes in solar potential because of orientation.

1 bar N/S	Solar potential [kWh]	Number of floors	Increase [%]
10x40	$10.4 .10^6$	75	23,5%
15x40	$8.42 .10^6$	50	17%
20x40	$7.18 .10^6$	38	9%
25x40	$6.61 .10^6$	30	-
10x100	$8.85 .10^6$	30	15.5%
15x100	$7.66 .10^6$	20	6%
20x100	$7.22 .10^6$	15	0.5%
25x100	$7.18 .10^6$	12	-

[Source: the author]

From 1 BAR N/S 25x40 to 1 BAR N/S 10x40, there is a 57% increase in solar potential. From 1 BAR N/S 25x100 to 1 BAR N/S 10x100, there is 23% increase in solar potential. From that it can be noted that the slimmer the building, the less compact it is and therefore will have more envelope area, presenting higher solar potential.

Moreover, the number of buildings have a large impact on the solar potential for both orientations. The range is smaller for deeper buildings since the total envelope area is generally smaller. The trend of solar potential increasing with the number of buildings happens due to the increase in the roof area.

1.3. TYPOLOGIES COMPARISON

After having looked at each typology in detail and having understood within each building type what are the factors that make the most impact on the performance indicators, it is time now to compare all the three typologies among each other and understand if this definition can indeed result in a better energy and daylight performance. The outputs can be seen in Figure 46:

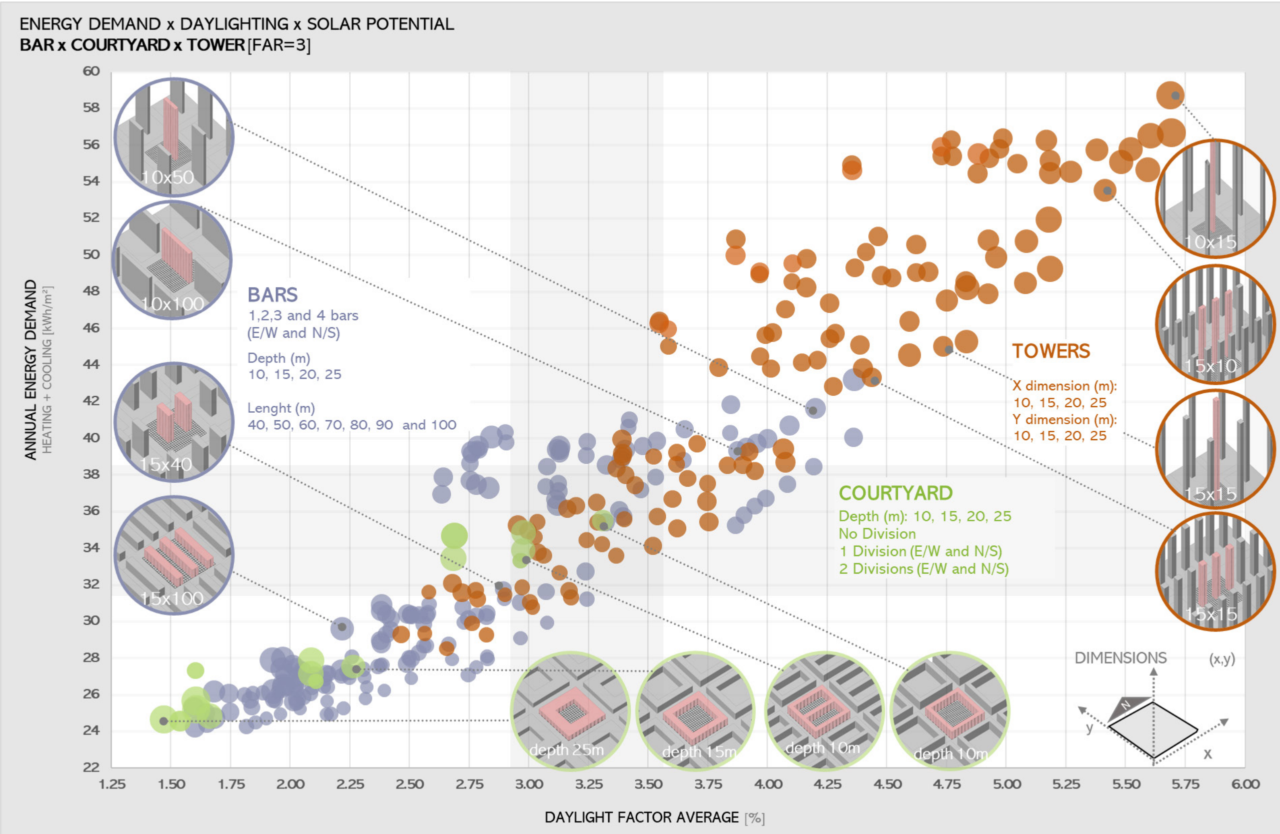


Figure 46: Overall scenario for TOWER, COURTYARD and BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

For this comparison, all the cases for each typology are assigned the same colour in order to compare only one typology to another. The dots in orange represent the tower cases, the green ones represent the courtyard cases and the purple dots represent the bar cases. At the first look, it is visible that towers present the highest energy demand as well as the highest Daylight Factor Average percentage, as the building cases become more slender and taller. As we have seen previously, the best cases for daylight are the ones with the fewer number of towers, which are the taller ones, and that is probably is the reason for DF to be higher.

Bars present lower energy consumption as they have fewer floors and become longer, following the same trend as the towers. Moreover, the DF improves as the count of bars decrease, probably for the same reason as before, because the unique bar cases are the tallest ones - not as tall as the towers, though.

Courtyards present a low height due to the extensive plan floor area, and their energy demand is low. Depths of 10 and 15m seem to be the best performing in terms of daylighting. When compared to towers and bars, courtyards have the best (lowest) ratio energy use / Daylight Factor. On the other hand, there appear to be a “ceiling” for daylight values that are lower than for the best performing towers.

Therefore, towers seem to demand more energy than courtyard and bars, while presenting the highest DF values. Courtyards seem to be a good compromise between towers and bars, due to the low energy demand and some acceptable values of DF. Because with courtyards it is possible to achieve a large plan floor in which, with a few floors, the FAR of 3 is reached. This allows for slender buildings (favouring DF) and low rise (favouring energy demand).

In order to analyse the graph in Figure 46 more closely, the same approach as before was applied, by taking a horizontal section at the energy demand of 35 kWh/m² (with a tolerance of 10% for more and less) and a vertical section at a Daylight Factor average of 3.25% (with a tolerance of 10% for more and less). These two sections are highlighted in the overall graph with grey rectangles.

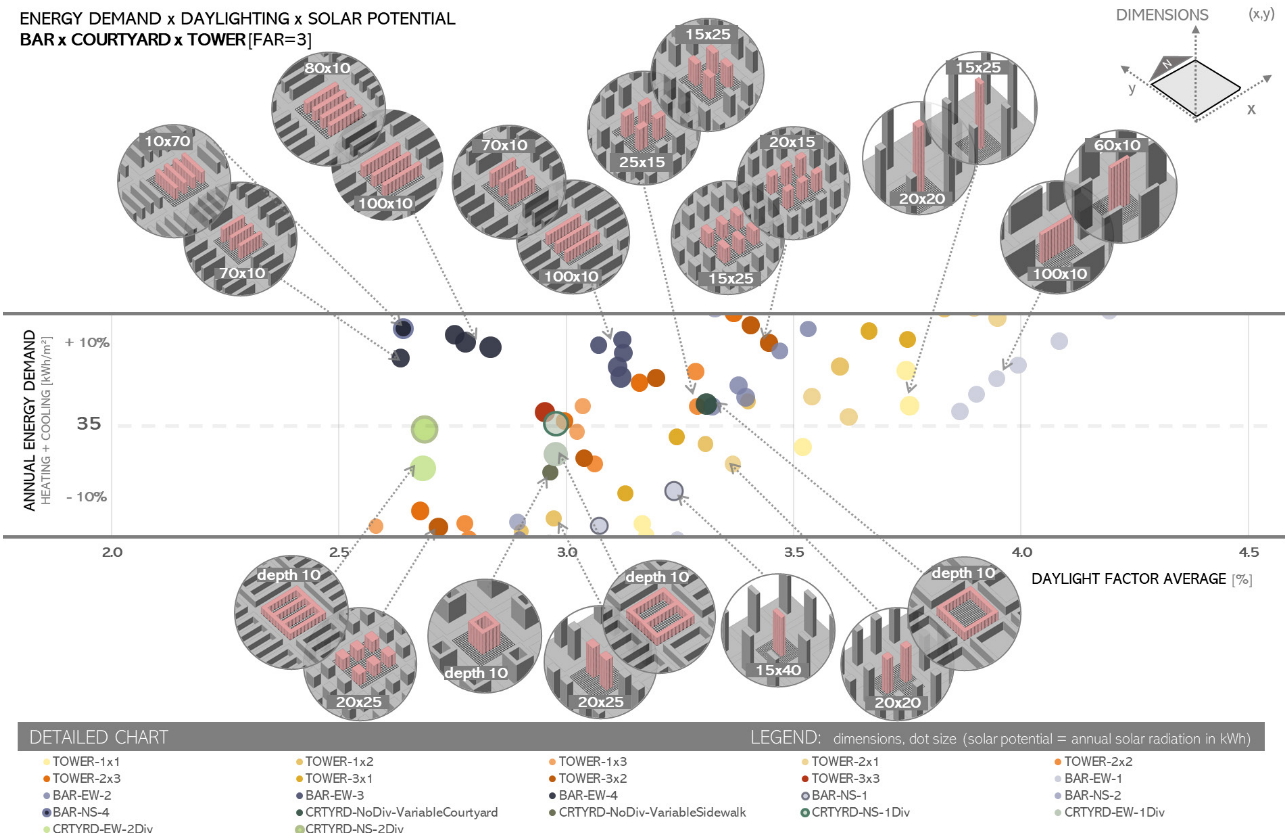


Figure 47: Horizontal detailed graph for TOWER, COURTYARD and BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

For the first section, where the energy demand is the same for all shown cases in Figure 47, the three typologies have cases that present this 35 kWh/m² of energy demand. The bars within this chosen range are mainly the ones with a depth of 10 m and lengths going from 60 to 100m, which means that at this depth, the length stops making a lot of difference in terms of energy demand. Moreover, it can be observed that the aspect ratio (bar count) has little effect on energy demand at this threshold, giving that in this graph are present cases with 1, 2, 3 and 4 Bars. It has, however, an effect in terms of improving daylight. One bar cases have double the floors that the Two bar cases and the DF increases around 20%.

Regarding the towers, there is a slight increase in the energy demand every time that the X dimension is smaller than the Y, when comparing for example 15x25 to 25x15. This means that when the side facing north and south is larger than the sides facing east and west, there is a decrease in the overall heating and cooling demand. Moreover, the squared cases of the towers have a lower energy demand when comparing to the cases with different dimensions in X and Y, but they do sometimes present a decrease in the daylight metric.

Courtyard cases within the selected range are all 10 m of depth, as happened with the bars. The cases with 1 and 2 divisions present an energy requirement increase when the long axis of the building is oriented along N/S. As expected, they do behave similarly in terms of DF. Nevertheless, when comparing the cases with no intermediate divisions, it is noticeable that the case with variable courtyard (in this case a very large inner patio) behaves much better in terms of daylight. A significant difference in energy demand and DF is seen between the case of the courtyard with no divisions with a variable street width (fixed inner patio dimension): in this case, it needs to have more floors to achieve the FAR of 3, and therefore it increases the overshadowing effect and it "loses" to the low rise cases.

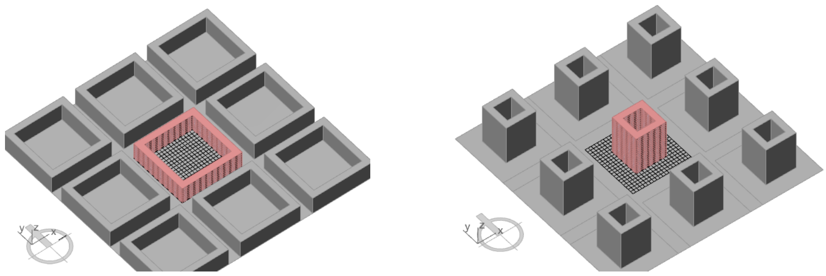


Figure 48: View of two 10m depth courtyard cases: "No division - variable courtyard" on the left image, and the case with "No division - variable sidewalk" on the right. [Source: the author]

Among those cases shown on the detailed chart, as a sampling of the overall scenario, we can see that the courtyards behave well both in terms of daylight and energy demand. As it is visible from the dot size, it also presents a high solar potential. In the cases of towers, the increase in depth (and therefore the decrease of height) results in a decrease in energy demand and in DF. The bar cases show that the length increasing (and therefore height decreasing) for 1 Bar count and 2 Bar count, means as well a lower energy demand and a lower DF than the cases of 60 or 70 meters long, for example. In the 3 and 4 bar count, this trend is attenuated and DF remains practically the same for all the cases from 60 to 100m.

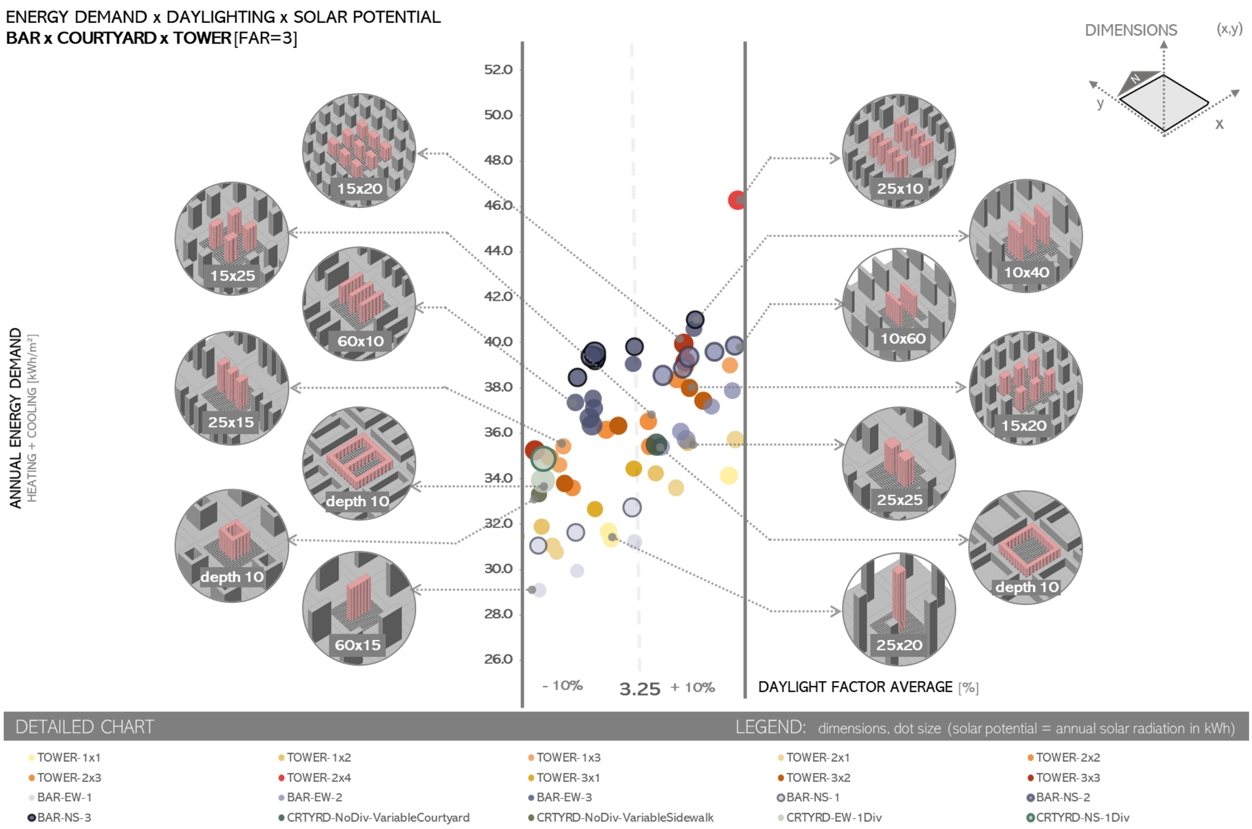


Figure 49: Vertical detailed graph for TOWER, COURTYARD and BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

In Figure 49, from the vertical section of the overall graph, it can be seen that all the bar distribution cases are appearing with exception of 4 BAR (both E/W and N/S). For 1 BAR count, the depth 15m are the cases shown in this section, with the other dimension being 40, 50 and 60 meters. For the 2 BAR and 3 BAR cases, the depth appearing here is 10m, with all the dimensions for the length of the bars close together. This means that for the cases with a higher aspect ratio, DF percentage is very similar (visible from the dots accumulated altogether), with more variation happening on the energy demand. For the 1 BAR cases, the dots are further apart, which means a small difference in DF when increasing the length of the bar.

As for the towers, the cases that present higher energy demand are the cases with high tower count (4x2, 3x3, 2x3, 3x2). As the red/orange dots start to go down, meaning decreasing energy requirement, it can be seen an increase of the plan floor and a decrease in the tower count, until the very lightest yellow dots that represent 1x1 tower, on the dimensions 20x20, 20x25, and 25x20, that are performing way better than the 12 or 9 towers cases with 15x20 or 25x10 previously mentioned. The case with 1 very tall building with a deep plan floor will present the same Daylight Factor as cases with 6 or more towers but with a difference of around 12 kWh/m².

Last, but not least, some attention should be drawn to the courtyard cases shown here. Only the depth of 10m appears in this section, with the DF values going from 3 to 3.25%. It can be seen that the case with No Division_Variable Sidewalk, has the lowest energy demand (around 33 kWh/m²) and the No Division_Variable Inner Patio the highest energy demand (around 35 kWh/m²) amongst the courtyard cases. Besides that, they are all lower in terms of height than the other cases, which can be an interesting advantage when designing a building. Other than that, Solar Potential is higher than the other cases, as it can be seen from the dot sizes and it's further investigated in the following Figure:

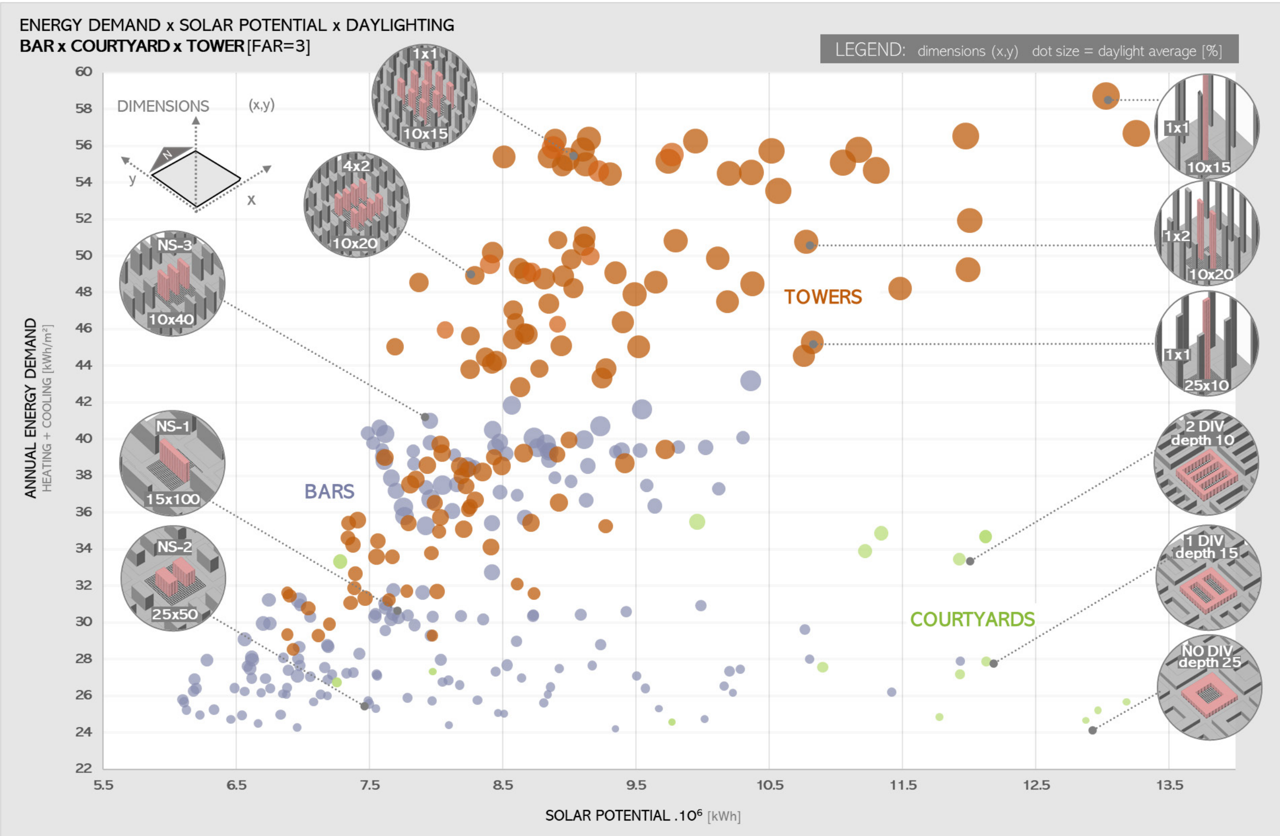


Figure 50: Overall scenario for TOWER, COURTYARD and BAR typology in terms of Solar Potential (x), Annual energy demand for heating and cooling (y) and Daylight Factor average (dot size). [Source: the author]

Courtyards are clearly best performing, with high Solar Potential and low energy demand. However, they are performing well because of the amount of roof available, which is more than in the other cases, especially in the 25m depth cases. Towers also present a high Solar Potential, but, on the contrary of courtyards, because they are tall buildings with a great envelope area exposed to solar radiation. Bars seem to have a lower Solar Potential, and this is probably because in the cases with more than one building the shadow that is cast on the others might get in the way of sunlight.

Further investigation was done to understand the best performing cases of all the typologies, and also the worst performing. Aligned with the previous graph, in Figure 51 it is demonstrated the worst eight cases among all considering the solar radiation study. It is visible that is the case with 1 BAR facing EW (mainly) and with depths varying between 20 and 25 meters.

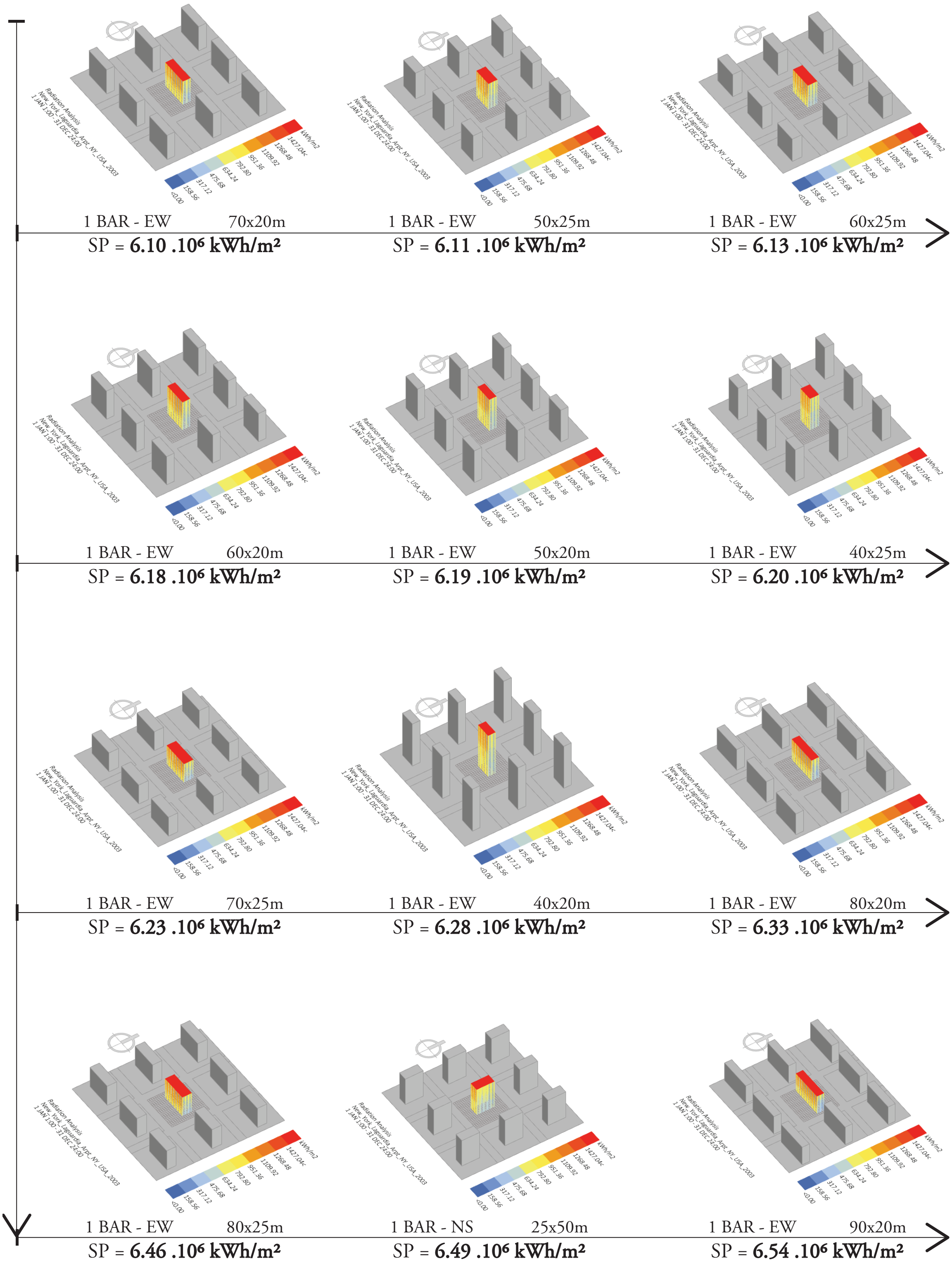


Figure 51: The eight cases that are worst performing in terms of Solar Potential, or, in other words, availability to useful solar radiation. [Source: the author]

These results were quite intriguing, as it seemed the depth of 15m was performing in a better way when speaking of solar radiation than the deeper buildings. At first, the assumption was that the more roof area, the more useful solar radiation as the horizontal surface is optimum for that. However, for the case of EW-1 bars, the height makes a great difference in the result of the south façade area, as can be seen in the following table:

Table 15: Comparison between the BAR EW - 1 cases, that are the worst performing in regards of Solar Potential to understand the parameter that causes this effect.

BAR EW - 1	Length	Depth	Solar Pot.	Number of floors	Area south façade (m^2)	Area roof (m^2)
BAR-EW-1-40x15	40	15	$6.97 .10^6$	50	7,000	600
BAR-EW-1-50x15	50	15	$6.70 .10^6$	40	7,000	750
BAR-EW-1-60x15	60	15	$6.56 .10^6$	33	7,000	900
BAR-EW-1-70x15	70	15	$6.61 .10^6$	28.	7,000	1,050
BAR-EW-1-80x15	80	15	$6.62 .10^6$	25	7,000	1,200
BAR-EW-1-90x15	90	15	$6.60 .10^6$	22	7,000	1,350
BAR-EW-1-100x15	100	15	$6.96 .10^6$	20	7,000	1,500
BAR-EW-1-40x20	40	20	$6.28 .10^6$	37.5	5,250	800
BAR-EW-1-50x20	50	20	$6.19 .10^6$	30	5,250	1,000
BAR-EW-1-60x20	60	20	$6.18 .10^6$	25	5,250	1,200
BAR-EW-1-70x20	70	20	$6.10 .10^6$	21	5,250	1,400
BAR-EW-1-80x20	80	20	$6.33 .10^6$	19	5,250	1,600
BAR-EW-1-90x20	90	20	$6.54 .10^6$	16	5,250	1,800
BAR-EW-1-100x20	100	20	$6.83 .10^6$	15	5,250	2,000
BAR-EW-1-40x25	40	25	$6.20 .10^6$	30	4,200	1,000
BAR-EW-1-50x25	50	25	$6.11 .10^6$	24	4,200	1,250
BAR-EW-1-60x25	60	25	$6.13 .10^6$	20	4,200	1,500
BAR-EW-1-70x25	70	25	$6.23 .10^6$	17	4,200	1,750
BAR-EW-1-80x25	80	25	$6.46 .10^6$	15	4,200	2,000
BAR-EW-1-90x25	90	25	$6.66 .10^6$	13	4,200	2,250
BAR-EW-1-100x25	100	25	$6.96 .10^6$	12	4,200	2,500

[Source: the author]

The dark highlighted cases are the best among the 1 - BAR EW. It can be noted that 40x15 is the best, even though it has only 600 m^2 of roof area. This happens because of the small plan floor area, to reach FAR = 3 it needs 50 floors. Which results in a south area of 7,000 m^2 that is compensating for the lack of roof area. The opposite case happens in 100x25, which performs great as well, but the roof area is accounting for more solar radiation than the envelope area.

On the other hand, the light highlighted cases are one of the worst and it is useful to compare the same length (60m) but different depths (15, 20, 25m). With 15m, the building requires 33 floors, which results in a considerable façade area. When it moves for 20m depth, the solar potential decreases around 6%, even though the roof area increases. This proves that the envelope area can be quite important for the best use of solar radiation.

Having discussed the worst cases for Solar Potential, it is worth to taking a look at the best performing, in Figure 52. It shows the confirmation of a first assumption and a clear output that either the roof plays a great role in solar capture, and then the building has quite a low height like in the cases of 3 BARS or COURTYARDS, or the envelope plays the main role but this requires a great area of envelope without any obstructions around it, like in the cases of 1 TOWER. The great height also works towards the use of solar radiation.

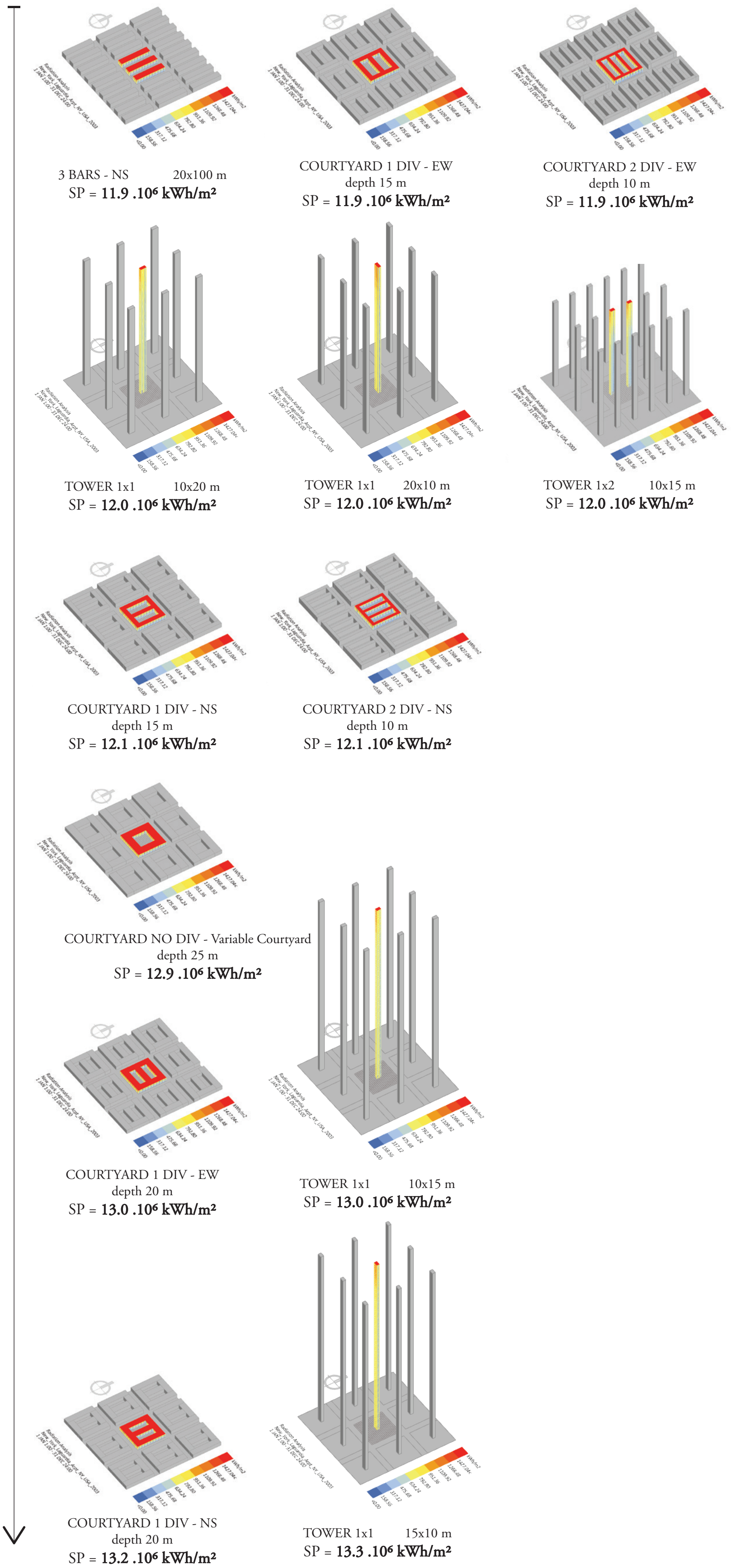


Figure 52: Thirteen cases among all the studied typologies and cases that are best performing in terms of Solar Potential. [Source: the author]

CHAPTER 02.

The Champions

2.1. INTRODUCTION

Having all the 312 cases among towers, courtyards and bars evaluated and analysed in Chapter 01, this Chapter is focused on understanding which is the best performing cases still considering the three main performance indicators: Energy Demand, Daylighting (measured as Daylight Factor in Chapter 01) and Solar Potential (measured as solar radiation falling on the envelope in Chapter 01). Understanding the best cases, it is now possible to simulate more detailed metrics and offset energy demand and production to understand if the behaviour is in fact beneficial. For example, it is not useful to produce a great amount of solar energy if the building also presents a great cooling and heating requirement. The best compromise is sought here and for that, some further assumptions must be taken.

As a reminder, the cases remain the same, located in New York - USA (La Guardia weather data file), still on the 100x100 m plot area, with a residential program and always keeping the same FAR = 3 and Glazing ratio = 0.3 in all orientations, to make sure all the results are comparable.

Following, the methodology and assumptions done to refine the values and select the cases are explained, as well as the outputs for the best performing cases, which are referred to here as "Champions". After going through the procedure and selecting them, further analysis will be performed with new energy and daylighting metrics, to see if the previous results are consistent with the new ones. Lighting electricity will play a significant role here, calculated in relationship with the daylight quality and not only on the occupants and floor area, which reflects on the energy required for artificial lighting and in the final electricity demand. Software utilized are basically the same, Rhinoceros and Grasshopper, but now DIVA will be introduced to perform these new simulations.

2.2. METHODOLOGY: PROCESSING THE DATA FROM CHAPTER 01

In order to select the best performing cases, some other parameters had to be set on the matters of Energy Demand, Daylighting and Solar Potential. Those parameters were used to post-process the data gathered from the simulations in Chapter 01 and are explained on the following topics:

2.2.1. ENERGY DEMAND

From the previous simulations, it was possible to understand the cooling and heating demand required to achieve indoor comfort. It was also possible to identify the potential for the use of solar radiation to cover this demand. Now, the aim is to offset the demand from the production to see the real electricity requirement. For that, some definition of building systems is required.

In order to be consistent with the reality and yet assuming we can reach good efficiency levels, the HVAC equipment chosen range between the values correspondent to the energy label **A+** , that is, they are not selected with extremely high efficiency (A++) but still presenting good values that are easily reachable in commercial systems.

The thermal requirement identified must be converted into electricity, and for that a heat pump system that can operate for heating, cooling and also provide domestic hot water is assumed, using as reference the Italian company "Vaillant" [39].

The largest temperature span is available when using outside air as a heat source, therefore this system consists of an air/water heat pump, which can operate in heating mode with external temperatures up to 20 degrees Celsius. The system also presents a very good acoustic performance, with noise levels around 32 dB(A).

To discover the required electrical energy to deliver the thermal energy previously identified, the air conditioning systems have specific terms to represent their efficiency. The terms COP (coefficient of performance) is used for heating systems and EER (energy efficiency ratio) for cooling systems efficiency. They indicate the ratio of heating or cooling provided by a unit relative to the amount of electrical input required to generate it. Thus, if an air conditioner generates 5 kW of heat from a 1 kW electrical input, its COP is said to be 5.0. Similarly, if an air conditioner generates 5kW of cooling from a 1kW electrical input its EER is also said to be 5.0. The higher the COP and EER, the more energy-efficient is the equipment.

$$\textbf{Efficiency} = \frac{\text{delivered thermal energy}}{\text{electrical power consumption}}$$

In the following Figure some of the ranges values are shown according to the energy efficiency class:

Classe di efficienza energetica	$EER_{nominale}$	$COP_{nominale}$
A+++	≥ 4,10	≥ 4,60
A++	3,60 ≤ EER < 4,10	4,10 ≤ COP < 4,60
A+	3,10 ≤ EER < 3,60	3,60 ≤ COP < 4,10
A	2,60 ≤ EER < 3,10	3,10 ≤ COP < 3,60
B	2,40 ≤ EER < 2,60	2,60 ≤ COP < 3,10
C	2,10 ≤ EER < 2,40	2,40 ≤ COP < 2,60
D	1,80 ≤ EER < 2,10	2,00 ≤ COP < 2,40
E	1,60 ≤ EER < 1,80	1,80 ≤ COP < 2,00
F	1,40 ≤ EER < 1,60	1,60 ≤ COP < 1,80
G	< 1,40	< 1,60

Figure 53: Energy efficiency class and nominal values for EER and COP according to the National Agency for New Technologies, Energy and Sustainable Economic Development, in Italy. [40]

Therefore, according to products from the company mentioned above, the values adopted are:

Table 16: Systems efficiency coefficients

System efficiency: Heating mode	
A2/W35 *Performance at the nominal working conditions of outside air at 2°C and outlet water temperature 35°C*	**COP* = 3.7** *(Ratio of the heating capacity to the effective power input of the unit)*
System efficiency: Cooling mode	
A35/W18 *Performance at the nominal working conditions of outside air at 35°C and outlet water temperature 18°C*	**EER* = 3.40** *(ratio of the total cooling capacity to the effective power input of the unit)*
System efficiency: Domestic Hot Water	
COP_{dhw} = 2.36 *According to BS EN 16147 with nominal cylinder temperature at 53 °C, on mode ECO, A7*	

[39] *data according to BS EN 14511-1:2018

Furthermore, some attention should be drawn to the consumption of Domestic Hot Water. It accounts for about 20% of the total primary energy-consumption by housing and it is used within a house for a variety of different purposes such as drinking, washing, laundry, and others.

Before discussing how to supply for the demand, it is important to understand how much it is needed. Therefore, the calculation of DHW is shown below, following the method from [31].

The daily energy-consumption can be calculated using the following equation:

$$E_{dhw} = \frac{C_p \cdot \rho \cdot V \cdot (T_{out} - T_{in})}{3600} \tag{1}$$

Where E_{dhw} is the domestic hot water load, in kWh/day; C_p the specific heat capacity of water (4.187 kJ/kg.K); ρ the density of water (1,000 kg/m³); and V the daily volume of hot water consumed for each component (m³/day); The calculation is shown in Table 17.

With the thermal load required for DHW in kWh, it is possible afterwards to subtract the production from the Solar Thermal Collectors. As explained in "Metrics" ("Solar potential (Energy production)" on page 42, the solar radiation falling on the envelope is divided according to a useful threshold either for the application of photovoltaic panels, that will produce electricity, or for the application of solar thermal collectors, that will supply for DHW. Therefore, after having calculated the demand here and understanding how much thermal energy the solar collectors will produce (which will be detailed in "2.2.3. Solar potential" on page 102), it is possible to understand if the full demand is covered, if there is an overproduction or if at least part of the demand is covered. This works both for the electricity demand coming from the heat pump for heating, cooling, lighting and equipment that will be covered (ideally) for the photovoltaic panels or for the DHW demand that will be covered (ideally) for the solar thermal collectors.

Table 17: Calculation for residential use of Domestic Hot Water

Appliance	DHW consumption [liters/pp.day]	Water temperature Outlet [°C]	Water temperature Inlet [°C]	Daily energy consumption E_{dhw} [kWh/pp.day]	Annual energy consumption for 857 occupants $E_{dhw - tot}$ [kWh]
Bath/shower	10.6	40	10	0.3699	127,281.8
Wash hand basin	15.8	35	10	0.4594	158,101.6
Dish washing	14.9	55	10	0.7798	268,372.5
Clothes washing	11.7	60	10	0.6804	234,150.5
				Total annual energy consumption [kWh]	**787,906.4**

Total area = 30,000 m^2 Occupancy = 1 person for each 35m^2

Total number of occupants = 857 pp.

[Source: the author]

2.2.2. DAYLIGHTING

As it was already mentioned in "1.1.2.3. Daylight parameters" on page 61, the metric used until now is the Daylight Factor. The acceptable range for this metric will be used here to filter the results and identify the cases that are in the comfort daylighting conditions.

The idea of this metric, abbreviated as DF, is to assume an outside illuminance of around 10,000 lux under and overcast sky, and then the minimum requirement for the room is an average of 500 lux, [23] which makes the 2% that composes the minimum threshold for the acceptable DF value. The higher the DF, the more natural light is available in the room, however, a maximum acceptable value is defined as 5%, composing the comfort range of good DF levels from 2% to 5%.

With the average percentage of Daylight Factor, it is possible to have an idea of the daylight conditions indoors. Filtering the cases with DF > 2%, along with the other filters, it will be possible to gather the best performing cases and then apply a dynamic climate-based simulation to have a more accurate daylighting scenario of the case studies.

2.2.3. SOLAR POTENTIAL

From the previous simulations, it was possible to identify the potential solar production both for electricity and hot water demand, by understanding how much solar radiation would be captured by the building surface over the course of a year. By post-processing this information, the procedure now is to assume that active technologies can be used both in the roof area but also on the envelope area, given that the integration of Photovoltaic (PV) technologies in buildings is a solar active strategy aligned with the current international sustainability and renewable energy criteria for buildings [18]. When placed on the envelope, the system for PV is called "Building-integrated Photovoltaics (BIPV)", and, even though they usually are placed oriented or tilted for better performance, for the sake of comparison and because tilting is not always possible, at this research they are assumed to be in parallel with the envelope area, where the data is generated from the solar radiation falling on the envelope surface. Leaving just the other factors, such as urban context, form and function of the building [18] as responsible for the outputs.

In [17] the method to calculate the active solar systems production is based on the metric built upon the results from the external solar e and geometry-based evaluation, by making use of the surfaces, simulated as a series of evaluation points or nodes, adequate for each system, based on the threshold values for PV application and for ST application. The method was adapted for the climate and case studies of this research, where the threshold followed to assign the areas for PV panels and ST collector are the following:

> *Threshold on solar radiation falling on the envelope:*
>
> *- Surfaces that receive 200 to 400 kWh/m² over the year receive solar thermal collectors;*
>
> *- Surfaces that receive more than 400 kWh/m² over the year receive photovoltaic panel;*

This parameter rule is written inside the Grasshopper script and the solar radiation simulation already divides the envelope mesh according to the system that will be applied. With these two separate yearly data, in kWh, the next and final step to find the energy production is to assign system efficiencies for the PV panels to convert solar radiation into electricity and for the ST collectors to convert solar radiation in DHW. The values selected for efficiency are the same ones as in [17], due to the fact that they are widely accepted over the market, and easily reachable in commercial systems, that are the following:

> *PV system efficiency: 0.15*
>
> *ST system efficiency: 0.7*

2.2.4. SELECTING THE CHAMPIONS

Having applied all the new assumptions that the previous topics have discussed, it is now possible to filter and discover the champions. Firstly, energy demand is offset by energy production. More specifically, the energy generated from the Solar Thermal Collectors and the electricity generated from the Photovoltaic Panels is calculated using the assigned efficiencies. Then, heating and cooling thermal loads are identified and converted in the electricity required to deliver the energy to reach thermal comfort indoors, applying each system's COP and EER, respectively. Those two electricity values are added to the artificial lighting requirement, at this point calculated based on occupancy only, and the appliances electricity demand.

Parallel to that, Domestic Hot Water demand is calculated and the ST energy production is deducted from the demand. Some of the cases present 100% or even more coverage of the demand and some do not produce enough to cover all this need. For the latter, the amount of DHW coverage left is converted in electricity to be used by the heat pump using the COP_{dhw} as efficiency. This value is then added to the previously calculated electricity demand, resulting in the total electricity need. From that, the PV production is offset. None of the building cases is energy auto-sufficient. An interesting observation is about the cases with the best percentage of energy demand covered by renewables. The maximum coverage reached is 90.24 % (Courtyard - NS - 1 Div - Depth 20m), followed by 88.86 % (Courtyard - EW - 1 Div - Depth 20m), and 87.70% (Courtyard - No Div - Variable Courtyard - Depth 25m). Those three cases are the best in energy coverage, however, they perform poorly in terms of Daylight Factor (1.47%, 1.61% and 1.61% respectively) and therefore are not selected as Champions. The best performing case after those, however, results to be a Champion. The case of "Courtyard NS - 1 Div - Depth 15m" covers 83.21% of the energy demand with renewables, and presents a DF of 2.09%.

As it can be seen, Daylight Factor is also assessed to define the Champions, where the acceptable cases are the ones with DF higher than 2%. Therefore, to finally say a case study is considered a champion, some questions are asked and, if the case's results are in accordance, it is selected as one of the best cases. A building is declared a champion if:

- It covers at least 50% of the electricity demand with Photovoltaic Panels.

- It covers at least 50% of the DHW demand with Solar Thermal Collectors.

- The Daylight Factor is above 2%, and

- The final electricity requirement (after offsetting from the PV production) that will have to be supplied by the grid is less than 25 kWh/m^2.

All of this process of selection and decision making is shown also in Figure 54. It should also be noted that the first two requirements, reaching 50% of demand covered by renewable energy, is based on the Italian normative (Decree n.28/2011) that deals with the Implementation of Directive 2009/28 / EC on the promotion of the use of energy from renewable sources. In Article 11, it is asked for projects of new buildings and major renovation projects of existing buildings to provide or the use of renewable sources to cover the consumption of heat, electricity and for cooling, according to the following:

> *" In the case of new buildings or buildings undergoing major renovations, the thermal energy production plants must be designed and built in such a way as to ensure simultaneous compliance with the roof, through the use of energy produced by plants powered by renewable sources, of the 50% of the expected consumption for domestic hot water and of 50% of the sum of the expected consumption for domestic hot water, heating and cooling"* ANNEX 3
>
> (Article 11, paragraph 1)

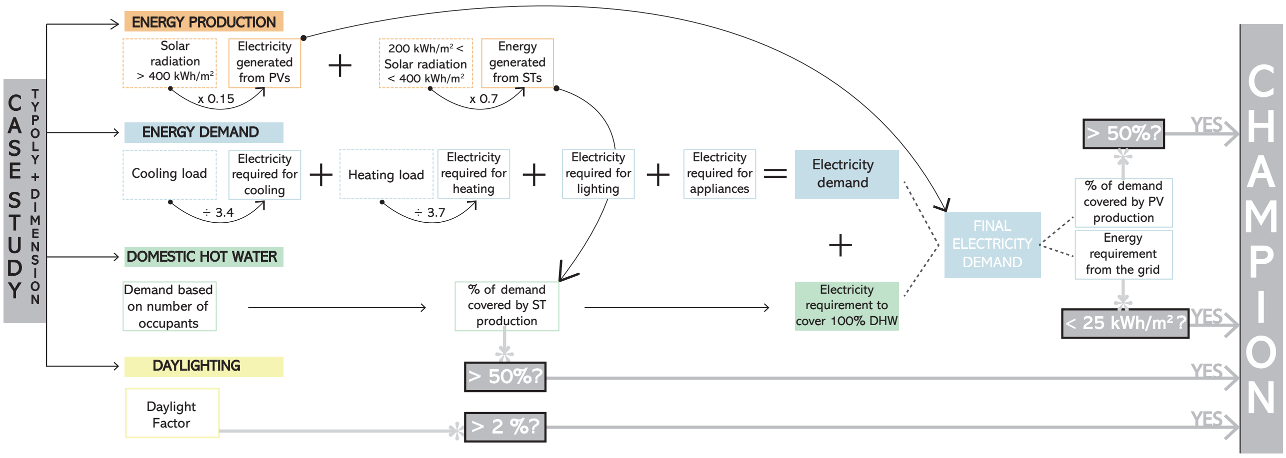


Figure 54: Diagram to show the process from all the building cases that went through the filtering and post-processing to understand the performance combined and be selected, or not, as a champion. [Source: the author]

2.3. THE CHAMPIONS

Finally, the filtering process results in 25 cases that are classified as "Champions" and are the following cases:

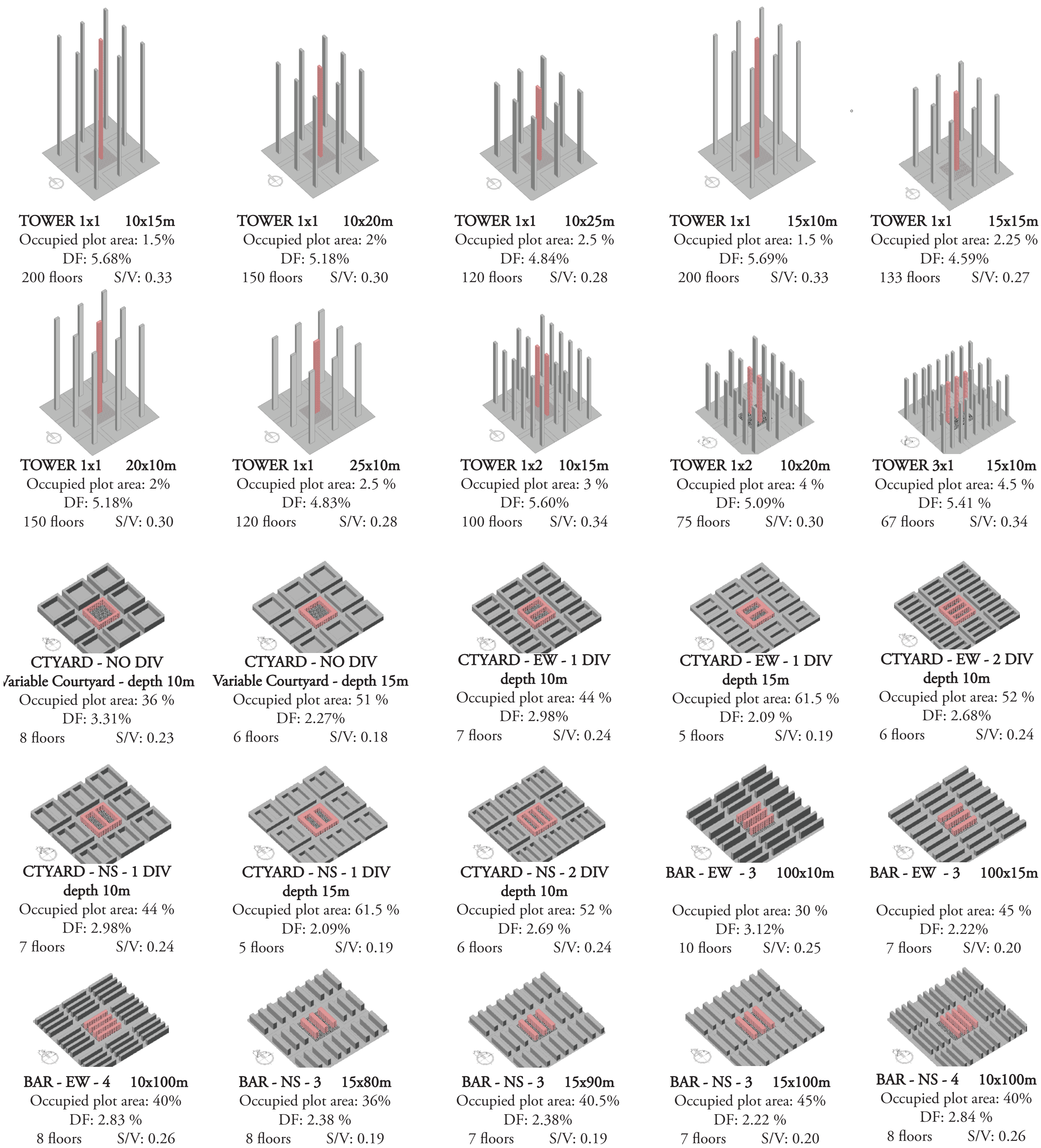


Figure 55: The champions, along with some information on them [Source: the author]

These cases are simulated and will receive <u>new values</u> for the lighting electricity demand, which will change the final energy demand and also the percentage covered by renewables. In order to make a fair comparison, the previous values are described in Table 18, and the values to be changed are highlighted in light grey.

Table 18: Values obtained in Chapter 01 for the Champions cases, that will be revised with the further detailed simulation.

Case Study	Annual electricity for heating and cooling [kWh/m²]	Annual electricity for lighting [kWh/m²]	Annual electricity for appliances [kWh/m²]	Annual electricity for remaining DHW demand [kWh/m²]	Total electricity demand [kWh/m²]	PV electricity production [kWh/m²]	Final electricity demand [kWh/m²]	% covered by renewables
BAR-EW-3 100x10 m	10.43	34.06	22.33	0.59	67.40	42.87	24.53	**63.60**
BAR-EW-3 100x15 m	7.96	34.06	22.33	4.68	69.03	47.74	21.29	**69.16**
BAR-EW-4 100x10 m	10.68	34.06	22.33	0.28	67.35	45.11	22.24	**66.98**
BAR-NS-3 15x80 m	8.87	34.06	22.33	0.00	**65.26**	41.20	24.07	**63.12**
BAR-NS-3 15x90 m	8.97	34.06	22.33	0.24	65.59	44.42	21.18	**67.71**
BAR-NS-3 15x100 m	8.61	34.06	22.33	0.34	65.34	48.37	16.97	**74.03**
BAR-NS-4 10x100 m	11.46	34.06	22.33	0.00	67.85	44.85	23.00	**66.10**
CRTYRD-NoDiv Variable Courtyard depth 10 m	10.21	34.06	22.33	0.76	67.36	44.55	22.81	**66.14**
CRTYRD-NoDiv Variable Courtyard depth 15 m	8.03	34.06	22.33	3.81	68.23	50.80	17.43	**74.46**
CRTYRD-EW-1Div depth 10m	9.77	34.06	22.33	0.00	66.16	50.42	15.74	**76.21**
CRTYRD-EW-1Div depth 15m	**7.92**	34.06	22.33	4.35	68.65	56.24	12.42	**81.91**
CRTYRD-EW-2Div depth 10m	9.64	34.06	22.33	0.00	66.03	53.58	12.45	**81.15**
CRTYRD-NS-1Div depth 10m	10.04	34.06	22.33	0.00	66.43	50.58	15.86	**76.13**
CRTYRD-NS-1Div depth 15m	8.12	34.06	22.33	4.12	68.62	57.11	**11.52**	**83.21**
CRTYRD-NS-2Div depth 10m	9.99	34.06	22.33	0.00	66.38	53.79	12.59	**81.03**
TOWER-1x1-10x15	16.57	34.06	22.33	3.95	76.91	**61.51**	15.40	**79.97**
TOWER-1x1-10x20	14.75	34.06	22.33	4.29	75.42	56.57	18.86	**75.00**
TOWER-1x1-10x25	13.74	34.06	22.33	5.00	75.13	54.31	20.83	**72.28**
TOWER-1x1-15x10	16	34.06	22.33	0.00	72.39	59.76	12.63	**82.55**
TOWER-1x1-15x15	12.72	34.06	22.33	0.98	70.09	48.66	21.43	**69.42**
TOWER-1x1-20x10	13.39	34.06	22.33	0.00	70.38	52.27	18.12	**74.26**
TOWER-1x1-25x10	12.91	34.06	22.33	0.00	69.30	47.62	21.68	**68.72**
TOWER-1x2-10x15	16	34.06	22.33	5.08	77.47	56.81	20.67	**73.32**
TOWER-1x2-10x20	14.43	34.06	22.33	3.59	74.41	50.08	24.33	**67.30**
TOWER-3x1-15x10	15.15	34.06	22.33	0.00	71.54	47.14	24.40	**65.90**

[Source: the author]

In the previous table, the best performing number for each category is highlighted. The lowest annual electricity for heating and cooling (7.92 kWh/m²), the lowest total electricity demand (65.26 kWh/m² - and it should be noted that the difference here is the amount of electricity required to cover the demand for Domestic Hot Water, that in one case was covered entirely by the solar thermal collectors and in the other the coverage was only 61% of the total demand for DHW), the highest PV production (61.51 kWh/m²), the lowest final electricity demand (11.52 kWh/m²) and finally the highest percentage covered by renewables (83.21 %). Looking at that, it is possible to understand that is not a unique case that performs well in all aspects, on the contrary, different cases have different strengths, and that's why it is important to combine all the aspects to find the truly best-performing cases in general, not only in one aspect.

A final comment before moving on to the new results is that perhaps it is interesting to see where the champions are located in the graphs presented before, like the overall graph for all the three typologies shown in Figure 46 on page 87, which is shown now in Figure 56:

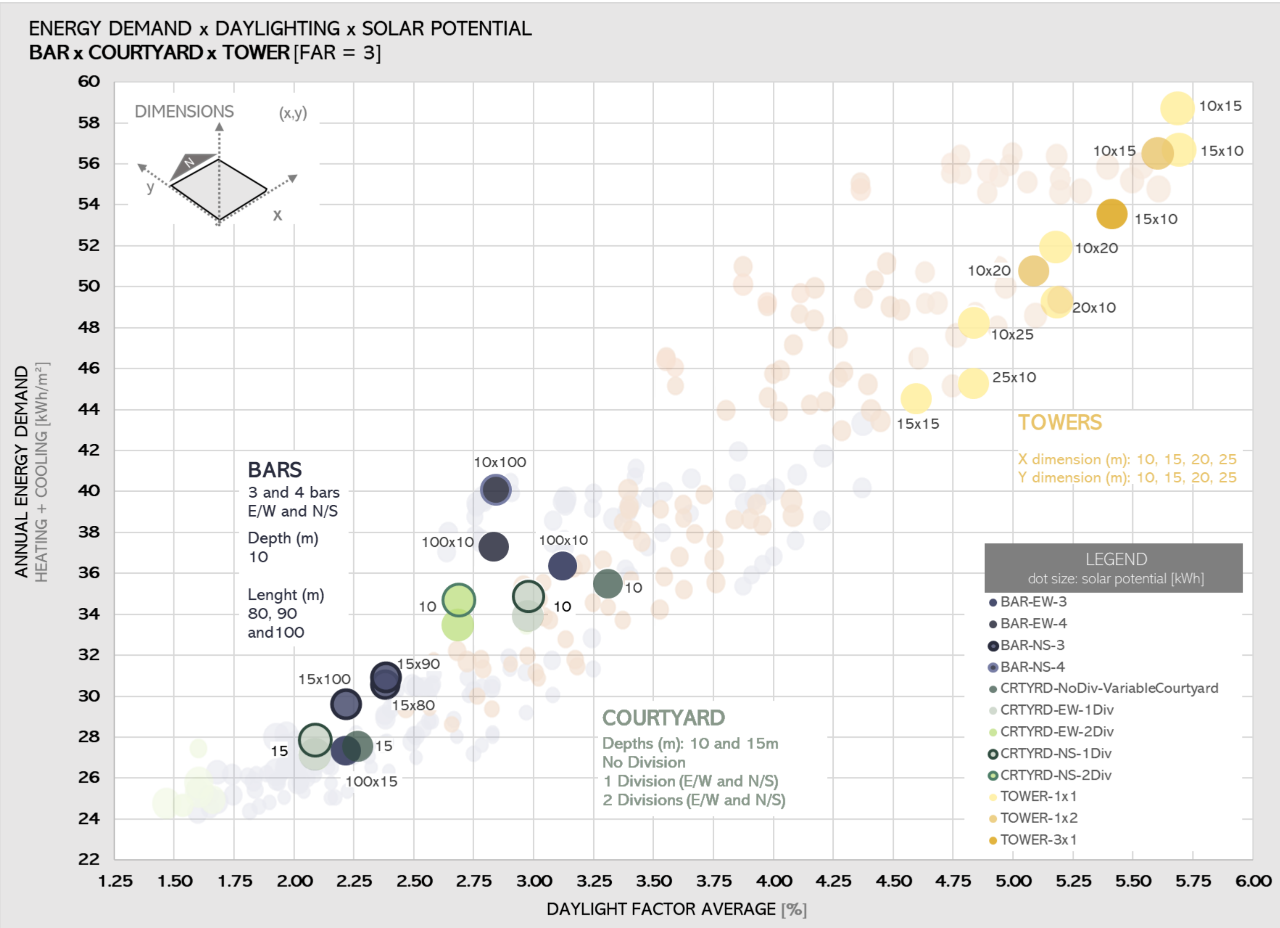


Figure 56: Same graph as in Figure 46 but with the champions highlighted. [Source: the author]

2.4. METHODOLOGY: FURTHER ANALYSING THE CHAMPIONS

2.4.1. BUILDING PERFORMANCE SIMULATION

The analysis performed on the champions is focused on further investigating the daylight conditions and with that, taking advantage of the cases well lit to save energy used for artificial lighting. Thus, the use of climate-based daylight metrics in the simulation analysis is the determinant aspect. This kind of metric allows for the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from the standard weather datasets. It delivers prediction of absolute quantities like illuminance (lux) that are dependent both on the site location and the building orientation (hence, the illumination effect of the sun and non-overcast sky conditions are included), in addition to the building's massing and geometry.

To choose one metric among the several that are climate-based and were discussed in "Metrics" ("Daylighting" on page 44), the Leadership in Energy and Environmental Design (LEED v4) certification method was investigated. This program is a green building certification program used worldwide, developed by the non-profit U.S. Green Building Council (USGBC) which establishes guidelines for all the metrics used to evaluate a building [41]. The method to evaluate the acceptable thresholds are shown in the following Table:

Table 19: Extract from LEED web-page on the specifications of metric and thresholds

LEED Daylight Credits - Option 01
<u>Intent</u> To connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.
<u>Requirements</u> Provide manual or automatic (with manual override) glare-control devices for all regularly occupied spaces.
<u>Simulation: Spatial Daylight Autonomy</u> Demonstrate through annual computer simulations that spatial daylight autonomy $_{300/50\%}$ ($sDA_{300/50\%}$) of **at least 75% is achieved.** Use regularly occupied floor area. <u>AND</u> Demonstrate through annual computer simulations that annual sunlight exposure$_{1000,250}$ ($ASE_{1000,250}$) of **no more than 10% is achieved.** Use the regularly occupied floor area that is daylit per the $sDA_{300/50\%}$ simulations. The sDA and ASE calculation grids should be no more than 2 feet (600 millimetres) square and laid out across the regularly occupied area at a work plane height of 30 inches (760 millimetres) above finished floor (unless otherwise defined). Use an hourly time-step analysis based on typical meteorological year data, or an equivalent, for the nearest available weather station. Include any permanent interior obstructions. Movable furniture and partitions may be excluded.

[41]

Therefore, in this research the climate-based daylight metrics chosen to further analyse the selected cases are **sDA** and **ASE**, which are detailed following to remember the previous explanation:

SPATIAL DAYLIGHT AUTONOMY

As it was explained previously, sDA describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. The result is an average per building, and it will be a percentage of the floor area (0-100%) that meet this requirement. The credits for LEED are as follows:

> **sDa > 75%** ⟶ preferred by occupants; *2 points in LEED evaluation*
>
> **55% < sDA < 74%** ⟶ "nominally accepted" space by the occupants. *1 point in LEED evaluation*
>
> **sDa < 54%** ⟶ not acceptable

ANNUAL SUNLIGHT EXPOSURE

ASE describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1,000 lux for at least 250 occupied hours per year.

Therefore, sometimes sDA percentage can be within the preferable range, since it puts only a minimum of 300 lux, but glare problems can be still happening. Thus, some attention is required when a lot of the area is receiving too much direct sunlight, which can cause glare and discomfort, usually close to the windows. It will also be presented in the % of the floor area that meets the ASE requirement, always aiming for the lowest values. (Lower than 10%, according to LEED criteria).

For the purpose of this comparison, it should be noted that the direct sunlight and glare can be controlled by several devices that are not considered in this study. The ASE results here presented can be greatly improved once the designer goes into detail and add features like overhangs, external or internal curtains, shading devices, etc.

Software

DIVA for Grasshopper [27] is the tool selected to perform annual hourly calculations by taking advantage of the Radiance / Daysim engine [5], which allows users to specify the scene geometry, materials, time and date and sky conditions. For this research, DIVA is used to run simulations throughout the entire year and evaluate sDA and ASE.

Daylighting can save energy by displacing the electrical energy that would otherwise be used to provide artificial lighting [21]. This is potentially one of the most significant energy-saving measures. Hence, as it was mentioned previously, besides daylight conditions, DIVA will also be used to simulate the lighting electricity requirement based on the daylight condition, and with some post-processing of the data it will be possible to recalculate the electricity demand and understand if some of the cases are able to reach 100% coverage by the active renewable strategies applied.

2.4.2. SIMULATION PARAMETERS

Occupancy load and schedule

The simulation process took into consideration the same parameters as before in terms of occupancy and schedule. For a residential building in the current scenario, the schedule of working days, from Monday to Friday, has an occupancy of 100% from 18h until 9h and 50% occupancy from 9h to 18h. The weekly schedule includes weekends, which considers 100% of occupancy during 24 hours. It also considers daylight savings time from the 2nd Sunday of March to the first Sunday of November. The schedule is imported and set in DIVA components, as it can be seen in the following Figure:

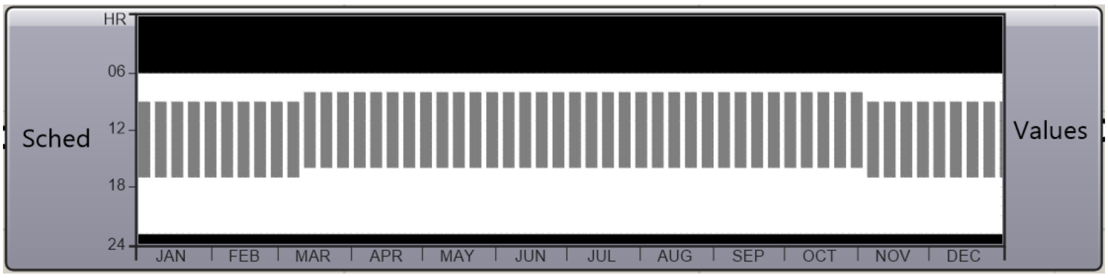


Figure 57: Annual occupancy schedule view in the component from the DIVA script. [Source: the author]

Regarding the occupancy load, the values are the same as before, considering- 1 person for each 35 m^2.

Lighting power density

Lighting Power Density technically represents a load of any lighting equipment in any defined area, or the watts per square foot of the lighting equipment. For the simulation, the value of 7.6 W/m^2 is applied, according to ASHRAE 90.1, Building Area Method, for "dining/family occupation".

Lighting Control Settings - Dimming with occupancy ON/OFF sensor

To calculate lighting electricity, the automated control mimics a continuous (only in occupied hours) dimming sensor with a user-defined set-point (300 lux). This means that during the occupied hours, when people are awake (lights are off from 23h until 06h) the sensor measures the amount of lux the grid surface is receiving. Once it goes below 300 lux, the lights are turned on. Once it reaches again 300 lux, the lights are turned off. Each floor generates a lighting schedule such as the one shown in Figure 58. The black areas represent the times that lights are turned off, and the white area represents times when the lights are turned on. Therefore, during the hours that people are sleeping, the pattern is totally black, and it also can be seen that during summer, when the sunlight hours increase, there is a decrease in the use of artificial lighting.

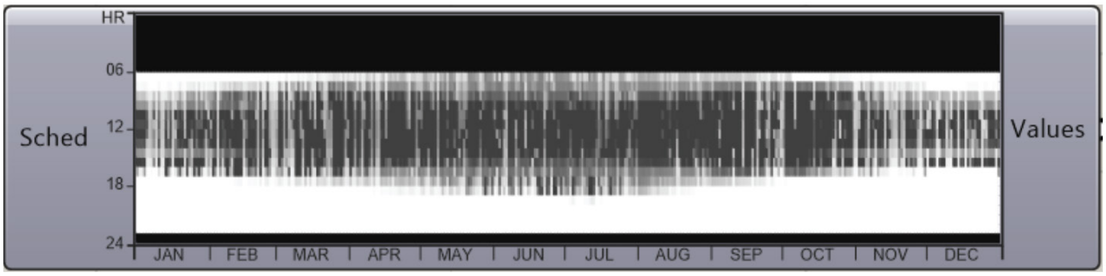


Figure 58: Annual lighting schedule view in the component from the DIVA script. [Source: the author]

Radiance materials and parameters

In Radiance it is necessary to define different material properties for the various objects plugged into the daylight simulation. For this case, walls, windows, roofs, etc. These different materials have different ways of manipulating the rays of light that interact with them, based on the physics of light. Depending on the type of material, properties like reflection, transmission, and/or refraction should be defined.

For opaque materials, named "plastic" in Radiance, the values for R, G, B reflectance values, specularity and roughness must be assigned. The reflectance values have the range of 0.0 to 1.0 (although 0.0 and 1.0 do not occur in nature). Specularity also has the range of 0.0 to 1.0, 0.0 for a perfectly diffuse surface and 1.0 for a perfect mirror. In reality, plastic materials are generally not very reflective and the specularity value is usually in the range of 0.0 – 0.07. Roughness, with the same limits, refers to how the surface scatters what light is reflected, 0.0 meaning perfectly smooth. Plastic materials generally have a roughness in the range 0.0 – 0.02.

For glass materials, the R, G, B transmissivity values must be set. The properties of glass are commonly defined by glazing manufacturers in terms of transmittance. In Table 20 the values and materials used for this simulation are listed.

Table 20: Building material optical properties

Construction	Material type	Values
External wall	Radiance opaque material	Reflectance: 0.5 Specularity: 0 Roughness: 0
Roof, floors and ceilings	Radiance opaque material	Reflectance: 0.8 Specularity: 0 Roughness: 0,1
Shading context	Radiance opaque material	Reflectance: 0.2 Specularity: 0 Roughness: 0
Window	Radiance glass material	Visible transmittance: 0.71

[Source: the author]

After defining the materials, a review of the Radiance Parameters is required. Now, the study is done on fewer cases, which allows to spend a bit more time on the simulations. Therefore, not only the metrics are improved and detailed but also the simulation conditions. The Radiance Parameters have a great influence on how the light is distributed and the number of reflections that are possible. Table 21 is a review of the Radiance Parameters used in Chapter 01, as shown previously in "Table 6: Radiance Parameters" on page 63, but now with the Rad Params used for the simulations here in Chapter 02. It is possible to compare and understand the improvement on detailing the simulation from there to here. In light grey it is possible to see previously used values, and in dark grey, the values applied now.

Table 21: Utilized Radiance Simulation Parameters

Param	Description	Min	Fast	Accurate	**DIVA**	Max	Notes
ab	ambient bounces	0	0	**2**	**4**	8	It is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.
ad	ambient divisions	0	**32**	512	**1024**	4096	-
as	ambient super samples	0	**32**	256	**256**	1024	Super-samples are applied only to the ambient divisions which show a significant charge.
ar	ambient resolution	8	**32**	128	**256**	0	This number will determine the maximum density of ambient values used in interpolation. The maximum ambient value density is the scene times the ambient accuracy.
aa	ambient accuracy	.5	**.2**	.15	**.1**	0	This value will approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

[38]

One last note on parameters, it must be reassured that the values recommended by LEED regarding the grid spacing (0.6m) and the work plane height (0.76m) were followed for these simulations.

2.5. CHAMPIONS RESULTS

Having filtered the best performing cases from Chapter 01 and having refined the analysis more in detail with the new parameters, the results now affect both the daylight conditions and the final energy demand. For the first aspect, it is now possible to understand how much of the plan floor area receives at least 300 lux for at least 50% of the occupied hours (sDA) as well as to understand the glare risk, which is evaluated by the percentage of the plan floor area that receives at least 1,000 lux for at least 250 occupied hours per year (ASE). For the latter, the energy demand, it was possible to re-assess the electricity requirement for artificial lighting based on the real daylight conditions, and then re-calculate the final energy demand with that information. Having the data for electricity for artificial lighting was able to make a significant difference in the energy demand when compared to the previous value found in Chapter 01, representing a maximum of 5.31 kWh/m^2 for the BAR cases, 6.33 kWh/m^2 for the COURTYARD cases, and 8.87 kWh/m^2 for the TOWER cases.

Figure 59 demonstrates all the new outputs. There, it is visible that all the TOWER cases present an average Spatial Daylight Autonomy of 100%, which is great, but an average Annual Solar Expose that range from 47.1% to 68.3% among the tower cases. Even though it is known that there are several measures to mitigate glare and that they are applied later in the design process, those values are quite concerning. The tower case of 1x1 - 15x10 is the best performing among all the cases on the final energy demand, with a requirement of only 3.77 kWh/m^2. This value is so low that it probably can be even improved by further detailing the building and it should not be difficult to reach a zero-energy building.

The BAR and COURTYARD cases are all quite below the percentage for sDA when compared to the TOWERS. None of the cases presents an average sDA higher than 75%, which makes them all falling outside of the "preferred by occupants range". While performing similarly for sDA, COURTYARDS are presenting a lower final energy demand. It should be noted that all the cases of Courtyards with a depth of 15m present an average sDA lower than 55%, which makes them outside of the "nominally accepted range", and therefore not a good daylight condition for the occupants. The same happens for all the cases of BARS with 15m depth (with the exception of BAR-NS-3 15x90m, which has a sDA value of 55.7%). Regarding glare risk, the cases with lower sDA logically also present a lower ASE, with values around 25 - 30%. Those values are yet very high, but more easily managed than the values found for the TOWERS.

It should be noted that this is still a study to compare the typologies, but obviously, further details can improve some conditions, such as increasing the glazing ratio to improve daylighting or, as it was previously mentioned, the addition of glare controlling strategies such as shading devices (Venetian blinds, for example), overhangs, special glasses and so on.

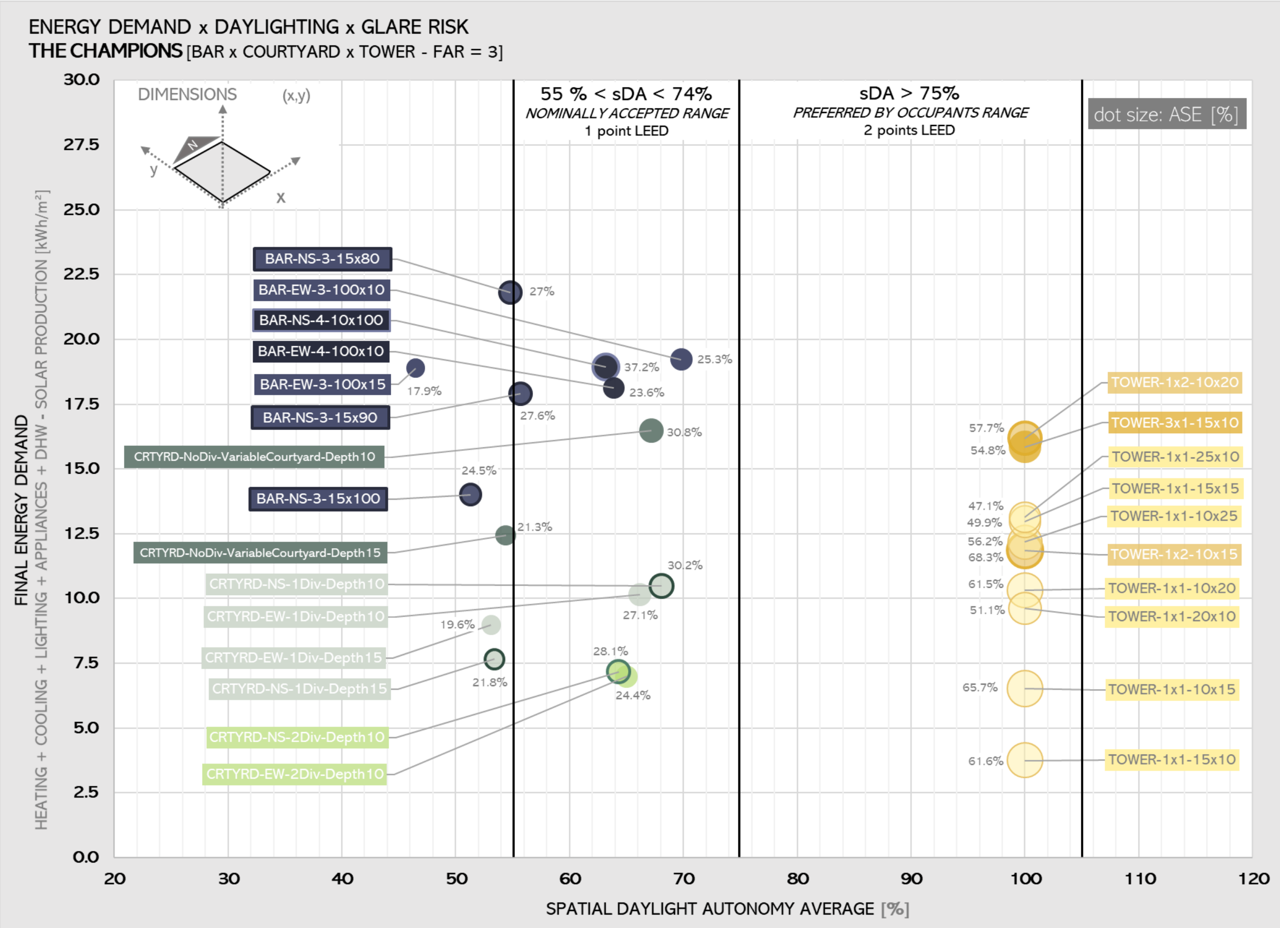


Figure 59: Overall scenario for the CHAMPIONS now with the climate-based simulation. Spatial Daylight Autonomy percentage in the x-axis, Final energy demand for heating, cooling, lighting, appliances and domestic hot water (considering PV production) in the y-axis, and Annual Solar Exposure in the dot-size representing the glare risk indicator. [Source: the author]

It is interesting to mention that the methodology to evaluate sDA and ASE for each building is to take the average value among the evaluated floors, as exemplified in Figure 60. In there it is possible to see the "rule" followed to evaluate each typology, resulting in the same amount of grids and square meters evaluated for all three typologies. Because the floors at similar height resulted in pretty similar results, it was decided to evaluate significant floors and average the value among them. Of course, results are different as the floors are placed towards the top of the building, generally with a better daylighting condition, for instance. That's why this is being highlighted here, giving that the ground floor is usually in a worse daylight condition, and therefore presents a sDA below the acceptable range, even if the building is classified as overall being inside the acceptable range.

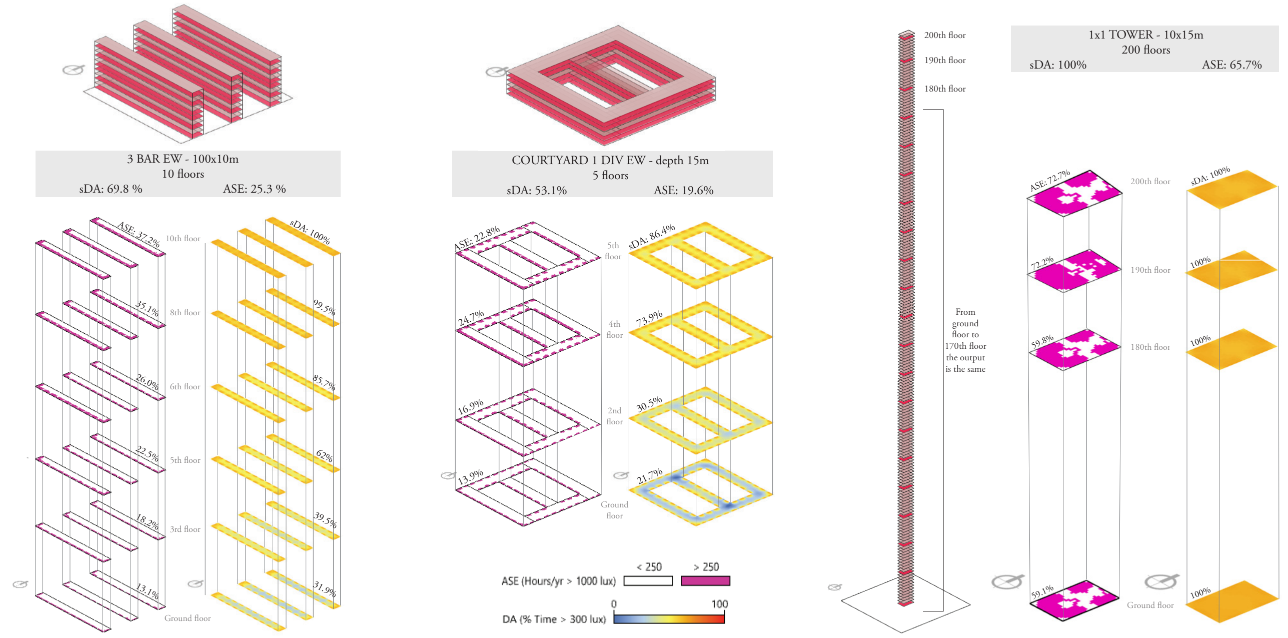


Figure 60: Example for BAR, COURTYARD and TOWER cases of the methodology to evaluate sDA and ASE in determined floors. This rule was followed equally for all the cases, aiming for the results and evaluation to be fairly compared. [Source: the author]

To make sure the legislation is complied, all the ground floors for the champions were analysed in detail considering Daylight Factor, that could be a metric to certify a reasonable minimum for the daylighting condition even though sDA is not perfect at this point (which might be improved if further detailing the building). That's why the values for ground floor DF are shown thoroughly in Figure 61, as well as with the visual representation of the plan floor. This study was made to make sure all the building cases are passive of being approved by building codes and regulations. The metrics of sDA and ASE are also displayed there so all the data is detailed and visible.

It can be seen that the values for DF from 0 to 1 are represented by the darker areas, while the higher values are represented by light grey up until yellow. For the tower cases, only the 15x15m case shows a central dark area, while all the others, that have a rectangular shape and a depth of 10 or 15m, have a central area with a light grey, showing that even in the middle of the plan floor the DF is higher than 2%. As a result of the plan floor shape, these cases have the highest DF values among all the Champions.

In Courtyards and Bars, however, it is visible that the plan floor central areas are dark and when there is a window the area is coloured with yellow, representing a really high DF percentage. In the visual representation, it is also clear the difference between depths of 10m and 15m, the latter having much darker areas than the first. The DF average values for both typologies are way lower than the towers, ranging around 2 and 3 %, but they are of course still acceptable, making all the Champions cases eligible for compliance with the regulation, even though sDA at the ground floor was not great at this stage, as mentioned previously.

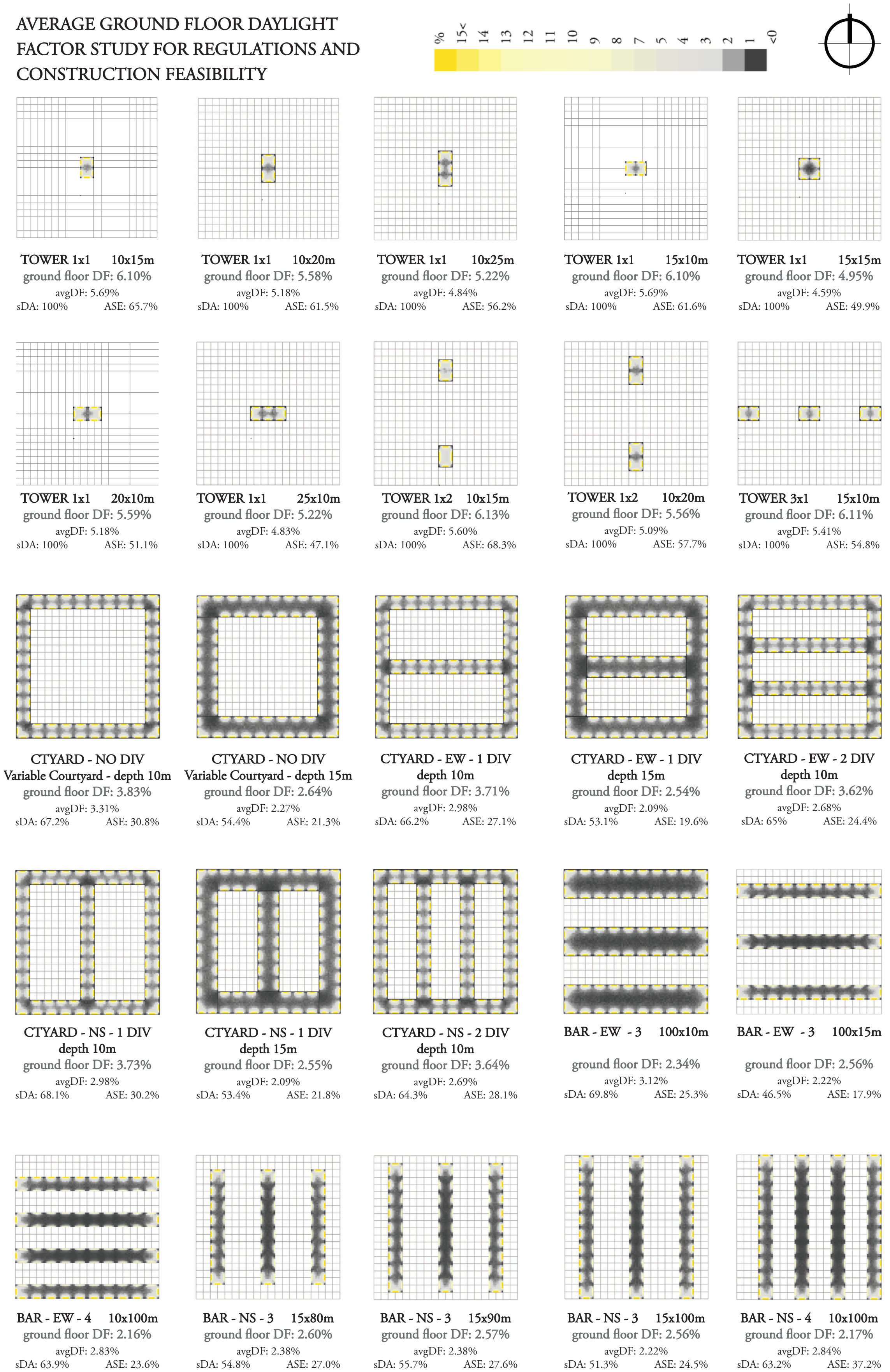


Figure 61: Ground floor Daylight Factor percentage for all the Champion's plan floors, as well as average DF, sDA and ASE values for each case as secondary information. [Source: the author]

It is interesting to highlight that the daylighting conditions' difference between the top floors and the bottom ones also reflect on the artificial lighting electricity requirement. As can be seen in Figure 62, the lighting schedule changes as the floors become higher. The black areas in the pictures of the schedule represent when the lights are turned off, and this area increases on the pictures from left to right. During the night time, the upper part of the schedule, the area is constantly black to account for the hours of sleep, and towards the bottom of the graph the area is constantly white to account for the useful hours after sunlight is gone, in which the lights are on. The middle area is the interesting one because it accounts for the hours of the day when one can require artificial lighting to work or perform tasks if daylighting conditions are not enough. It is visible that this requirement is greater towards the ground floor, which goes in line with the smaller percentages found for sDA also on the ground floor.

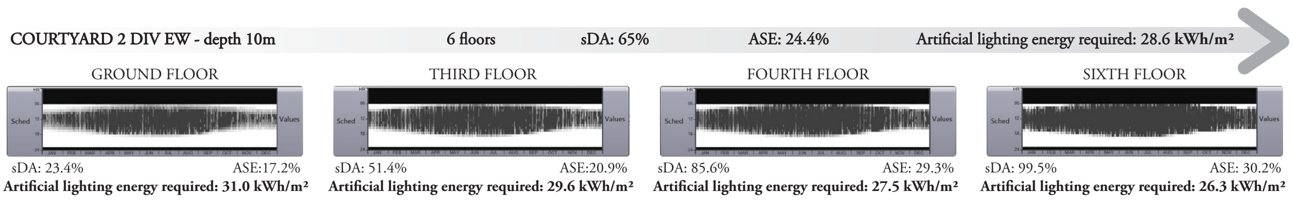


Figure 62: Example of the outputs for artificial lighting schedule and demand on each floor evaluated for the case of Courtyard with 2 divisions oriented East / West, with depth of 10m. [Source: the author]

Having covered and understood the new daylight outputs, some attention should be drawn to the new final energy demand, that was recalculated with the real electricity requirement for artificial lighting, that changes according to each daylighting condition. Besides taking a look at the final energy demand, it can be interesting to see the percentage of energy demand covered by renewables, as shown in Figure 63. As expected, the cases with more coverage are the ones with lower energy demand. This might seem obvious but it was worth to checking it giving the demand and solar production for energy are different according to each case. For instance, one case might require more energy for cooling and heating but also capture more solar radiation, which compensates the high energy requirement, and the other way around.

From this graph, it can be seen that in the case of TOWERS 1x1, for the cases 15x10m; 10x15m and 20x10m; 10x20m, it happens that when the X-axis dimension is smaller than the Y-axis (10x15m, for instance) there is a small increase in the energy requirement. However, for the first case the coverage of renewables drops almost 5%, while for the second the coverage remains the same, meaning that the original demand or the ability to capture solar radiation was not the same. This trend gets reversed for the cases 10x25m; 25x10m. In this case, having the X-axis dimension greater than in the Y-axis (25x10m) represents a small increase in the energy demand and a drop of 3.5% in the renewables coverage. Once again it can be seen that the aspect ratio for towers matters, giving that the cases with 1 very tall tower generally perform better than having 2 or 3 bars with a lower height.

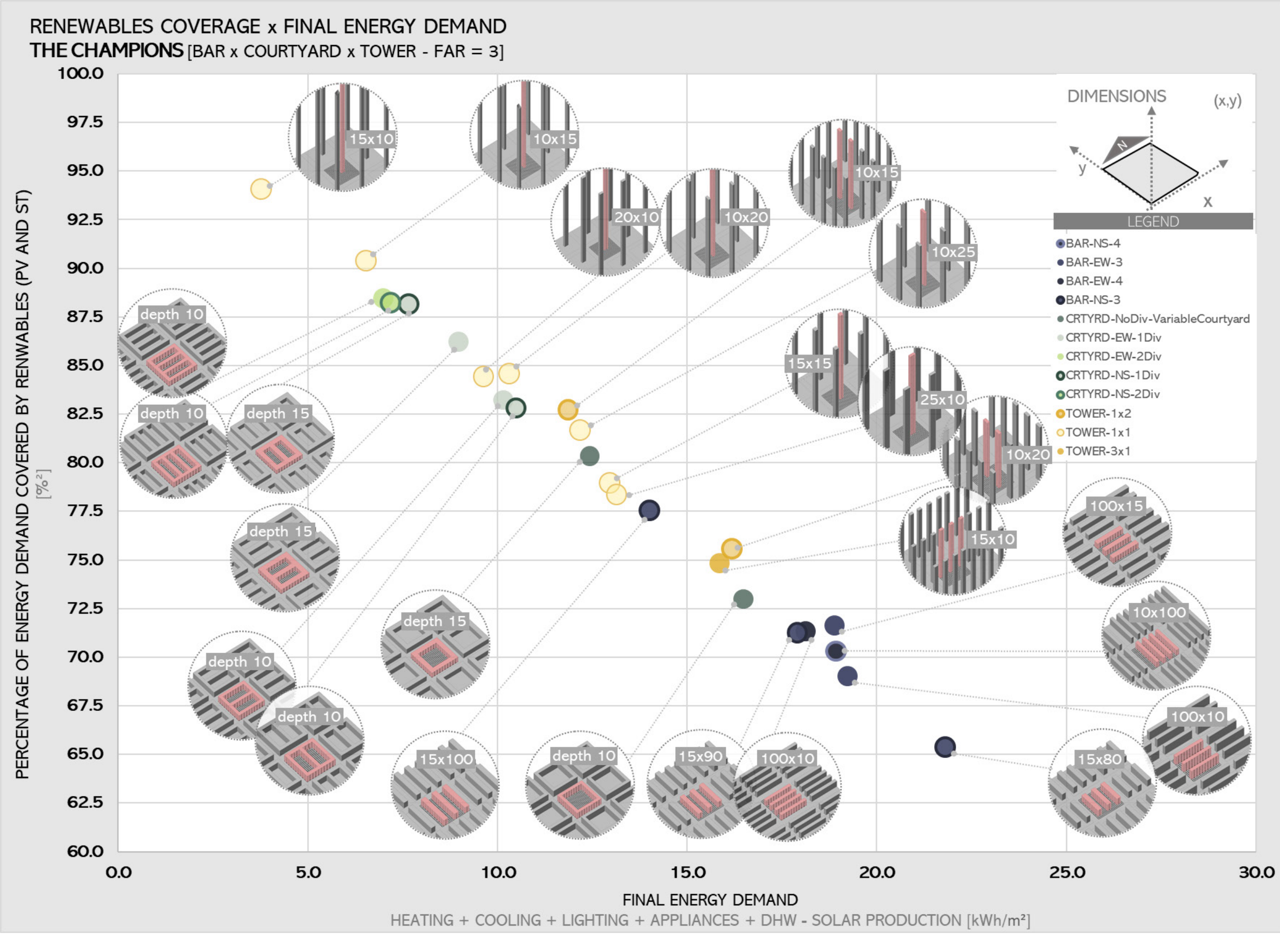


Figure 63: CHAMPIONS results for the new energy demand on the x-axis and the percentage of energy demand covered by renewables on the y-axis. It should be noted that this graph, unlike the previous ones, does not show any information on the dot size. [Source: the author]

On the COURTYARD cases, there are three best performing with pretty similar values for final energy demand and renewables coverage: 2 DIV - depth 10m - NS and EW, and 1 DIV - depth 15m - NS. Even though the 15m deep case seems to perform well here, it was mentioned before that in terms of daylighting this depth is not performing so well, and that should always be kept in mind.

The BAR cases are the ones towards the right side of the graph, meaning that in comparison to all the Champions they have the worst energy demand performance, as well as renewables coverage. The only case that seems to be able to compete with the others in Figure 63 is the 3 BAR NS 15x100. This one, however, was completely outside of the sDA acceptable range in the graph shown previously in Figure 59.

As a matter of fact, let's look again at that Figure 59 to understand if some more filtering can be done to truly find the best performing cases. On the TOWER cases, it seems clear that the best case is **TOWER 1x1 15x10**: it has the lowest energy demand among all and the sDA average of 100% - which is great. The only concern is the ASE value of 61,6%, but this glare risk is not changing so much between the other cases for towers, so it remains this matter to be solved with further detailing. For the

COURTYARD cases, it seems that the **CTYARD-EW-2Div-Depth10m** is the best one: a very low energy demand of 7 kWh/m^2, a value of 65% on sDA that probably can also be improved, and an ASE of 24.4%, a very manageable glare potential. On the BAR cases, it is probably worth selecting **BAR-EW-3-100x10m**. It has an 18.9 kWh/m^2 energy requirement, significantly higher than the other two selected, but one of the best among the bar cases that present sDA higher than 55%. This case, in fact, has a sDA of 69.80% and an ASE of 25.30%. Those last two values are pretty similar to the best case for courtyards, but the energy requirement 2,7 times higher makes it clear which typology performs better when looking at only those two.

As it can be seen, because of glare risk and other values such as sDA that still can be improved, it might be worth it to take some time on those 3 cases, the best performing for each typology, and see how their envelope can be improved to reach a perfectly efficient building, which will be developed further in Chapter 03.

CHAPTER 03.

Improving the envelope

3.1. INTRODUCTION

As it has been discussed so far, all of this research was done to mainly understand what massing and building form can do on building performance, considering not only thermal but also daylight and comfort aspects. That being said, it was able to arrive at a point and identify the best performing typologies as well as the best performing cases within each typology.

All of that is part of the intent to prove that building form is indeed a significant passive design move, that can contribute and make a significant difference in the building final behaviour. Choosing wisely the building mass can, as it was proven here, optimize daylighting conditions to its best and provide a great energy performance. This is all aiming to tune the buildings so that they moderate external environmental conditions and maintain internal conditions using the minimum resources of materials and fuel.

The passive measures do not involve mechanical or electrical systems, and the ones associated with building form were applied along the path of this research. Moreover, they were combined with active strategies, measures that make use of active building services systems to create comfortable conditions, such as boilers and chillers, mechanical ventilation, electric lighting, and to produce energy from natural resources, such the solar radiation.

In spite of those already applied strategies, there are a number of other design strategies that can be applied in a process of further detailing the building fabric, and to show that these aspects were not forgotten, this final Chapter will explore a few of them and see if more improvement can be enforced and can improve even more the building performance of the best case for each typology.

Following, there is an overview of some other examples of passive design, excluding the ones already used such as the optimization of the orientation to control solar gains and maximize daylighting, the manipulation of building form and fabric or the envelope build up performance. They are listed here:

- Optimization of the spatial planning and internal layout,

- Natural ventilation,

- Passive cooling or heating,

- Thermal mass,

- Envelope surface, pattern and technology,

- Shading elements,

- Material selection,

- Openings distribution and position, to allow the penetration of solar radiation, visible light and ventilation.

Taking advantage of all or even a few of those ideas, of course with due diligence on what truly represents a benefit to each scenario, represents a possibility to improve the overall performance. Those ideas are usually applied after the building mass has been defined and that is why this research followed the same sequence of the design process: the first architectural move was studied in-depth, the building form, and afterwards, the intent now is to apply other measures that will usually follow along in the building creation process, even if with a less in-depth study, based on previous knowledge and experience.

Such knowledge can be exemplified in its simplest form, for example: it is known that a shallow building orientated perpendicular to the prevailing wind with openings on both sides, will allow sunlight to penetrate to the middle of the building and will enable cross ventilation. This should reduce the need for artificial lighting and may mean that cooling systems and mechanical ventilation are not necessary. Or, on another aspect, elements such as shading, shutters, overhangs and louvres will allow low-level winter sun to penetrate into the building, but will block the higher summer sun, and can be used to deal with overheating and glare problems. Therefore, the idea is to test some of these well-established design strategies to see if and how effective they are when applied to an optimised shape.

3.2. METHODOLOGY: IDENTIFYING POSSIBLE PROBLEMS AND PROPOSING A STRATEGY

The main idea of this final Chapter is to demonstrate that the following design decisions after the first massing on early project stages can improve even more the good performance reached by selecting the most appropriate building form. The results obtained for each of the best performing cases for every typology are again reported here, and the attempt is to improve those values with simple design moves that can be beneficial according to previous experience and common knowledge, mainly from years of study on how to apply passive strategies and design towards more efficient buildings. For the sake of simplicity, the measures will take action on the three following aspects:

1- Insulation / envelope performance

2 - Openings distribution with the same WWR (0.3) or adapting the size of the openings according to the necessity

3 - Tilting or deflecting the envelope surface

The case studies will shift for a shape or configuration that goes further in detail than the other cases studied so far, which of course makes them not comparable with the previously studied ones, but gives an idea of how well a building can perform if simple yet efficient strategies are combined.

The simulations of daylight (sDA and ASE) follows the method from Chapter 02, and were performed using the same software already detailed in "2.4.1. Building performance simulation" on page 108, where the parameters and software selection is discussed in summary, for the daylight conditions DIVA and Grasshopper are platforms where the case with the new actions is evaluated once again. For energy demand and solar radiation, Ladybug and Honeybee are applied, also following the method used since the beginning of this study. It must be highlighted that dynamic artificial lighting demand was taken into consideration, as it is in Chapter 02, therefore matching energy and daylighting conditions.

3.3. TOWERS: TOWER 1x1 15x10

The first case to be studied is interesting for meeting some extreme outputs among all the cases studied previously. This case has only one shallow tower in the 100x100 m plot, with the smallest dimensions evaluated (15x10 m is the minimum dimension set for this entire study due to internal spacing distribution limitations for a residential program). It is also the tallest case evaluated: 200 floors are necessary to meet FAR = 3 in this dimension. Moreover, it presented the lowest energy requirement (3.77 kWh/m²) among all the Champions, regardless of typology.

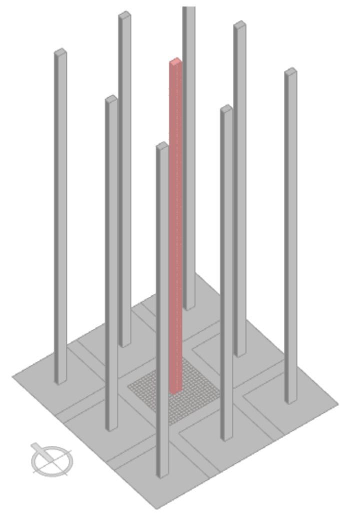


Figure 64: On the left. Visual aspect of the case TOWER 1x1 15x10 when evaluated purely on terms of building form and massing [Source: the author]

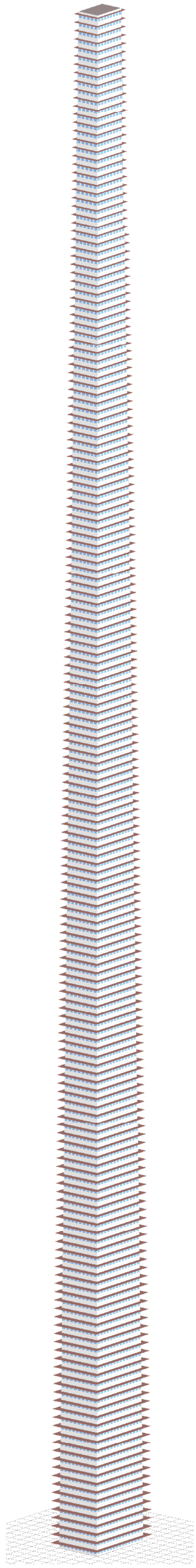


Figure 65: On the right. Visual aspect of the case TOWER 1x1 15x10 when the improvement strategies are already applied. [Source: the author]

Still on the energy requirement, it must be noted that the gross energy demand is 63.53 kWh/m², but then considering the PV production it remains only the 3.77 kWh/m² to be taken from the grid. It means the building is almost producing enough energy to cover itself. The attempt will be to see if the proposed strategies can increase the solar capture and on the other hand decrease the gross energy demand.

It should also be remembered here that in terms of daylight conditions this case performs very well, with a Spatial Daylight Autonomy of 100%. However, the glare risk is very high (ASE = 61.6%) which is a valid concern and one of the main issues that must be addressed at this step.

Expanding on the just mentioned result for the active strategies, and therefore regarding the solar potential for this case, its façade and roof receive 13.25 $.10^6$ kWh of annual solar radiation, and from that, after applying the thresholds for useful solar radiation and the active systems explained in "2.2.3. Solar potential" on page 102, the Photovoltaic system produces 1.79 $.10^6$ kWh of electricity, covering 82.6% of the electricity demand for cooling, heating, artificial lighting and appliances; and the Solar Thermal system produces 0.92 $.10^6$ kWh of thermal energy, which covers 115.7% of this building's Domestic Hot Water demand.

With this scenario from Chapter 01 in mind, the first issue to be dealt with was the high glare risk. For that, it was decided to reorganize the openings dimension in terms of height and width, keeping the same 0.3 of Window-to-Wall ratio, in order to better distribute daylight. Moreover, small overhangs were added on each floor to stop the direct sunlight. The overhangs also helped in this case to reduce the cooling load, and that, associated with the improvement on the thermal performance of the opaque façade (the previous U-value of External Wall was 0.38 W/m^{2}K and it was reduced to 0.21 W/m^{2}K) made a great difference on the energy requirement. Having tackled daylight and energy aspects, the action to try to improve solar radiation capture was to tilt the previously straight and rectangular façade at a way that the envelope faces the solar rays in a more efficient angle than the previous 90 degrees. These actions are summarized in Figure 66.

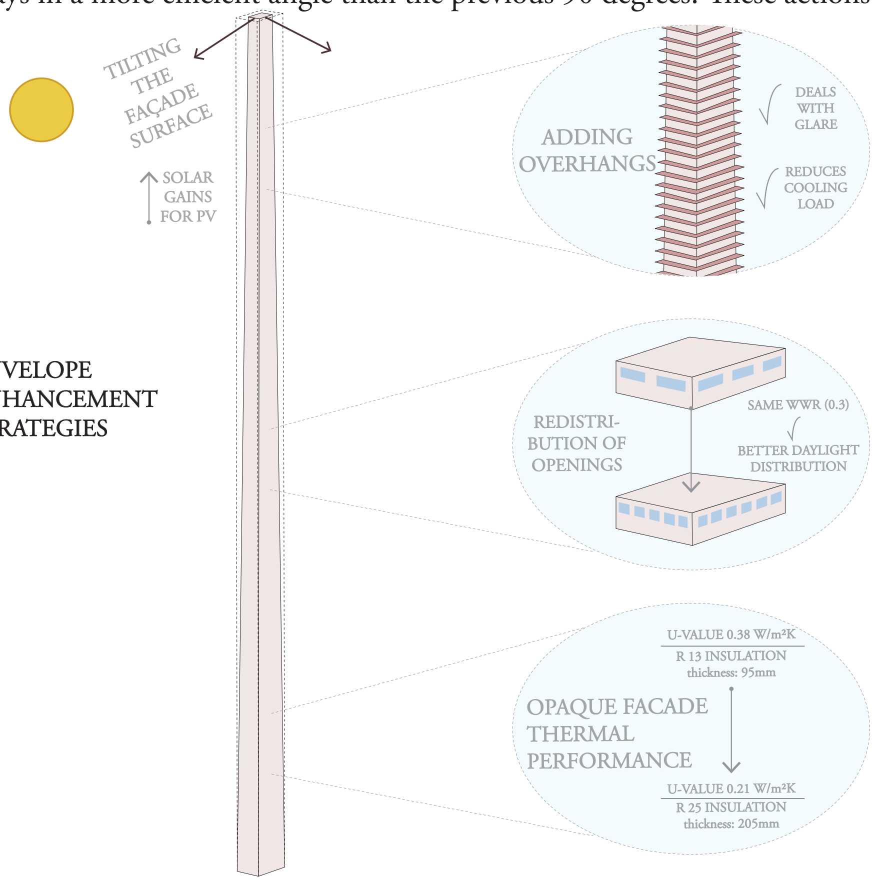


Figure 66: TOWER 1x1 15x10 Envelope enhancement strategies [Source: the author]

The results from applying only those design moves are quite satisfactory. It's important to know that there is always a trade-off: for instance, the sDA has decreased from 100% to 82.4% due to the addition of the overhangs. However, the overall glare scenario is much better: from ASE = 61.6% now the overall value for the building is 24.4% of glare risk. It is still not ideal, once that the goal is below 10% (for comfort conditions but also for LEED points) but the remaining 14.4% can surely be dealt with blinds, that were not included in the daylight simulation.

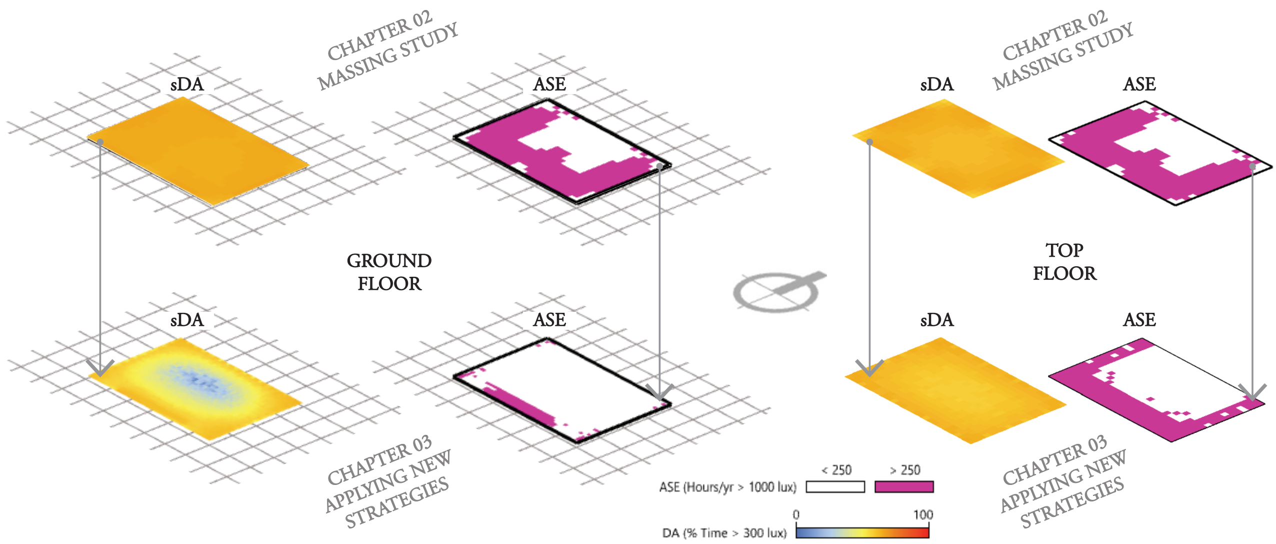


Figure 67: Daylight conditions comparison for ground floor and top floor between the TOWER case in Chapter 2, when it was just considering the regular massing and then with the new results after applying the strategies here in Chapter 3. [Source: the author]

The building still has its particularities according to the floor, but for this research we are dealing with averaged values for the entire building as an overall scenario indicator. Looking closer to the ground floor and the top floor, as shown in Figure 67, it is visible the change in the sDA and ASE output. Ground floor improved significantly in ASE and lost some performance in sDA, and the top floors didn't suffer massive changes regarding sDA but a significant improvement on the ASE percentage, even though it is probably still slightly high in the upper part of the building. A number of strategies can be applied here that can mitigate glare, from the simplest ones like adding roller blinds (manual or automatic) to the more complex ones (but still feasible) such as electrochromic glass (also known as dynamic or smart glass).

Moving on to the other outputs, the effect of improving the thermal performance of the envelope and the overhangs acting on the cooling load has caused a drop in the gross energy demand. Before, in Chapter 02, without accounting for any PV production, the demand was 63.53 kWh/m^2 and now it has decreased to 62.19 kWh/m^2. One might argue that it's not a significant decrease, but it should always be considered that while the cooling and heating load have dropped significantly, there was also an increase in the requirement for artificial lighting, a consequence of the drop in the Spatial Daylight Autonomy.

Now, the most interesting fact is the effect of tilting the façade fabric and considering the overhang surfaces to receive active systems (always according to the threshold, but since they are horizontal surfaces, it is clear that the solar capture there will be dedicated to photovoltaic panels). Improving the angle to receive the solar radiation has resulted in an annual solar radiation capture of 26.14 $.10^6$ kWh over the year. Furthermore, considering the assumptions for division of useful solar radiation, the DHW demand is covered entirely with thermal energy to spare as well as the electricity production from PV systems, which remarkably will cover entirely the demand and even produce more energy than the building requires.

To elucidate: the PV electricity production results in 98.87 kWh/m^2, and considering the aforementioned gross demand of 62.19 kWh/m^2, this means covering 159% of the demand, with energy to spare and give back to the grid. All of this information on scenarios for this case study and the outputs for each step of the research are summarized in Table 22, in which we can clearly see the great increase in solar capture at the expense of the daylight condition. We can also see that, in fact, the energy use did not improve so much, but energy production suffered a huge improvement, almost doubling the radiation capture.

Table 22: Tower case study building performance comparison throughout the entire research process

	Chapter 01* Baseline	**Chapter 02** Champion	Improvement from previous result	**Chapter 03** Envelope optimisation	Improvement from previous result
Tower - 1x1 - 15x10					
Daylight Factor [%]	5.69 %	-	-	-	-
Spatial Daylight Autonomy [%]	-	100 %	-	82.4 %	**- 17.60 %**
Solar potential [kWh]	13.25 $.10^6$	same as Ch. 1	-	26.14 $.10^6$	97.28 %
PV Production [kWh]	1.79 $.10^6$	same as Ch. 1	-	2.97 $.10^6$	65.92 %
ST Production [kWh]	0.91 $.10^6$	same as Ch. 1	-	4.46 $.10^6$	390.11 %
Energy demand [kWh/m^2]	72.39	63.53	12.24 %	62.19	2.10 %
Final Energy Use [Demand - production] [kWh/m^2]	12.63	3.77	70.15 %	0 (Production of 36.7 kWh/m^2)	100 %

[Source: the author]

*__Note__: Chapter 01 Baseline accounts for the energy demand considering the systems assumption for heating and cooling but with the appliances and artificial lighting based on the number of people and schedule, not yet accounting for the real daylighting conditions and the real need for artificial lighting. The energy use result that accounts for the daylighting condition and therefore real artificial lighting requirement is the one reported for Chapter 02.

This finding that it is possible to make the building produce energy above what it requires to function traces back to a concept of *energy-plus buildings*, that was mentioned on page 19, and now it is exciting to say it is an achievable goal according to the findings of this research.

3.4. COURTYARDS: COURTYARD 2 DIV - E/W - DEPTH 10m

The best performing courtyard case amongst this typology has a great output on its very low final energy demand found in Chapter 2: only 6.99 kWh/m^2 required from the energy grid. Interestingly, it's the case with more divisions in the courtyard. One might have thought that the cases with a greater inner patio would perform better. In reality, comparing the "2 div" and "No Div" both in 10 meters depth, they presented similar sDA values, but the case with greater courtyard showed a higher glare risk as well as more energy required from the grid. This is probably due to the fact that, giving the low height of the courtyard building, the element that really works for solar capture and therefore energy production is the roof, and the case with 2 divisions (5,200 m^2 of roof area) has almost 1,5 times the roof area than the case with No Divisions (3,600 m^2).

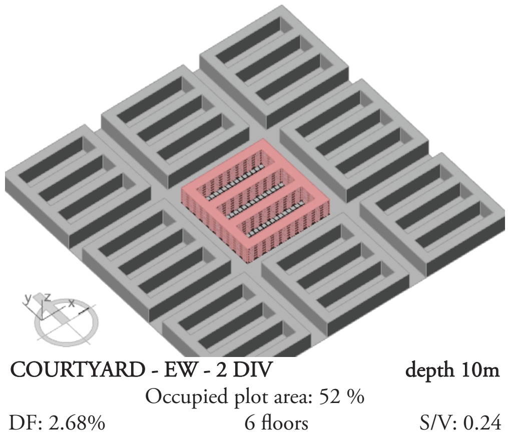


Figure 68: Visual aspect of the case COURTYARD 2 DIV E/W - DEPTH 10m when evaluated purely on terms of building form and massing, and its outputs from earlier stages of this research. [Source: the author]

As the solar potential is so significant in this case, let's look at some numbers to be able to make a fair comparison after the changes to improve the envelope are proposed: In Chapter 01, this case study receives a total of 11.93 .10^6 kWh of annual solar radiation on the envelope, from which the PV panels produce 1.61 .10^6 kWh of electricity, which covers 81.1% of the requirement from cooling and heating needs, artificial lighting and appliances, and 0.84 .10^6 kWh of thermal energy, that covers 107.5% of the Domestic How Water demand.

The energy performance is very good, but some strategies can be looked at to make it even more efficient. Nonetheless, the daylight conditions are not excellent: 65% of the Spatial Daylight Autonomy is what concerns the most, giving it is not even falling under the >75% "preferred by occupants" range.

The ASE of 24.4% is not a concern, even though the ideal is lower than 10%, it can be easily managed with manual or automated blinds, as mentioned previously in other cases.

To tackle those aspects and improve the building performance, some actions were taken in this specific case: to improve the internal daylighting condition, the WWR that was previously 0.3 was adapted according to the need for each floor. The bottoms floors were quite dark having only 30% glazing, so now the ground floor and second floor will have 0.5 as WWR. The third and fourth floors have a 0.4 WWR and the fifth and sixth floor the original 0.3 WWR. Besides changes in the opaque x transparent relationship, the windows were redistributed: before they had a sill height of 1.1m as more traditional residential buildings, but now the windows start only 20cm above the floor, becoming higher than the previous setting. This alteration can bring some technical issues like the requirement of a barrier at 1.1m height, but this is easily manageable with a number of different solutions. The positive side of the window with almost full height dimension is that the daylight can penetrate further, and distribute more uniformly over the space.

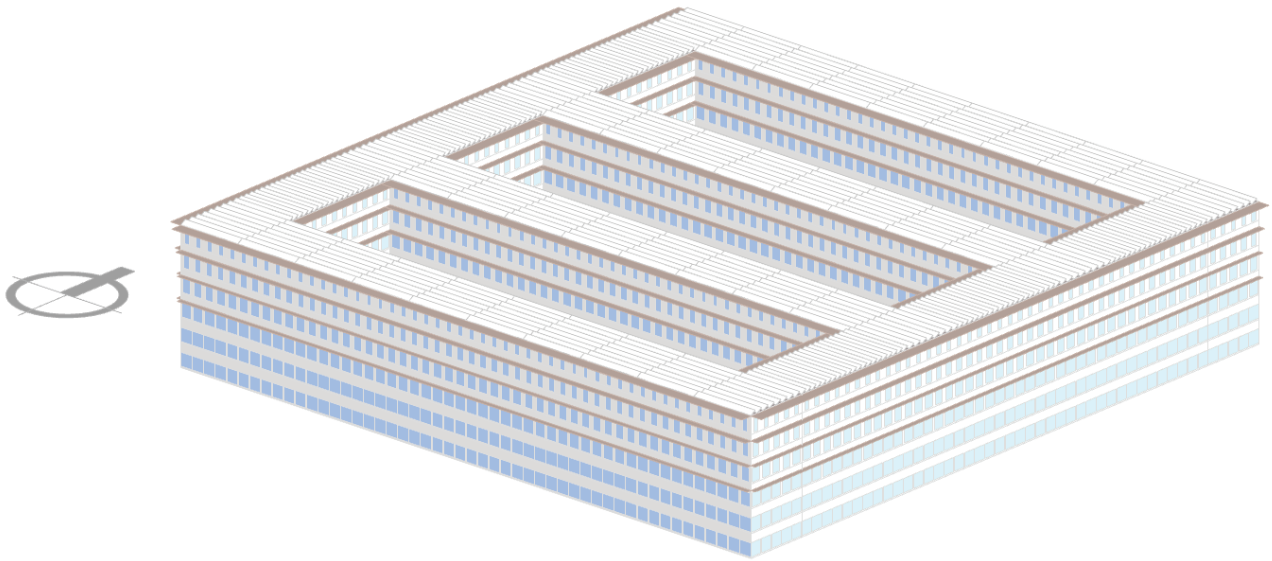


Figure 69: Visual aspect of the case COURTYARD 2 DIV E/W - DEPTH 10m when the improvement strategies are already applied. [Source: the author]

As in the case of towers, overhangs were added at the three top floors of the building. They aim to mitigate glare and reduce the cooling load. However, this case required more fine-tuning because daylight needs to be allowed in, and then the overhang dimension starts at the upper floor with 1.5 meters (Figure 70), but it decreases as the floor becomes lower, and the three bottom floors do not received overhangs. Moreover, as it can be seen in Figure 70, the overhangs were placed on the east, west and south elevations of the building, but not on the north, since it is an already dark elevation, the overhangs were not going to be beneficial in this location.

Two more strategies were applied here, both aiming to improve the energy performance of this case: firstly, instead of evaluating only the horizontal roof and envelope to understand the amount of solar radiation received annually, the PV panel surfaces were modelled on the roof and were tilted 30 ° to obtain a better angle towards the sun rays. After that, the thermal performance of the envelope was revised and the opaque facade U-Value decreased from 0.38 W/m²K to 0.21 W/m²K and the transparent U-Value was improved from 1.98 W/m²K to 0.8 W/m²K.

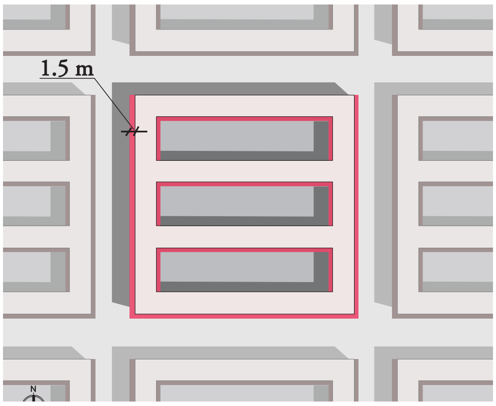


Figure 70: Overhang addition shown in darker red. [Source: the author]

Before looking at the results from the changes, in Figure 71 it is possible to see a summary of the modifications, that are pretty simple design moves but can produce a significant upgrade in the building performance.

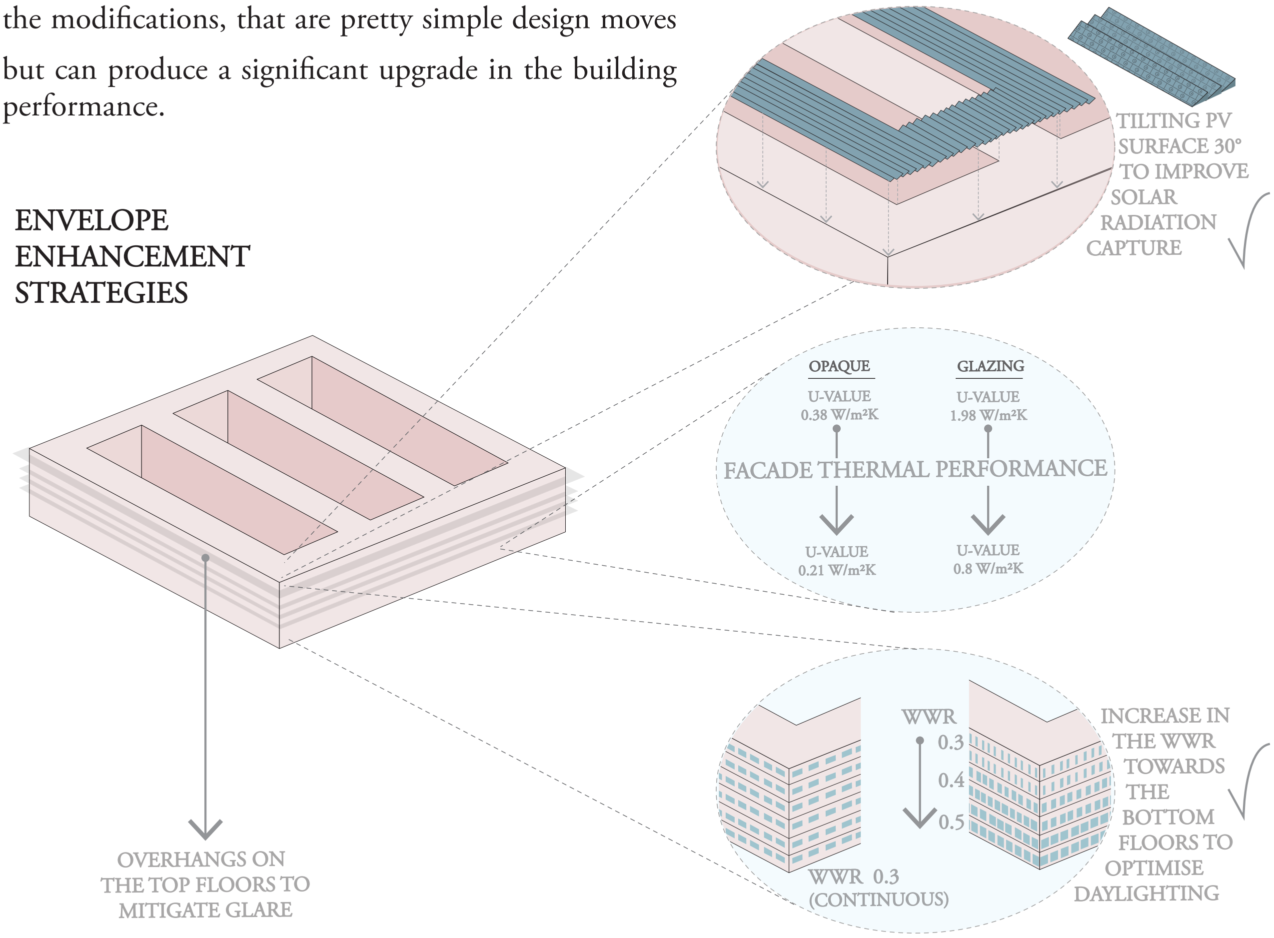


Figure 71: Envelope enhancement strategies for the Courtyard E/W 2 DIV - depth 10m [Source: the author]

After running the simulation again with these new actions, it is satisfactory to see that the biggest concern from before, the daylighting conditions, were successfully improved. The sDA is now 86.8%, a considerable increase from the previous output of 65%. Moreover, not only the percentage of well-lit space increased but in the plan floor output it is visible that the light is better distributed and more uniform along with all the space, whereas before it was concentrated almost punctually on the windows locations, as it can be seen in Figure 72. There was not so much change in the glare risk, as previously the ASE value was 24.4% and now it has decreased slightly to 22.4%. If looking at the numbers breakdown, it seems the overhang was more useful to decrease the cooling load and to distribute more uniformly even the plan floor areas at glare risk. However, as stated previously, glare is not a concern because it can be easily managed with blinds, brise-soleils, glass coatings and so on. Having a low number is enough to know that further detailing on the next stages of the design process will be able to solve this issue.

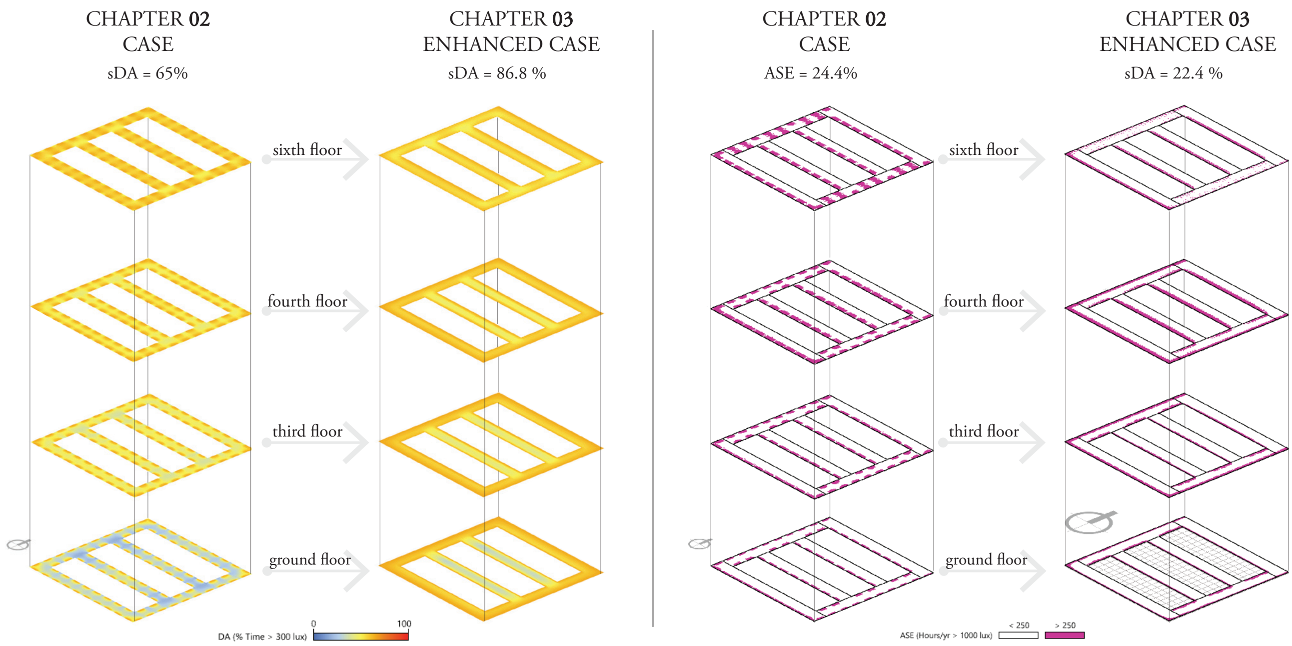


Figure 72: Comparison between the daylighting conditions from the cases prior the design moves proposed in Chapter 03 and the new outputs after them. [Source: the author]

As it was discussed in Chapter 01 when talking about the Courtyard typology, once again it is shown that the solar potential really reaches a ceiling and probably has arrived at the maximum benefit one can extract from this massing, as the solar potential practically remained the same. The case with the PV panels tilted 30° towards the sun proved that this angle didn't make such a difference then when oriented on the flat horizontal surface. The case presented 11.85 $.10^6$ kWh of solar radiation capture over the year, from which it was possible to produce 1.52 $.10^6$ kWh/m^2, an amount that did not cover 100% of the electricity demand but increased a little since Chapter 2, reaching 89.4%. The coverage of DHW by the solar thermal systems also increased, with an annual number of 1.19 kWh/m^2, covering 151.4% of the demand. This shows, of course, that the thresholds that divide the useful solar radiation in either PV panel system or ST system should be adapted to this scenario, making better use of the 51.4% of energy production that is currently not considered in the electricity calculation. The solar radiation study output can be seen in the following Figure 73:

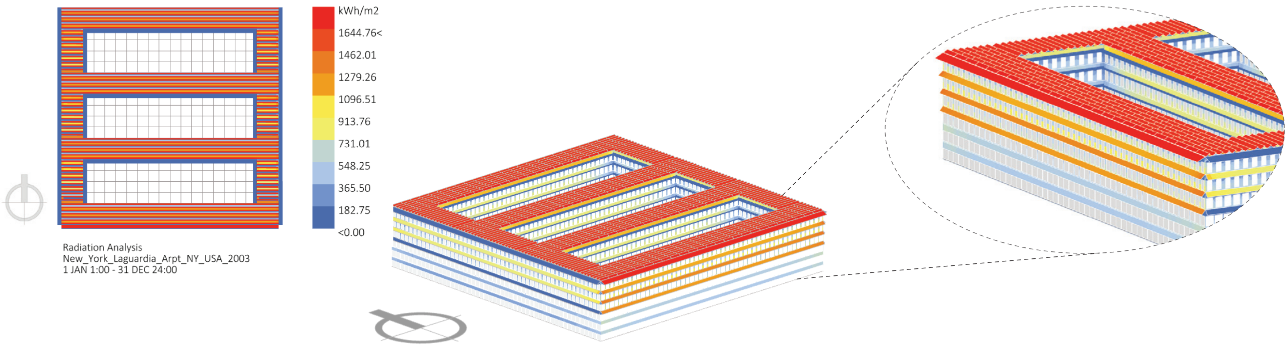


Figure 73: Solar radiation output from Ladybug+Honeybee simulation in Grasshopper. [Source: the author]

At last, a few words on the final energy performance. The effect of the modifications on the final energy demand, after deducting what is produced from renewables, was not excellent: it decreased from 6.99 kWh/m^2 to 6.02 kWh/m^2. Improving the envelope thermal performance had significant effects that were counterbalanced by the small decrease in solar production. For instance, the thermal heating demand itself decreased from 8.43 kWh/m^2 to 2.36 kWh/m^2 and the cooling load from 25.03 kWh/m^2 to 24.5 kWh/m^2. However, the redistribution of the solar radiation between the two systems redefined the balance for the final energy demand. To clarify, the PV system production was 1.61 .10^6 kWh and decreased to 1.52 .10^6 kWh, while the solar thermal system production was 0.84 .10^6 kWh and increased to 1.19 .10^6 kWh. Therefore, the overall solar potential remained practically the same, but the thresholds to use solar radiation should be adapted and only then the results will be notably improved.

This balance is clearly seen in Table 23, where the improvement in daylight conditions is highlighted, as well as the solar potential remaining overall the same (worsening 0.67 %) and the redistribution in the active systems energy production. This is a clear output of the still high potential that the courtyard typology has to improve in daylight after the early-design stage. This is a typology with low height and low energy demand, and it can be quite exciting to know that with the correct design, it can also achieve a very good indoor daylighting scenario.

Table 23: Courtyard case study building performance comparison throughout the entire research path

	Chapter 01* Baseline	**Chapter 02** Champion	Improvement from previous result	**Chapter 03** Envelope optimisation	Improvement from previous result
Courtyard - 2 DIV - E/W - Depth 10m					
Daylight Factor [%]	2.68 %	-	-	-	-
Spatial Daylight Autonomy [%]	-	65 %	-	86.8 %	33.54 %
Solar potential [kWh]	$11.93 .10^6$	same as Ch. 1	-	$11.85 .10^6$	**- 0.67 %**
PV Production [kWh]	$1.61 .10^6$	same as Ch. 1	-	$1.52 .10^6$	**- 5.59 %**
ST Production [kWh]	$0.84 .10^6$	same as Ch. 1	-	$1.19 .10^6$	41.66 %
Energy demand [kWh/m²]	66.03	60.57	8.27 %	56.73	6.34 %
Final Energy Use [Demand - production] [kWh/m²]	12.45	6.99	43.85 %	6.02	13.87 %

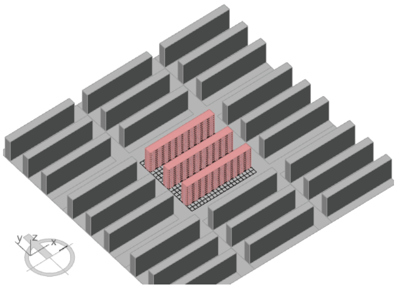
[Source: the author]

**Note: Chapter 01 Baseline accounts for the energy demand considering the systems assumption for heating and cooling but with the appliances and artificial lighting based on the number of people and schedule, not yet accounting for the real daylighting conditions and the real need for artificial lighting. The energy use result that accounts for the daylighting condition and therefore real artificial lighting requirement is the one reported for Chapter 02.*

3.5. BARS: BAR - 3 E/W - 100x10m

The bar cases have proven to be less effective in the final energy demand and this is due to a number of factors. First of all, they present the lowest solar potential, mainly due to overshadowing from one building to another and the limited amount of roof area. As a result, the electricity production from the PV panels is low: the BAR cases have a production of around 43 kWh/m², while courtyards and towers mainly range from 50 to 60 kWh/m², and the solar thermal production is not so great, but still covers around 90% of the domestic hot water. This means that the majority of the radiation on the envelope is falling under the lowest threshold area, that is selected to ST production and not much direct high solar radiation, that should be directed to the PV system to cover for the electricity need.

For the final energy demand found in Chapter 02, not considering the renewable systems production, the case for 3 BAR E/W 100x10m has a requirement of 62.10 kWh/m^2. After offsetting the energy produced, the energy requirement from the grid is 19.23 kWh/m^2. The interesting part of that is that the gross energy demand is quite similar to the other cases and typologies, even lower than some towers cases that were selected as Champions. On the other hand, the net final energy requirement is quite higher than the other typologies. This means that solar production is the key point and the main issue to be dealt with in this improvement attempt.



BAR - EW - 3 100x10m
Occupied plot area: 30 %
DF: 3.12%
10 floors S/V: 0.25

Figure 74: Visual aspect of the case 3 BAR E/W - 100x10m when evaluated purely on terms of building form and massing, and its outputs from earlier stages of this research. [Source: the author]

Other outputs from Chapter 02 must be reminded here for the sake of comparison, and still on the solar potential matter, the regular massing for bars oriented with the longer axis from east to west, on the dimensions of 10x100m had an amount of 9.64 .10^6 kWh of annual solar radiation on the envelope, which resulted in a PV system production of 1.29 .10^6 kWh of electricity, that was able to cover 63.60% of the electricity demand for cooling, heating, artificial lighting and appliances. Furthermore, the Solar Thermal production was 0.74 .10^6 kWh, an amount that was able to cover 94.7% of the Domestic Hot Water Demand.

In terms of daylighting, the numbers were not great but were acceptable: a Spatial Daylight Autonomy of 69.80% and a low glare risk of 25.30% in the Annual Solar Exposure metric. The sDA is not falling under the best category, which would be 75% and above, and the actions taken in this case aim to improve that as well as to improve the solar radiation capture, as mentioned before.

The first action was tilting the buildings in order to increase the solar exposure of the south facade. This move is likely to increase the capture of direct solar radiation, that is directed to the PV system and was pretty low in the previous scenario. The act of tilting the building also aims to improve the daylight conditions internally, and that combined with the strategy of increasing the Window to Wall Ratio towards the bottom floors, that presented a lower sDA before, should be able to provide some enhancements.

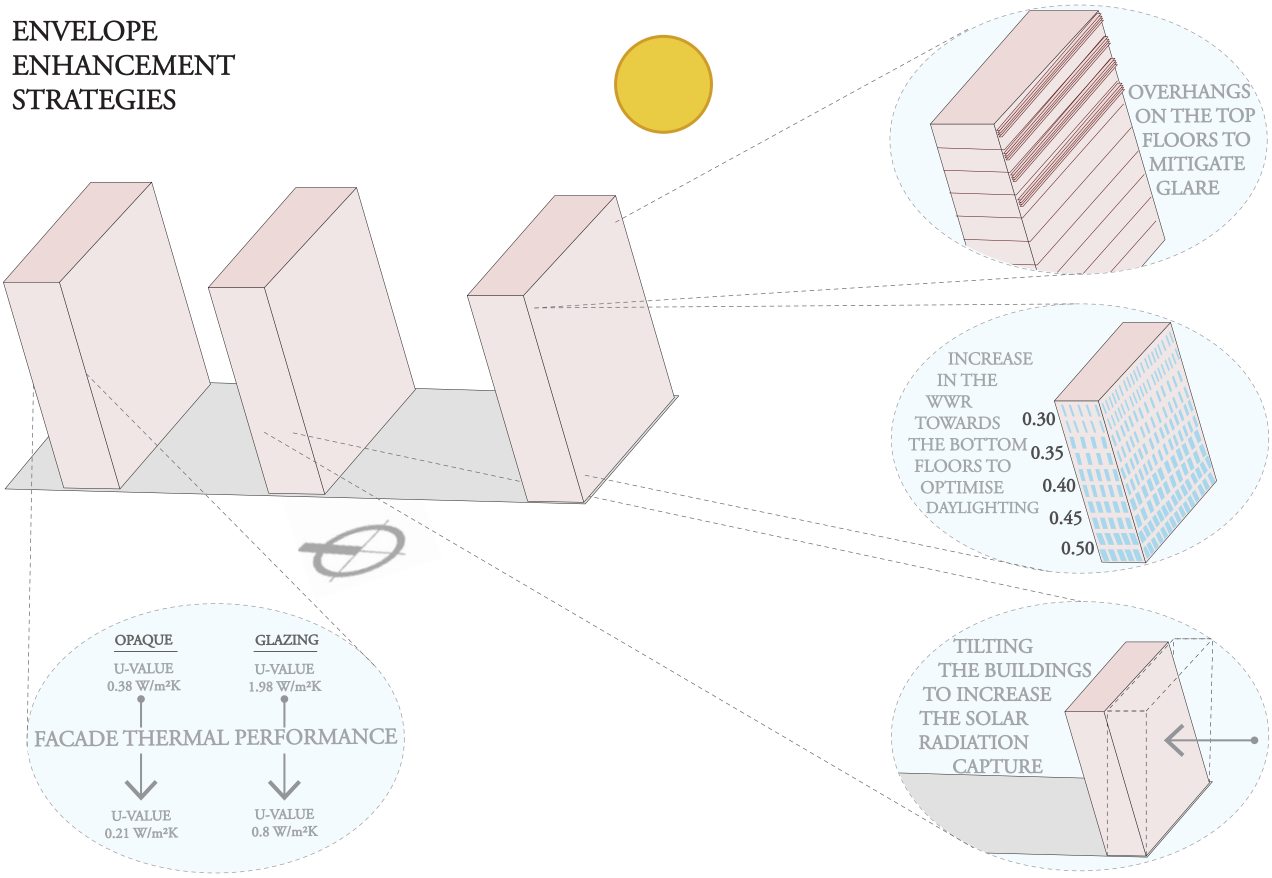


Figure 75: Envelope enhancement strategies for the case of 3 BARS E/W - 100x10m [Source: the author]

It should be highlighted that the above-mentioned actions in this case study are likely to improve the glare risk, and trying to mitigate that horizontal louvres were added to the windows on the top floors of the south facade. In this case, large overhangs could also help the glare situation, but they would cause a significant shadow on the envelope that would harm the solar capture, practically cancelling the benefits gained from tilting the building. On the energy side, as it was done for the previous 2 cases, the thermal performance of the envelope was revised and the opaque facade U-Value was decreased from 0.38 W/m^{2}K to 0.21 W/m^{2}K and the transparent U-Value was improved from 1.98 W/m^{2}K to 0.8 W/m^{2}K. All of these changes are summarized in Figure 75.

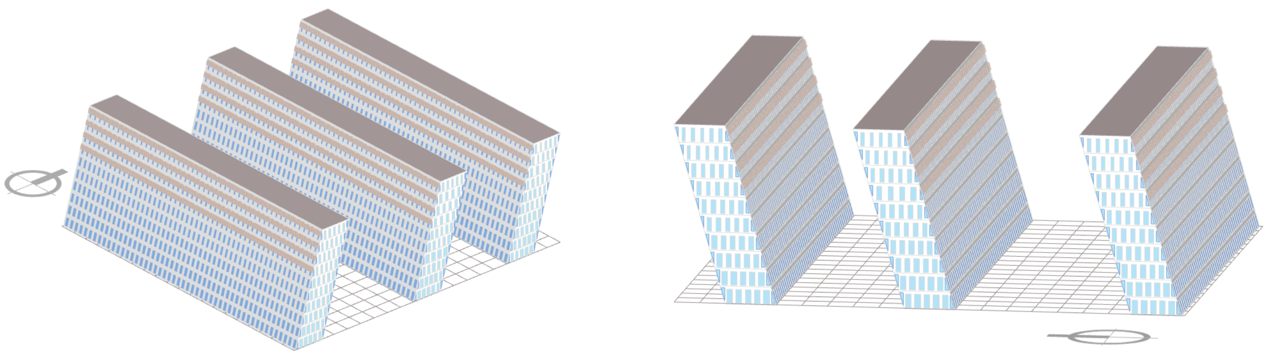


Figure 76: Visual aspect of the case 3 BARS E/W - 100x10m when the improvement strategies are already applied. [Source: the author]

After running the simulation with the modifications, it turns out that the assumptions were correct and just by changing the façade angle, the solar capture greatly improved. For this scenario, the buildings will receive $10.7 .10^6$ kWh of total annual solar radiation on the facade and roof, a 12% increase from the last value. The interesting is not only that, but the resulting PV production is $1.55 .10^6$ kWh, representing an increase of 21% from the last PV production. This means that the new building form is able to capture more direct and high solar radiation, which was one of the first goals. However, the lower threshold solar radiation has suffered a decrease, resulting in a ST production of $0.26 .10^6$ kWh, which covers only 33% of the demand for DHW. The rest of the demand is then converted into electricity and added to the energy demand that will be covered by PV. The outputs of the solar radiation study can be seen in the following Figure 77.

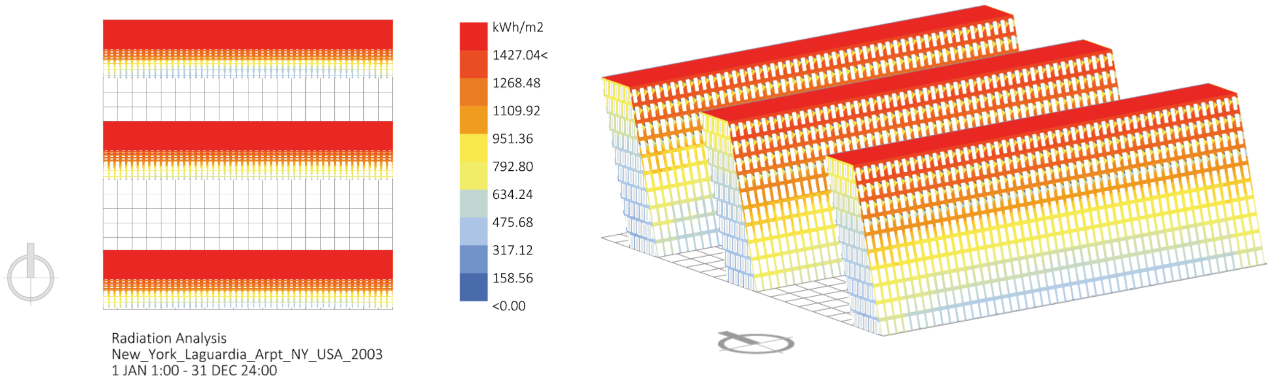


Figure 77: Solar radiation output from Ladybug+Honeybee simulation in Grasshopper. [Source: the author]

The energy requirement suffered some benefits but also some drawbacks. The artificial lighting requirement has decreased 1.6 kWh/m² due to the better daylighting conditions, and the heating demand has decreased significantly with the envelope's improvement on thermal performance: from 3 kWh/m² of thermal energy to 0.65 kWh/m². On the opposite direction, the higher exposure to solar radiation has caused an increase in the cooling requirement from 25.3 kWh/m² to 35.2 kWh/m², and that combined with the increase in the energy to cover the domestic hot water demand that couldn't be covered with the ST system, resulted that the gross energy demand was actually higher than the previous one: a total of 68.05 kWh/m² (an increase of 5.95 kWh/m² - or a 9.58% worsening - from the results in Chapter 02).

However, when deducting the now improved PV production from this demand, that is when the trade-off proves to have paid off: the final energy requirement from the grid is 16.28 kWh/m². A 15.34% improvement from the last scenario. Therefore, it is visible that it is not an enormous problem having the energy demand increase slightly if the renewables' production is optimised to cover it. Of course, highlighting once again, this is just a simple attempt to improve results with known actions, and the cases can be much more balanced and fine-tuned in a more detailed approach and consideration.

Regarding the daylight outputs, the expected happened. The Spatial Daylight Autonomy has increased to 86% and shows a much more uniform internal light distribution, as it can be seen in Figure 78. Another output that could be foreseen was the slight increase in the glare risk: ASE of 30.2%. Even with the horizontal louvres, they were not enough to prevent glare from happening in the most exposed positions. This matter will have to be dealt with probably with a combination of factors, like internal blinds and the horizontal louvres in a denser scenario.

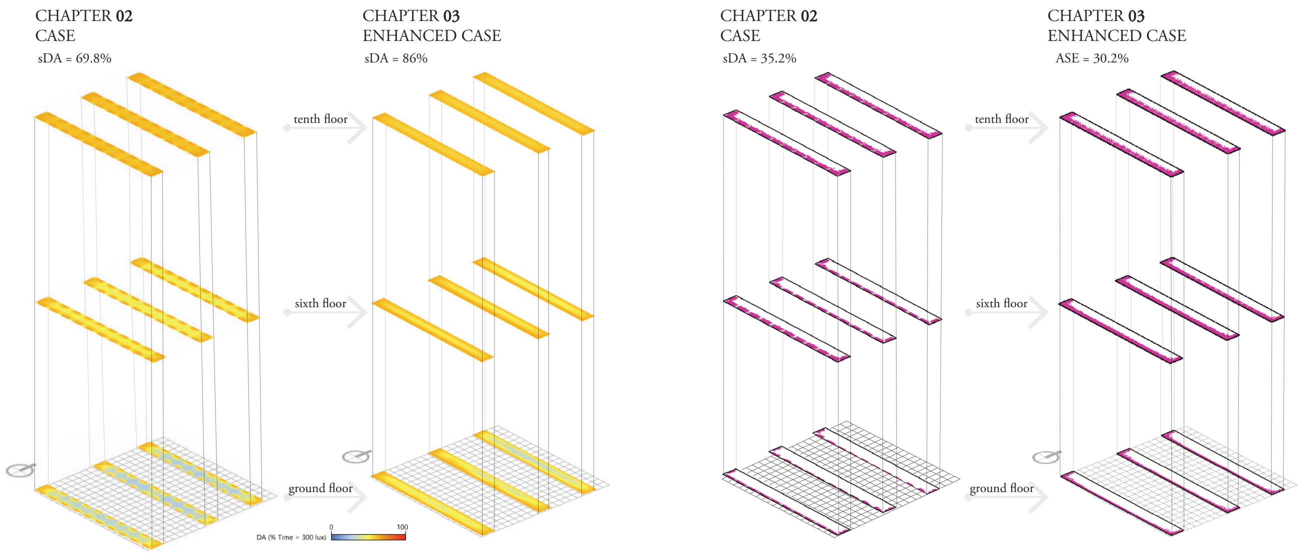


Figure 78: Comparison between the daylighting conditions from the cases prior the design moves proposed in Chapter 03 and the new outputs after them. [Source: the author]

For this last case, it can be said that the changes were positive but not really greatly effective. The slight improvements in daylight and solar capture as well as the worsening in ST Production and energy demand can be evaluated in the summary of outputs for each scenario, in Table 24. Furthermore, the results continue to not be great when comparing to the previous two cases evaluated in Chapter 03, that presented "room" for a lot of improvement while for the bar case the improvement happened, but not enough to make it at least near to a zero-energy building, for instance. This once again proves that a key decision the designer has to make in the early-stage design is on the typology and massing, that will be carried to all the design process and is, in fact, one of the main responsible for the consequences on energy performance, later on, both positive and negative.

Table 24: Bar case study building performance comparison throughout the entire research path

	Chapter 01* Baseline	**Chapter 02** Champion	Improvement from previous result	**Chapter 03** Envelope optimisation	Improvement from previous result
Bar - 3 - E/W - 100x10m					
Daylight Factor [%]	3.12 %	-	-	-	-
Spatial Daylight Autonomy [%]	-	69.8 %	-	86 %	23,21 %
Solar potential [kWh]	9.64 $.10^6$	same as Ch. 1	-	10.7 $.10^6$	11.00 %
PV Production [kWh]	1.29 $.10^6$	same as Ch. 1	-	1.55 $.10^6$	20.20 %
ST Production [kWh]	0.74 $.10^6$	same as Ch. 1	-	0.26 $.10^6$	**- 0.67 %**
Energy demand [kWh/m²]	67.40	62.10	7.86 %	68.05	**- 9.58 %**
Final Energy Use [Demand - production] [kWh/m²]	24.53	19.23	21.61 %	16.28	15.34 %

[Source: the author]

**Note: Chapter 01 Baseline accounts for the energy demand considering the systems assumption for heating and cooling but with the appliances and artificial lighting based on the number of people and schedule, not yet accounting for the real daylighting conditions and the real need for artificial lighting. The energy use result that accounts for the daylighting condition and therefore real artificial lighting requirement is the one reported for Chapter 02.*

3.6. FINAL ASSESSMENT ON THE EVALUATED CASE STUDIES

Following the same exact numbers provided in Table 22, Table 23 and Table 24, two graphs were developed to aid on the visual understanding of the three cases, how they improved with the proposed design actions on the envelope scale and more than that, how they compare to the other two typologies in the two scenarios: the first with the outputs from Chapter 02 and the latter with outputs from Chapter 03.

For both the following Figures, the chart shows the main outputs for the three cases studied more in detail here in Chapter 03: Tower 1x1 15x10, Courtyard 2 Div E/W depth 10m, and Bars 3 E/W 100x10m. They show the main outputs combined to visualize and compare: daylighting conditions based on the percentage of sDA and ASE, the energy gross demand and energy net demand (after offsetting the renewables contribution) in kWh/m2, both plotted on the left Y-axis, and the solar potential in terms of solar radiation, PV production, and ST production, in annual kWh plotted on the right-sided Y-axis.

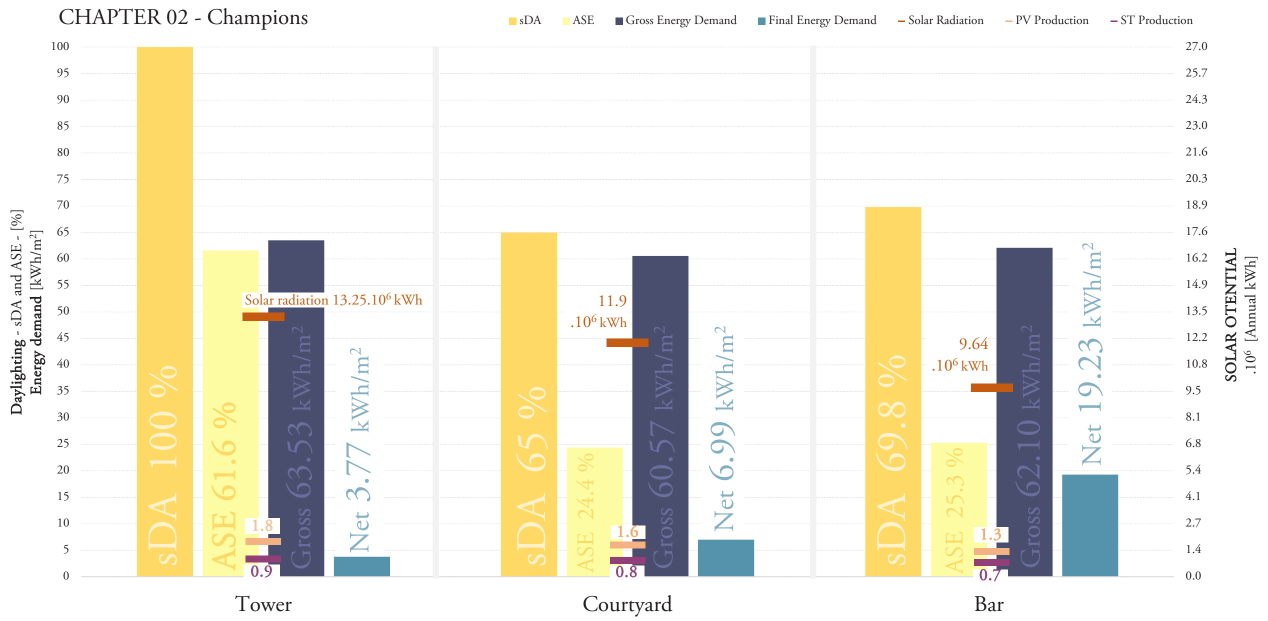


Figure 79: Daylight (sDA and ASE), Energy (Gross demand and Net demand) and Solar Potential (Annual solar radiation, PV production and ST production) outputs from Chapter 02, for the three cases studied in Chapter 03 before the envelope enhancements. [Source: the author]

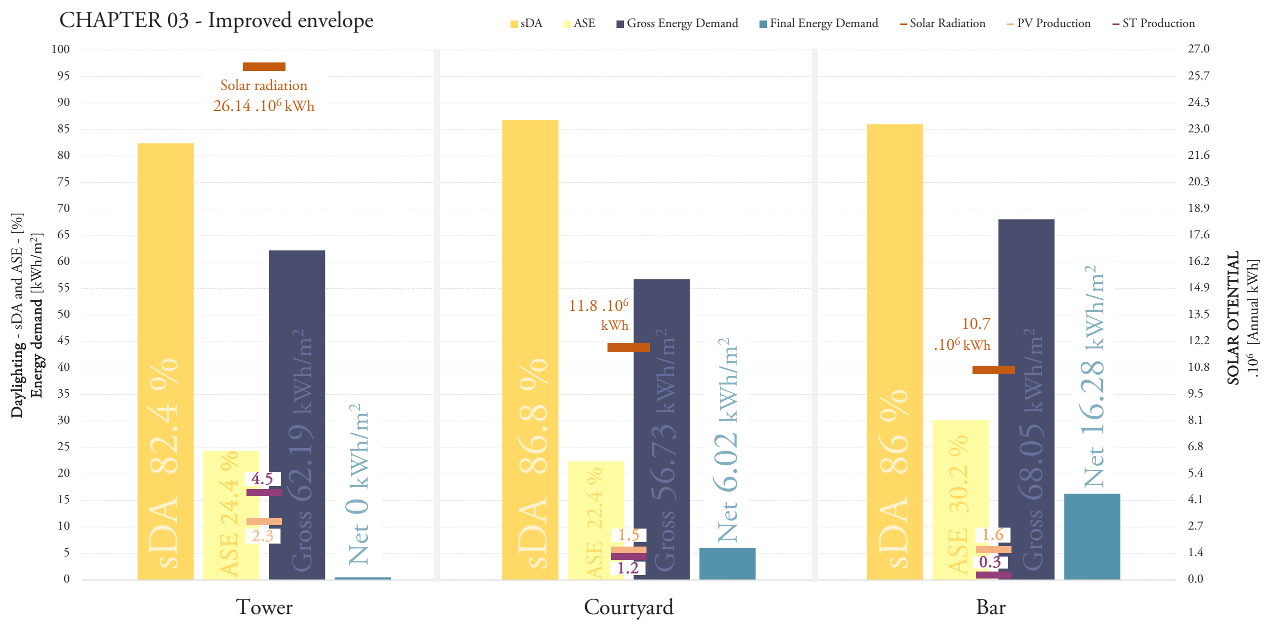


Figure 80: Daylight (sDA and ASE), Energy (Gross demand and Net demand) and Solar Potential (Annual solar radiation, PV production and ST production) final outputs from Chapter 03, for the three cases studied here after the envelope enhancements. [Source: the author]

In Figure 79, there are the outputs from Chapter 02, where the daylighting condition was measured and the artificial lighting consequence of the indoor illuminance levels is considered in the energy demand calculation. It is possible to summarize the finding showed there and already discussed all over this research:

- The tower case has the greatest solar potential, followed by the courtyard and lastly the bar case;

- The tower case also presents the highest sDA percentage and consequently ASE percentage, in this case followed by the bar case and lastly the courtyard;

- Courtyard presented the lowest gross energy demand, followed by the bar case and placing the tower case in the most energy-consuming case of the three.

- Offsetting energy production from demand makes the tower case to have the lowest net energy requirement, followed by the courtyard and only after that, with a significant difference, the bar case.

From that, moving on to Figure 80, the exact same cases' outputs are shown but after suffering the changes proposed by the envelope enhancement strategies discussed and simulated in this Chapter 03. The findings visible there are also summarized here:

- Tower case has improved greatly the solar potential, while the courtyard remained (practically) the same and bars improved slightly. The ranking remains the same as in Figure 79: towers receiving the highest amount of solar radiation, followed by courtyard and with bar case in the last position;

- Tower case has suffered a decrease in the daylight conditions (sDA) but the high glare risk was controlled. For this scenario, all three cases are equally performing with good daylighting conditions.

- The design strategies have altered the trend from gross energy demand: the courtyard is still the lowest consuming case, but now the tower case occupies the second place (showing the previously high energy requirement can indeed be optimised) and leaving the bar case showing the highest gross energy use.

- Matching energy production and demand, the result is the same trend from before the envelope strategies. Tower case presents an outstanding performance with 0 kWh/m^2 requirement as net energy demand (in fact, it is producing more energy than it consumes), followed by the courtyard case (that likely can be improved to become an energy-zero building) with the bar case as the least performing one on energy use.

CONCLUSIONS

There are no more doubts that Baker and Steemers were right when stated that *"there is growing evidence that the environmental performance of buildings is determined, to a considerable extent, at the conceptual stage"* [21]. This research corroborates that the decisions taken at early-stage design are crucial to achieving the desired performance. Whether we are speaking of aiming for "only" sustainable buildings, zero-energy or even energy-plus buildings, the massing, site location and building orientation can impact greatly on the final efficiency of the building, and this was demonstrated all over this study.

This study started with some fundamental research questions, wondering if building mass can be a determining factor at the early-stage design to influence building performance and, if so, if it would be possible to identify a typology that stands out. Besides, if the discovery is that a building form does impact the performance, would it be possible to mitigate possible problems caused by the wrongful decision-making with envelope scale strategies?

To search for some answers, in 'CHAPTER 01. Massing and Performance', three residential building typologies (towers, courtyards and bars) were tested to identify emerging trends in energy-related indicators affected by geometric variations of building mass. The work takes a methodical, iterative approach to test every reasonable geometric configuration of building mass within a 100mx100m urban plot, using 5-m step intervals to vary building's depth, length and height, as well as the distance between buildings and from buildings to the property line. A total of 312 cases corresponding to a constant FAR=3 have been tested using 3 main indicators: energy demand (accounting for cooling, heating, artificial lighting and appliances), energy production (accounting for the amount of solar radiation falling on the building envelope and its energy production from PV and ST systems) and daylighting conditions (firstly with static metrics, and afterwards with climate-based metrics).

The plot is centred and 8 surrounding blocks were replicated to mimic urban context. Thermal parameters and the assumptions of a constant WWR = 0.3 were applied for all the cases (for the sake of comparison) always assuming values that are feasible and existent. On that, aiming to have the most updated possible data, the residential building program schedule was adapted to the new housing trend consequence of the COVID-19 pandemic. For this study, the "Residential 2020" schedule accounts for people staying more time inside their houses and not leaving every single day for work, which is now possible as technology and smart working became more advanced.

All of the scenario and case studies set, the simulation results have been tabulated, compared and ranked by grouping cases by typology and then making a comparison between the typologies themselves, as can be seen once again in Figure 81. The most significant patterns and trends that emerged from comparing results are described following:

TOWERS

It was possible to see that taller and thinner cases present a greater energy requirement for heating and cooling as well as a higher solar potential, due to the great envelope exposure to solar radiation, balancing one another. It was possible also to see that the Daylight Factor decreased as the aspect ratio increased (more towers on the plot, less daylight availability) and as the dimensions of the plan floor increase.

COURTYARDS

Presenting an overall low energy demand, the cases had good solar potential and somewhat limited daylight condition. The variation in height was not so great for most of the depths and distribution schemes, with an average of 7 floors (variation from 4 to 19 floors). This means that the solar potential was mainly guided by the amount of roof area available, that would receive direct high-level solar radiation, and consequently, the deeper buildings proved to take the best advantage of that. As matter of fact, the depth is, in this case, the indicator that most impacts the Daylight Factor and Energy demand outputs. While deep buildings have a lot of roof area to produce solar energy, they perform poorly in terms of daylight, with the depths of 20m and 25m ranging around 1.5 % DF, which is outside of the acceptable threshold (2 to 5%). Therefore, at this stage in Chapter 01, 10m and 15m deep cases were presented as the most viable cases, but the energy requirement for heating and cooling for the 15m cases was significantly lower than the 10m ones. Later on, daylight is re-assessed with climate-based metrics and this will make a difference in the courtyard outputs, revealing that 15m ones were not performing so great after all.

BARS

The bar cases were evaluated, showing that variations of floor depth (compactness) and the number of buildings (aspect ratio) have both an impact on energy demand and daylighting. Deeper buildings struggle with daylight conditions, while also present the lowest numbers for heating and cooling energy demand. More building on the plot (aspect ratio) means that the buildings behave as obstructions to the others, decreasing the Daylight Factor. On the solar potential, the longer cases (100m) gather more solar radiation because the driver is clearly the roof area and not the height of the building, that is practically negligible to solar potential due to the overshadowing effect. Taller and slender buildings, such as the ones with 10m, have good daylight and solar potential conditions due to the overshadowing minimisation. But the high aspect ratio and deep buildings also have a good solar potential due to the amount of roof area. It was also possible to understand that bars oriented along N/S, which means the wider façades facing east and west, received more solar radiation than the ones oriented E/W.

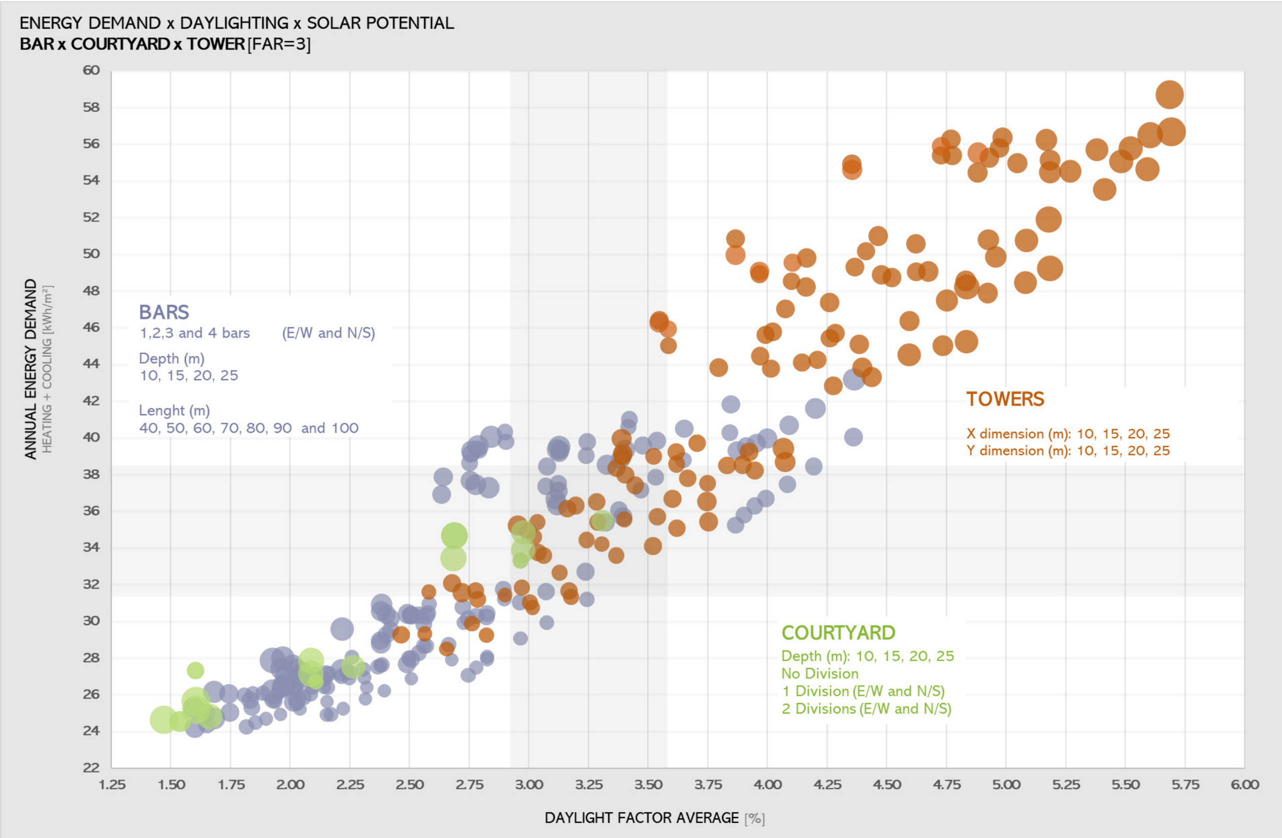


Figure 81: Overall scenario for TOWER, COURTYARD and BAR typology in terms of Daylighting Factor Average (x), Annual energy demand for heating and cooling (y) and Solar potential (dot size). [Source: the author]

These geometric variations were meant to test the most common morphology indicators, validating successfully some previous assumptions. Finally, results from all 3 typologies were tabulated on a single matrix (Figure 81) to identify any general trend pertaining to each typology intended as a "family", as well as to compare typologies in search for any potential "trait" belonging to a specific family. Some of the findings are:

- Tower cases present the highest energy demand and the highest Daylight Factor percentage, that increase as the buildings become taller and slender. Towers also are able to receive a great amount of solar radiation, making them good options also in solar potential requirements, and therefore final energy demand.

- Courtyards have a very low energy demand, with a good solar potential due to the roof area. They are, however, slightly limited in the Daylight Factor.

- Bars have a very limited possibility to receive direct high-level solar radiation, which results in having a high final energy demand. That's because even though the heating and cooling thermal requirement can be quite low, when including artificial lighting, appliances and domestic hot water, the requirement is not covered by the renewables production, while in the other two typologies with better solar capture, the demand and production are offset and end up performing better.

Until this point, Chapter 01 employed a simplified method that allowed for a relatively quick evaluation of a large pool of cases. This approach, of course, had some limitations on the grain and precision of analysis, like the fact that Daylight was accounted using Daylight Factor, a metric with some accuracy constraints, which led to the artificial lighting requirement being accounted as a fixed value in function of the program and square footage.

Thenceforward, 'CHAPTER 02. The Champions' relies on some assumptions to make use of these preliminary results to narrow the number of cases to only the “best” configurations (so-called “Champions”) in order to apply a more refined analysis.

Firstly, HVAC systems were assumed with the efficiencies, and secondly, it was assigned a threshold for the solar radiation received by the building envelope to rule on the active systems of photovoltaic panels or solar thermal collectors, making it possible to offset energy production and demand. Considering the net energy demand from the grid, the minimum of 2% of Daylight Factor and a minimum of 50% of the energy requirement being covered by renewable energy, it was possible to select the best 25 cases as the Champions, from which 7 are Bar cases, 8 are Courtyard Cases, and 10 are Tower cases. Interestingly, if looking again at Figure 56 on page 107, it is visible that they were placed in the middle of the graph, representing the compromise between energy demand and DF percentage, with exception of the towers that are placed towards the upper right end of the graph.

It was then possible to improve the level of accuracy on the daylight evaluation, applying the climate-based metrics of Spatial Daylight Autonomy and Annual Solar Exposure as they paint a daylight scenario based on the 8760 hours of the year, and thus much more accurately. The final energy demand shown here can be faced as a final synthetic indicator, as it accounts for the energy demand, offsetting energy production from renewables and also accounts for the daylight condition due to its consequence on saving or requiring more energy for artificial lighting. It is possible almost to rank the results and form a "Podium", which can be evaluated in Table 25.

This table shows the base numbers that were used to build Figure 59 on page 114. The best performing cases are evidently the towers, with the highest daylight sDA percentage and lowest final energy demand (in the Table ordered from lowest to highest). After the towers, courtyards also present a good overall scenario, with all the cases ranging on practically the same energy use but a very different daylighting condition. To highlight that, the cases in the table were then ordered by the greatest sDA % to the lowest. And finally, on the third position of the "podium" the bar typology cases show a higher final energy demand and a limited daylight percentage.

Table 25: Champions "Podium", ranking showing sDA and Final Energy Demand.

Champions	sDA [%]	Final electricity demand [kWh/m²]
Towers		
1x1 - 15x10	100	3.77
1x1 - 10x15	100	6.53
1x1 - 20x10	100	9.63
1x1 - 10x20	100	10.31
1x2 - 10x15	100	11.87
1x1 - 10x25	100	12.17
1x1 - 15x15	100	12.96
1x1 - 25x10	100	13.14
3x1 - 15x10	100	15.85
1x2 - 10x20	100	16.18
Courtyards		
N/S - 1 Div - Depth 10m	68.1	10.5
Variable Ctyard - No Div - Depth 10m	67.2	16.5
E/W - 1 Div - Depth 10m	66.2	10.2
E/W - 2 Div - Depth 10m	65	7.0
N/S - 2 Div - Depth 10m	64.3	7.2
Variable Ctyard - No Div - Depth 15m	54.4	12.4
N/S - 1 Div - Depth 15m	53.4	7.7
E/W - 1 Div - Depth 15m	53.1	9.0
Bars		
E/W - 3 Bars - 100x10 m	69.8	19.2
E/W - 4 Bars - 100x10 m	63.9	18.1
N/S - 4 Bars - 10x100 m	63.2	18.9
E/W - 3 Bars - 15x90 m	55.7	17.9
N/S - 3 Bars - 15x80 m	54.8	21.8
N/S - 3 Bars - 15x100 m	51.3	14.0
E/W - 3 Bars - 100x15 m	46.5	18.9

[Source: the author]

Still on the path of proving that the decision for massing does matter, the 'CHAPTER 03. Improving the Envelope' aimed to select the best performing cases for each typology and apply simple and validated strategies that could improve the results gathered in Chapter 02. Selecting the TOWER 1x1 15x10m, the COURTYARD 2 Div E/W - depth 10m and the BAR 3 E/W 100x10m (highlighted in Table 25), it was possible to make some changes that indeed improved the results. The outputs were:

- The tower case became an energy-plus building (producing more energy than it consumes) with excellent daylighting conditions.

- The courtyard case had its final energy demand from the grid decreased to a very low number that can certainly be further improved to reach a zero-energy building and its daylight conditions were improved greatly, reaching a very satisfactory level.

- The bar case was the one that least improved with the actions taken in the attempt of its enhancement, making it clear that one output from this research is that the decision for a bar typology in the early-stage design can lead to a least performing building regardless of the strategies applied afterwards.

Having all the steps analysed, it might be useful to remind the reader of a similar typology study [4] detailed in the Literature Review, more specifically on page 22, in which its results found that courtyards were presenting the lowest energy use when compared to the other typologies, and towers having the optimal daylight performance as well as having a significantly higher energy consumption. It can be seen that those results were confirmed at this research, and as the solar potential indicator was also considered, the results of energy were able to be counterbalanced by the renewables energy production, making it clear that, for instance, towers have the higher energy demand but also have a way of offsetting that with its great potential for solar capture.

To conclude, let's try to answer some of the research questions from page 29. It is visible that the careful consideration of each building component and its detailing impacts the building performance, but those measures only can do so far if the building massing was wrongfully chosen. Urban form and massing are, thus determining factors at early-stage design and influence greatly the final results.

From this research, towers and courtyards seem to have an advantage on the bar typology, while to be comparable in terms of performance courtyards present a low height and towers need to be very high, and this can be a factor to influence the design's decision according to site constraints and other aspects. Passive design measures can and should be taken along the design process to aid towards the desired performance, such as the implementation of overhangs or louvres or the manipulation of the building envelope, like was proved in Pavesi's work [5], and several other actions, but the starting point should be the correct and more appropriate typology risking to end up with an irreversible poor building performance at the end of the design process.

At last, according to the results found in this study and other results from previous literature, it is possible to make an echo to the statement from [5], that highlights the birth of *"a new architectural language - one that reconnects form to performance",* highlighting the importance of the perfect integration between architecture and engineering, technology and art, science and experience to achieve the goal of a better and more sustainable and efficient built environment.

FURTHER WORK

As this study is part of a broader research that happens in collaboration between Pratt Institute (NY, USA) and Politecnico di Milano (Milan, IT), a lot of the topics on building performance and optimisation, with a focus on solar capture, that were not covered in this thesis were already or will be dealt with by other colleagues.

As matter of fact, in parallel to this study, the thesis "Outdoor Comfort, Solar Potential and Building Form: Early-stage design guidelines for solar access regulation in summer urban environments (a case study in New York City)" is being developed by the colleague Ludovica Rossi, also an MSc student from the Building and Architectural Engineering program at Politecnico di Milano. In her research, outdoor comfort on the same typology case studies is analysed, following the same principles used for this study. It deals with an entire set of indicators different from the ones applied here, due to the fact that this research focused on the building and its indoor comfort levels. Meanwhile, the work from Ludovica studies the effect on the same buildings but for outdoor conditions.

From her research, it is stated that the ratio of horizontal to vertical surfaces is lower in urban areas, which inhibits heat loss through thermal radiation. This means that the expansion of large urban centres greatly affects global warming and this phenomenon is then called Urban Heat Island which determines the increase of neighbourhood temperatures. This concept is thus implicitly linked with outdoor comfort. The same case studies for tower, bar and courtyard are then tested on the basis of summer performance during the hottest week of the year, to determine their effects on the external temperature. Indicators like the UTCI (Universal Thermal Climate Index) are applied, taking into account the main environmental variables such as temperature, relative humidity, solar radiation and wind speed. After this first stage, another parameter is introduced and deals with solar potential (in her case, meaning the ability of the envelope to store solar energy). Lastly, she compares the parameters and identifies best performing cases, which are also called Champions, as was done in this study. To have this wide knowledge on indoor and outdoor parameters is intended to provide a global scenario, joining forces from both of the researches towards the improvement of building massing knowledge.

Furthermore, there are other works related to this that could be interesting to expand, such as other optimization objectives, including cost, other ways of energy generation, further facade detailing, and building life-cycle performance. Future work also could include the application of this optimization process on more complex design projects, where more design variables and constraints exist, and sensitivity analysis could be performed before the optimization to simplify the design problem.

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