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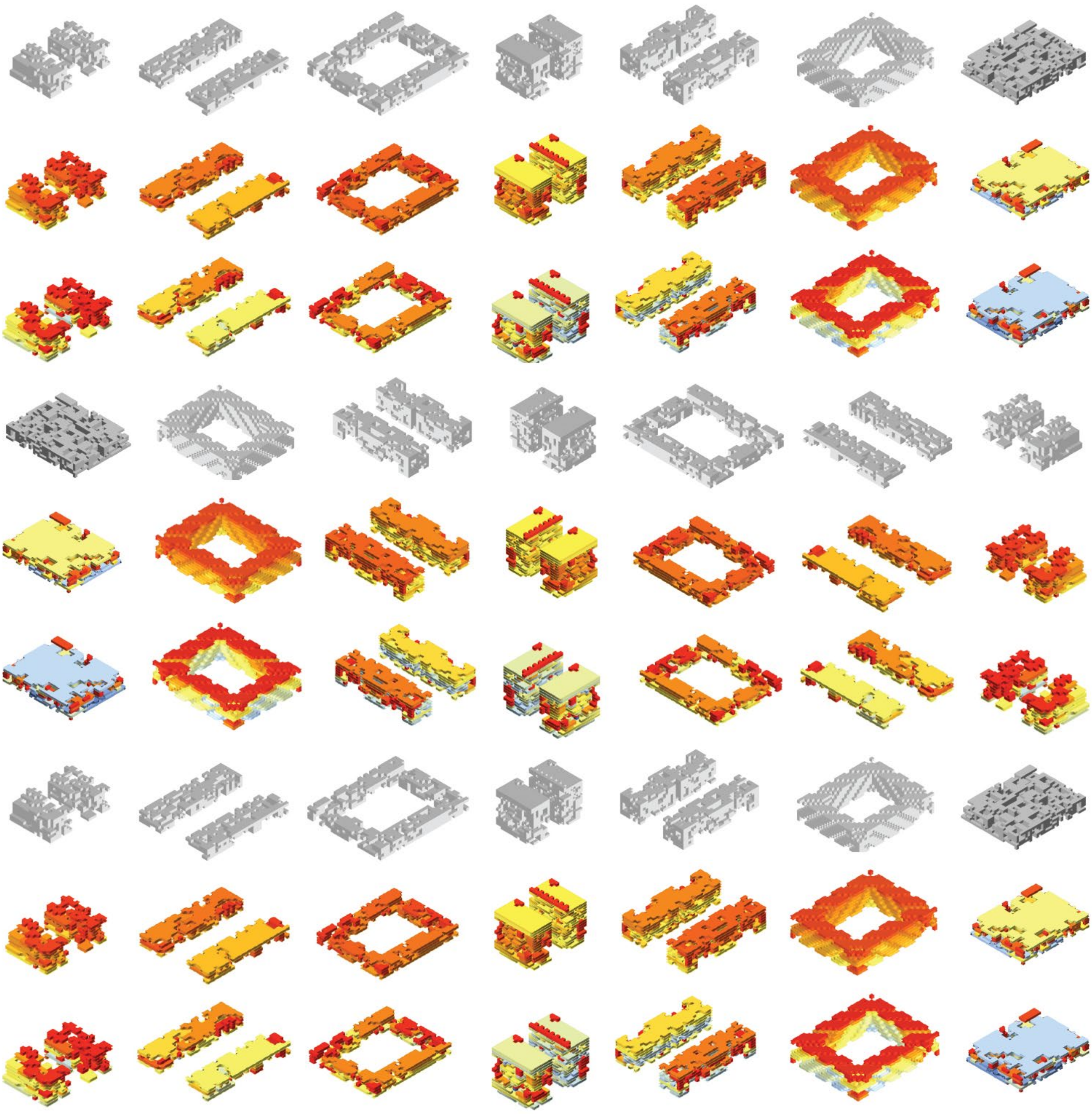

Cellular Automata:

A Bridge Between Building Variability and Urban Form Control

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ABSTRACT

In Porto Alegre, a Brazilian town with 1,5 million inhabitants, zoning guidelines assign similar density parameters but fail to be context-specific. As these regulations are linked to individual plot dimensions, physical growth resulted in heterogeneous and unpredictable urban space. The Floor Space Index (FSI) has been used as physical currency which influences the plot value there hence creating a straightjacket to architects wanting to explore new shapes. This research describes a simultaneous top-down and bottom-up strategy to allow urban rules to emulate architectural flexibility and, at the same time, to empower the city with morphological controls over the urban space. A proposed integrated model was set to generate a wide variety of geometries through the association of morpho-types urban blocks (top-down) to bottom-up strategies using cellular automata integrated to Rhinoceros' Grasshopper as a generative tool. The model includes context sensibility and daylight evaluation but runs with a similar FSI to the existing urban regulations. The proposed model was applied to an existing block in Porto Alegre demonstrating to be an effective tool to support the design of urban rules. It also indicated possible paths for built environment model integration and the creation of innovative perfomative urban indexes as building's porosity.

Keywords: *Generative Design, Urban Modelling, Cellular Automata, Daylight Simulation.*

RESUMO

O Plano Diretor da cidade de Porto Alegre paradoxalmente atribui índices de densidade por região geográfica ao passo que falha ao desconsiderar o contexto imediato. Uma vez que os índices aplicados estão associados às dimensões de cada lote, o crescimento do ambiente construído é restringido pela unidade de divisão territorial (lote) e resulta em um espaço urbano imprevisível e heterogêneo. Nesse contexto, o indicador de intensidade 'Índice de Aproveitamento' (IA) é usado como 'moeda física' pelos incorporadores, influenciando o valor do lote e limitando a exploração formal dos arquitetos, via de regra, a prismas regulares. Esta pesquisa propõe um modelo alternativo que une estratégias centralizadoras (top-down) e emergentes (bottom-up) a fim de possibilitar a flexibilidade arquitetônica e o controle da forma do espaço urbano simultaneamente. O modelo generativo proposto objetiva gerar geometrias variadas por meio da associação de tipologias morfológicas de quadra (controle) e autômatos celulares (emergente). O modelo gera edificações de IA similar ao existente e aos especificados no plano diretor ao mesmo tempo que é sensível ao contexto e avalia o desempenho de iluminação natural no ambiente de modelagem Rhinoceros 3D e programação visual Grasshopper. O modelo foi aplicado a uma quadra existente em Porto Alegre e os resultados demonstraram a sua eficácia como ferramenta de projeto para a concepção de regras urbanas. Os resultados indicaram a possibilidade de integração com modelos de outras naturezas e da criação de novos índices urbanos performativos como 'porosidade'.

Palavras - chave: *Design Generativo, Modelagem Urbana, Autômato Celular, Simulação de Iluminação Natural.*

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CONTENTS

LIST of FIGURES

LIST of TABLES

Introduction

The world is facing an unprecedented urbanisation growth. According to the United Nations (2014), the urban population has increased from 746 million in 1950 to 3.9 billion in 2014, and it is estimated to meet 6.34 billion in 2050. The projected growth estimates that there will be 62% more people living in cities in the same period, representing 66% of world's population. The UN report (op cit) asserts "As the world continues to urbanise, sustainable development challenges will be increasingly concentrated in cities, particularly in the lower-middle-income countries where the pace of urbanisation is fastest." The IBGE projections confirm that Brazilian cities might increase their population in 50 mi inhabitants (2010-2050), representing 91% of all Brazilian population in approximately 30 years from now. (IBGE, 2000) It is therefore of critical importance to develop knowledge on how urban growth will affect the world's sustainable development, not only with respect to the efficient use of natural resources but specifically how the city making will affect the urban inhabitants' life quality.

In recent times, the city-making process results from a negotiation between the **public** and **private** sectors and, since planning has taken part in the process, rules have mediated this negotiation (BERGHAUSER-PONT and HAUPT, 2010). Lehnerer (2010) defines rules as "precise and unambiguous formulations, yet they produce a multiplicity of alternatives realities." In the urban scale, rules role goes beyond to define multiple possibilities; it is a powerful public instrument to manage private interests. Regulations like zoning guidelines and construction codes specify rules and parameters to negotiate the space.

Whereas cities are recognised for its complexity, the process of urban planning (designing urban regulations) has historically been associated with an abstract reduction, not necessarily for the better (MARSHALL, 2012). Moreover, Beirão (2005) calls attention to the different speed of the urban planning and the city transformation resulting, thus, in regimes unable to absorb the renovations. While the configuration of cities drastically change in short periods of time, this transformation is not simultaneous with new mechanisms of land use regulation.

New buildings are built in consolidated areas without considering aspects as cultural context and ambience.

Brazilian cities are continually growing since 1950, and the projections infer that this process will continue for the following next decades (IBGE, 2000). After the 10.257 Federal Law known as 'City Statute' (*Estatuto da Cidade*) was passed in 2001, the regulation of land use concerning environmental aspects has intensified (BRASIL, 2001). To guarantee minimal habitability patterns, urban regulations addressed aspects as infrastructure, daylight accessibility and ventilation as major factors to enforce the control over the land use intensity, coverage, setbacks and maximum heights. Even before the City Statute's recent influence, major Brazilian cities have used different types of urban regulation to control the urban space quality and the vicinity between buildings.

That is the case of Porto Alegre, a town with 1.5 million inhabitants situated in the south of Brazil. Similarly to other cities in Brazil, Porto Alegre's current urban rules were inspired by hygienist urban planning. Conceptually embedded in these regulations, environmental issues such as daylight, solar radiation and ventilation are invoked to establish different types of volumetric constraints. The primary tool to control the city configuration is the Zoning Guidelines (*Plano Diretor*), which define (a) geometric and (b) analytic parameters to control buildings (a) shapes and (b) density. The zoning guidelines define indexes as (a) maximum building heights and (b) side setbacks proportional to building's height to control building shapes to control building's shapes. Zoning regulations define indexes as (a) maximum coverage related to the building's footprint (b) maximum floor space index (FSI) related to the building's construction potential (total area) to regulate density aspects. Like many growing cities, the basic goal for private investors directly involved in the city's development is to reach the maximum allowed FSI for each plot. The plot's building potential, functions as a physical currency, influencing the plot value. The public sector determines the rules to be applied in each city's plot thus influencing not only the shape of the building but also its value.

Porto Alegre's urban blocks feature a very heterogeneous pattern of plot sizes and building setbacks, which are directly related to these plot sizes. Zoning guidelines assign similar density parameter indexes for these plots but, at the same time, fail to be geometrically context-specific. The geometrical constraints being correlated to individual plot dimensions' result in an excessively heterogeneous and unpredictable urban space. Urban rules, like the ones in use in Porto Alegre, constitute top-down explicit strategy where a similar FSI value applies to different plots sizes; but have a complementary non-declared bottom-up strategy where the shape of the public space and the urban block non-built space is determined by the size of each plot. The random and excessive variation of building heights and setbacks do not correspond to optimal relations between buildings concerning natural light accessibility, nor helps to achieve the most consistent urban ambience. The diagram in Fig 1 illustrates the randomness of Porto Alegre's urban form in a block. The diversity of plots associated to the urban regime results in a wide range of heights and setbacks, which configures a too heterogeneous public space and uncontrolled and discontinuous space in the interior of the block.

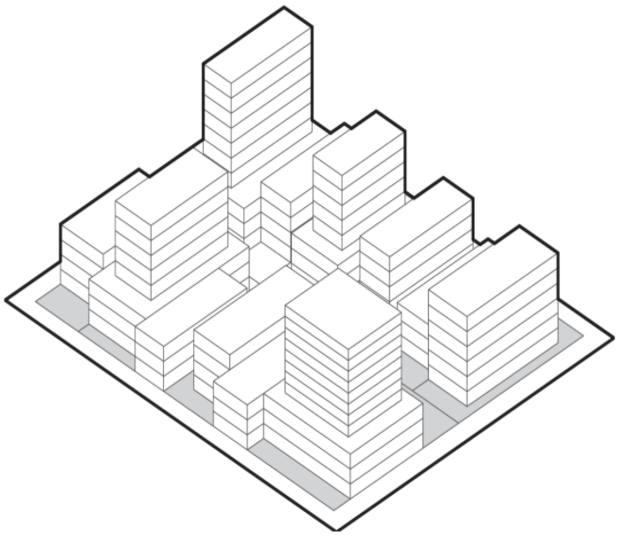


Figure 1. The randomness in a block due to its current rules.
Source: The author (2019)

The optimisation of the FSI compelled architects to design regular geometries as the most efficient way to comply with each plot's FSI. Therefore, designs most recurrently fall into two morphologies. These are: in narrow plots, mid-rise buildings with minimum setbacks that require daylight sheds; and in wider plots (>18m), towers, where heights vary but are still constrained by the height setback ratio. Fig 2 illustrates these two recurrent options, the first one, in the left-hand side, exemplifies the mid-rise morphology without setbacks thus requiring light wells. In the two other schemes the setback is related to building height: the taller is the building, wider will be its setback. Under these circumstances, any form exploration would happen at the expense of floor space areas, thus limited to few examples. Moreover, architects argue that more freedom to design would result in finer buildings and a more valuable urban environment.

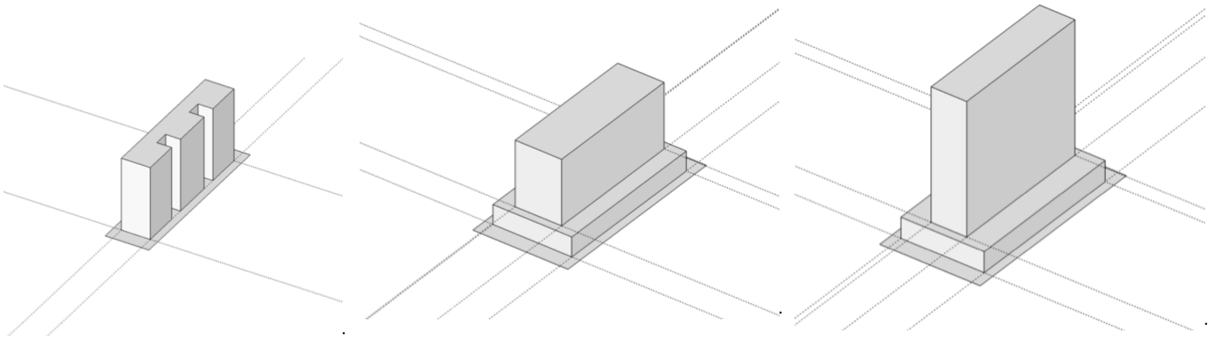


Figure 2. Porto Alegre's recurrent morphologies: the mid-rise in the left-side and the towers with different heights and setbacks in middle and in the right-side.
Source: The author (2019).

Lack of connection between successive urban plans also aggravated the discontinuity of Porto Alegre's urban space. Porto Alegre has implemented three urban plans dated of 1959, 1979, and 1999; each of these with several and sequential adaptations being amended during intervals between plans. Prescriptive rules without consideration to previous ones regulated the interface between public-private and private-private spaces. Except for historical areas, few rules were put forward to consider the new constructions' impact over the existent fabric.

Planners addressed, for each new plan, vacant and consolidated areas alike, resulting in decontextualised urban planning rules. Without considering the existing fabric, the transition from one plan to the other brought influences from opposite ideologies to the current plan, PDDUA.

Irrespective of the considered Porto Alegre's Urban Plan, the FSI has shown clear limitations to provide top-down architectural control over the city's urban space configuration. On the other hand, Porto Alegre's FSI combined with other planning rules has imposed rather rigid constraints towards architectural freedom. Although the urban space and the non-built block space is shaped out of a bottom-up strategy, the building's shape variability is determined by top-down constraints. This duality is schematically summarised in Table 1.

Table 1 - The paradox of Porto Alegre's Urban Development

Ideology	Technical	Communicational
Approach	Top-down	Bottom-Up
Effect	Control	Variation
Scale	Building	Urban
Problem	Few variations	Randomness

Source: The author (2019).

The evolution of these three urban plans reveal a rather consistent and shared feature: the design of the urban space and the design of the interior of the urban block is weakly addressed. This might be partially due to the influence of the Ville Radieuse modernist concept whereby buildings are scattered in open urban space. (CORBUSIER, 1973 – originally published in 1933) This concept leads to a rather free layout of the urban block (Brasilia's superblocks are examples of this concept) since the randomness of the buildings positions does not affect the accessibility to natural light nor the natural ventilation. For instance, distances between buildings are generous enough to preserve reasonable levels of environmental comfort. The space generosity has also allowed a considerable range of building typologies to emerge from the building envelopes designed by urban planners.

This relative architectural freedom has given place to a *straightjacket* in Porto Alegre's urban plans. Urban blocks disaggregated in plots of different dimensions have made planners to restrict Le Corbusier's ideals to a *pilotis* area within each plot's ground floor. The spatial generosity of the superblock had been replaced by minimal distances between buildings. By instance, the building envelope volumetric restrictions and other urban planning rules end up by defining the final shape of buildings. Architectural freedom was practically confined to the building façade and building interior. Despite the urban space narrative present at each of these plans continued to be closely linked to the Corbusian utopia, their results were disastrous: no spatial coherence between one building and its neighbours and almost no consideration related to the environmental performance of individual buildings.

The conforming strategy of the existent Porto Alegre's urban Plan has been challenged by non-conforming strategies or performance-based strategies in 1994. A study led by Turkienicz *et al.* (1994) has demonstrated that it was possible to design buildings with better natural light access and considerably higher quality level of control of the urban fabric (both at the interior of the block and at the public space) with the same and even higher FSI indexes. The study had been based in the comparison of five neighbourhood blocks with different plot's sizes and shapes under two scenarios: a conforming plan scenario (using the existent planning rules) and a performance-based scenario based on solar envelopes constraints. The conclusions of this study were never adopted by the Porto Alegre's Planning Department whose preference had been to continue to use the conforming strategy of the previous urban plans.

Since 1994 many computational tools had been developed to provide support for non-conforming strategies. These unfold into two types: generative and environmental assessment of attributes such as thermal, natural light, natural ventilation. The combination of these two types of tools allow urban morphologies to be generated following one or more attributes. In other words, it is possible to automatically generate designs using parametric principles based on natural environment performance models' criteria or emulate the interaction between **extended generative systems** and **performance models** to support the creation of formal configurations appropriate to architecture and urban design (HERR and FORD, 2015).

This work addresses the question on whether it is possible to automatically generate urban fabrics with architectural control over the public space and, simultaneously, (a) stimulate building form flexibility and (b) to control building's access to natural light. Or, putting it differently, to increase the top-down control over the urban fabric and, at the same time, increase the bottom-up development of individual buildings, improving each building's access to natural light. This work's methodology associates (a) **built form** (b) **generative** and c) **performance** models to be incorporated into early stage design processes. Figure 3 illustrates the general model's concept, which would require (1) to define the parameters for each performance model (represented by lines), (2) to chose the desired performance model acording to which will the generative model work (represented by the red lines), and (3) to integrate the built form, generative and performance models (represented by the grey fill). In the right side, a diagram summarises the concept of simultaneous integration and simplification.

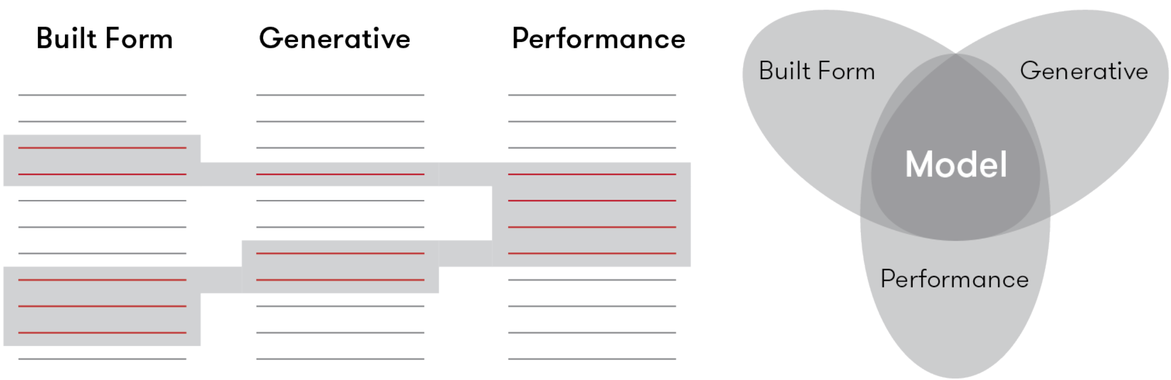


Figure 3. Model's Concept associates built-form, generative model and performance in a simplified way. Source: The author (2019).

Generative models can be used to obtain a variety of solutions for a specified problem trough similar rules structure. Generative systems are one possible path to "take advantage of the computational power of the computer." (TERZIDIS 2006). Cellular Automata (CA) constitute one example of generative systems capable of generating intricate patterns based on rules relating to local cell neighbourhoods (BURKS, 1970) and are therefore classified as "bottom-up" systems. These contextual and local behaviour systems can generate forms based on vicinity relations which are analogous plots vicinity within an urban block. The influence of the immediate surrounding (neighbourhood) in the system enables to address the context as a core element explored by previous works (COATES *et al.*, 1996) (FORD, 2013). Additionally, as also demonstrated in previous implementations (COATES *et al.*, 1996) (KHALILI-ARAGHI and STOUFFS, 2015) (WATANABE, 2002), CA's local behaviour produced high levels of interface with the building's environment, demonstrating an affinity with daylight requirements.

Top-down restrictions were associated with the bottom-up system (CA) whereby block boundaries followed urban requirements as maximum heights and footprints following predefined 'morpho- typologies' (court, street and pavilion or tower) (MARTIN and MARCH, 1972) Finally, the generated built form model has been associated to the performance model to evaluate the buildings' daylight performance. The study predetermined fixed cells as global restrictions to define overall boundaries for generated buildings. To allow the comparison between the generated built form models' daylight performance the FSI was kept stable and equivalent to the original urban rules. The performance model has used dynamic simulations for two metrics: Continuous Daylight Autonomy and Spatial Daylight Autonomy.

This dissertation discuss the results of two case studies where the general model has been applied to an existing block in Porto Alegre. In these two case studies the maximum FSI indexes has been applied to compare the building's geometry architectural flexibility and context sensibility. The comparison strategy is schematically illustrated in Fig. 4: in the left hand-side, the elevations of a possible outcome resulting from the existing urban plan is graphically represented, and in the right hand -side, the elevation reports the potential outcome of the proposed generative model. Voids represent non-built cells, while grey represent built cells. Both elevations, the ones for the existing plan (left hand-side) and the ones for the proposed generative model (right hand-side) have similar densities (32/48 built cells). Building on previous generative research, this study presents an innovative methodology that allows increased building flexibility under urban form control, improving daylight performance under maximum density indexes.

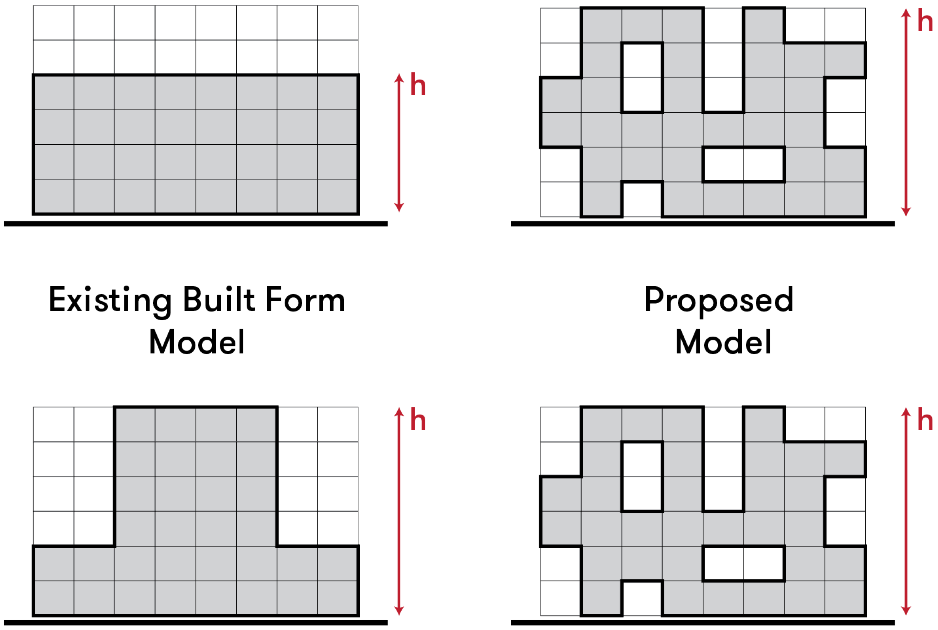


Figure 4. The comparison of the existing plan and the proposed model with an equal number of occupied cells (in grey).
Source: The author (2019).

This dissertation is divided into five chapters. The following chapter, **Chapter one,** sketches a concise historical background about cities research from a variety of perspectives. The selected authors and their work influenced the development of this dissertation and built the foundation to conceive the model.

Chapter two defines cellular automata systems and its use as a tool for computational design for the built environment. It also discusses a concise review of cellular automata applications in architecture, underlining previous applications from a multi-level approach (urban form, building and performance). The review investigates previous works regarding their approach to (a) context sensibility, (b) form variability, (c) daylight performance and (d) multi-scales. To conclude, it summarises the contributions and limitations found in the actual state of the art, explains how each of the examples contributed to the model's development, and demonstrates the contribution of the proposed model.

Chapter three presents the methodology proposed for the model's framework. First, it describes and justifies the computational and programming environment used for the algorithm design. Followed by a detailed explanation of each step: the geometry simplification process used to transform built environment 3d models into CA regular grid models; the strategies used to achieve urban form control and context sensibility; the CA automated building form generation and its association to daylight performance evaluation.

Chapter four presents two study cases applied to an actual block aiming to evaluate the model effectiveness concerning form, performance and context sensibility. These two tests aim to evaluate whether the proposed model can overcome the existing limitations of the current plan. The first study case generates new buildings that respect the overall top-down restrictions but also enables variability for the edification. The second test case is used to redesign the block morphology adding new constructions while respecting the existing ones. Both study cases used the maximum FSI indexes to generate the buildings, which were later evaluated according to their daylight performance.

The last chapter draws conclusions that offer answers to the questions and problems posed here in this introduction based on the Chapter 4 test cases results. **Chapter five** discusses findings from the analysis of the test cases about the model's effectiveness to support designers to rethink the existing rules. Moreover, the conclusion attempts to outline how the model can contribute with not only presented problem, but also with other situations.

1. The City Phenomenon: Abstractions and Analysis

Architectural historians have portrayed cities based on chronological aspects (BENEVOLO, 1980) building up iconic classifications based on periods; such as classical, baroque, and post-industrial revolution. In the mid-fifties, architectural theorists started to use analytical standpoints requiring diverse levels of abstraction (HILLIER, 1996) to understand the city's behaviour as an important support to city planning. Urban morphology studies are one example, as follows. Influenced by the Anglo-German geographer M.R.G. Conzen, and the Italian architect Saverio Muratori, urban morphologists disseminated a standpoint focused on the physical and spatial aspects of the built environment. Moudon (1997) highlighted that "The urban morphologists: focus on the tangible results of social and economic forces.", which suggests that the city's shape reflected the social and economic behaviours.

More specifically, the School of Architecture of Versailles, founded by the architects Philippe Panerai and Jean Castex, along with the sociologist, Jean-Charles Depaule brought to light morphology associated with ideological influences rescuing historical aspects. "*Formes Urbaines: de l'lilot à la barre*" (PANERAI et al., 1997 – originally published in 1977) discussed the refusal of historical aspects by the modernist architecture movement. It presented the block's morphological evolution from the Haussmann's block in Paris to the hypothetical Le Corbusier's *Ville Radieuse*. Panerai et al. (1997) criticise the cities' transformation from a dense island pattern to an assemblage of dispersed isolated buildings resulting in an architecture historically and aesthetically out of context.

Moudon (1997) highlighted the impact of figure-ground[1] diagrams methodology into the Versailles School analysis. This graphic method reinforced the morphologists' belief that the city texture was a result of the sum up of individual buildings. To Lamas (1993), '(…) morphology studies the objects' configuration and their exterior structure in regard to their respective

[1] A figure-ground diagram is a two-dimensional urban space representation that shows the complementary relationship between built and unbuilt space.

instigators'. To explain how the parts of the city connect and influence each other, 'Lamas (*op cit.)* recurs to four aspects: (a) 'quantitative' related to a dimensional form control, (b) 'functional' related to the land use, (c) 'quality' related to user environmental comfort, and (d) 'aesthetics'. Lamas has additionally advocated that the texture of the city is a result of architecture and vice-versa: "(…) Only in recent times, a new level of urban space construction arose: the urban planning. This level specifies uses and zoning that precede and regulate urban design." And continued: "(…) It is no longer desired to design the city and buildings in two distinct time periods. It is necessary that the plan surpasses zoning and plot subdivisions instruments and become a real tectonic instrument for city production." (Lamas 1993). In other words, Lamas separated urban form from urban planning and claimed for an object-oriented approach for planning instruments.

From a different standpoint, North-American theorists investigated the cities' social and visual aspects. Jane Jacobs, through "The Death and Life of Great American Cities" has suggested that mixed-use and diversity would improve urban quality (JACOBS, 1961). Jacobs criticised the American structural economic segregation, mostly portrayed by the car's priority over the pedestrian in the city centres. The author specified guidelines to generate diversity, such as (a) multiplicity of land uses, (b) street network configuration, (c) coexistence of building´s age and variety, and (d) concentration of users in the area (residents included). Kevin Lynch has developed empirical methods, which included interviews and users' opinions. As Jacobs, the author called attention to the importance played by performed activities in urban daily life and emphasised cities as "an agglomeration in continuous growth and transformation" (LYNCH, 1981). His concerns focused on how the 'good city' should look like based on people's perception. Jacobs and Lynch clarified the relevance of two city aspects recurrently revisited in the contemporary investigation practice: (a) **density** and (b) **people as city agents**. (BERGHOUSER-PONT and HAUPT 2010) (BATTY, 2005) (BATTY, 2013) (PORTUGALLI, 2012) (PORTUGALLI, 2016). At the time they contributed to a shift in urban planners' strategies and their impact is still felt in theoretical discussions nowadays (BATTY, 2005).

Christopher Alexander's two innovative works, "Notes on the synthesis of form" (ALEXANDER, 1964) and "A city is not a tree" (ALEXANDER, 1965), discussed the overlap between 'social' and 'structural' urban components through a mathematical approach. The author criticised planned cities, stating that "(...) It is more and more widely recognised today that there is some essential ingredient missing from artificial cities." (1965 *op cit.*). To illustrate this argument, Alexander (1965) further contrasted two abstract structures: a simplified one, a tree, and a more complex abstract structure, called semilattice. While the first is linear and does not present components interconnections, the latter represents the components' relationship overlapping, as demonstrated in the schemes below (Figure 5 and Fig 6). The author instigated that social and physical components (dynamic and stable behaviour) occurred in simultaneous overlays. The cited and subsequent Alexander's works contributed to the development of methodologies able to describe the city through abstract models (Space Syntax and Built Forms). Mathematical approaches such as the 'topology' were used to describe and analyse space, transforming its social aspects formerly hard to quantify into measurable entities.

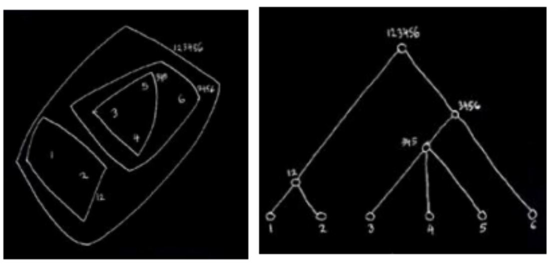


Figure 5. Tree Structure – Linear distribution.
Source: Alexander (1965).

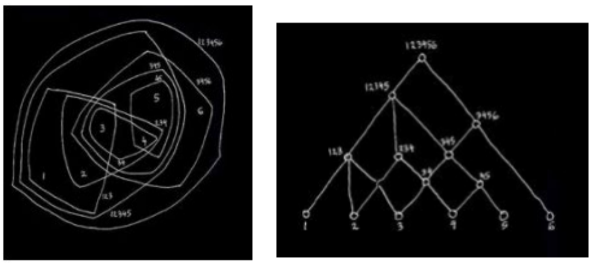


Figure 6. Semilattice – Overlapping Relations.
Source: Alexander (1965).

The following paragraphs present two theories based on mathematical approaches that directly influenced this work development: (a) '*built forms*', which investigated buildings geometry and its performance; and the (b) '*space syntax*', which established spatial configuration metrics through topological representation. The concept of built forms was originated by Leslie Martin and Lionel March studies in the "Land Use and Built forms" (MARTIN and MARCH, 1972) and more recently developed by Philip Steadman (STEADMAN et al. 2000, STEADMAN 2014a, 2014b). According to Martin and March (1972): "Built forms are mathematical or quasi-mathematical models (…), which are used to represent buildings to any required degree of complexity in theoretical studies." In Martin and March (1972) publication, the authors correlated attributes as density and daylight to 'built forms' to investigate how each predefined geometry makes use of the land.

In order to investigate each geometry behaviour, they proposed an experiment (*op cit.*, 1972) that aimed to measure land-use optimisation through the relation between density and land area. Therefore, the authors evaluated three generic building geometries. Each geometry was conceived concerning its territorial expansion directions. The image below composed by three elements illustrates and contextualise Martin and March (1972) proposed geometries, named: 'pavilion' or 'tower', 'street' and 'courts'. (Fig 7, 8 and 9) Firstly, the image show (a) the diagrams of each geometry and its expansion direction, (b) an array of sixteen figure-ground units, and (c) the image of the city illustrates each built form in a city where its use is dominant.

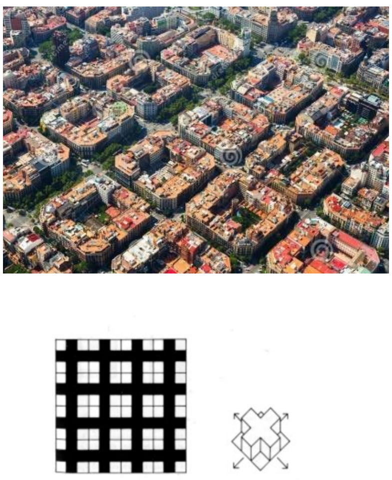


Figure 7. Barcelona – Court.
Source: Martin and March (1972).

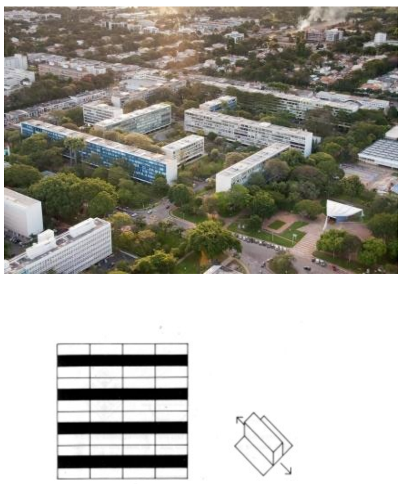


Figure 8. Brasília – Stripe.
Source: Martin and March (1972).

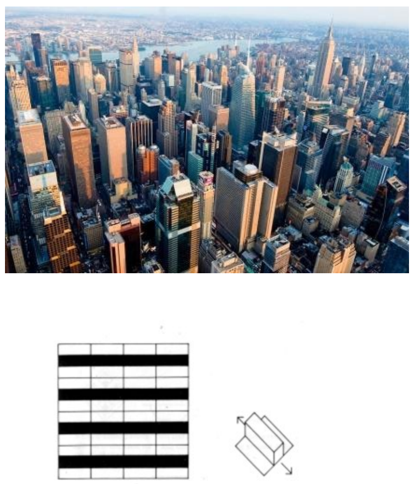


Figure 9. Manhattan NY – Pavilion.
Source: Martin and March (1972).

The experiment (op. cit.) proposed equivalent arrays in both vertical and horizontal axes to verify each built-form performance. The vertical expansion was associated with buildings heights, and consequently to the number of storeys. The horizontal expansion, in turn, was associated with buildings array offset. In order to compare the performance results on an equivalent basis, their study used equal quantity (floor area, square meters) and quality (daylight, cut-off angle) parameters. The storey height, the beam depth and the cut-off angle were fixed along the simulations. The cut-off angle was set to guarantee equivalent day-lit areas in all the building areas. As an effect, while the angle was a fixed variable, as forms were made higher they were pushed apart. Thus, as illustrated in the figure below (Figure 10), while the number of storeys influenced the cut-off angle, it also affected the open space between the buildings, as illustrated in the drawing below.

The simulation results, plotted in the chart below (Figure 11), show that along the storeys expansions, the density indicator (floor space index – FSI) raised in all the three forms, as expected. However, from a specific moment, 'court' and 'street' geometry FSI density value, approached a maximum value and stabilised. Unexpectedly, 'pavilion' geometry FSI values raised to the maximum value and, after that, as storeys increased, the density decrease. The results have also shown that when the number of the storey are equal, 'court' geometry always deliver much more floor area in a fixed land than 'street', which delivers substantially more floor area than 'pavilions'.

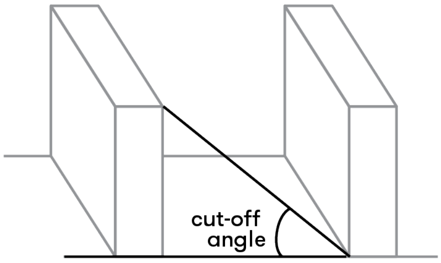


Figure 10. Cut-off angle between two buildings.
Source: Martin and March (1972)

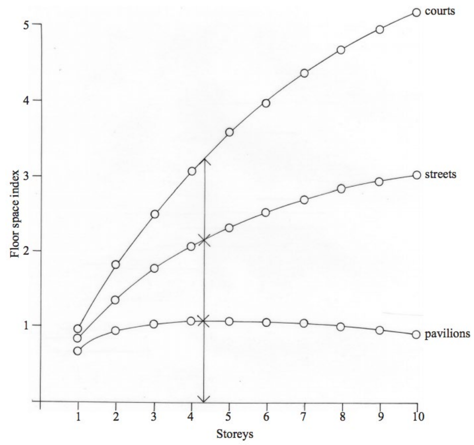


Figure 11. Martin and March land intensity use experiment results comparing pavilion, street and court typologies.
Source: Martin and March (1972)

Steadman (2014b) emphasises that these were "counter-intuitive" findings because Martin and March's results contradicted the common sense, which defends that to raise densities it is always necessary to build higher. Even though the original daylight assumptions were not as accurate as they can be nowadays, (RATTI, 2001), their studies have demonstrated that density is a broader and more sophisticated metric than it might have appeared at in the first place. From a methodological point of view, the unpredicted outcomes in these experiments were due to the association of independent and dependent variables. In other words, while vertical expansion used an absolute parameter, the horizontal expansion used a relative parameter (dimension vs angle), resulting in unexpected performances.

"Land Use and Built forms" shed light on metrics and experimentation importance in architecture and urban design research. Martin and March were precursors of geometry and performance association and have motivated others - including this author – to broaden the field (BERGHOUSER-PONT and HAUPT 2010) (STEADMAN, 2014b). Nevertheless, their contributions can be related to contemporary urban rules. Lehnerer (2006) indicates that absolute and relative bulk restrictions, as maximum height and proportional setbacks, are still in use, and their naive use can mislead to undesirable results, -- which is this works' original discussion topic.

While Martin and March broaden experimentation and measurements to geometry, Hillier and Hanson focused on the socio-cultural impact in the built environment based on spatial configuration (HILLIER and HANSON, 1984). The 'Space Syntax' is a family of techniques for representing and analysing spatial layout, aiming to determine an implied structure and pattern. The initial motivation for Bill Hillier was to investigate why social housing from the 60's and 70's in the United Kingdom was not working at the time. Together with Julienne Hanson they proposed means of describing (representation) and metrics for analysis of spatial relations regarding that what happens in any individual space is fundamentally influenced by the relationships between that space and the network of spaces to which it is connected. Their methodology was later applied for any urban and architectural scale, from housing layout (HANSON, 1999) to urban network analysis.

According to Hillier and Hanson (1984), the configuration defines the spaces' essence. Hillier (1996) further stressed that spatial configuration relates not only to the physical arrangement but moreover to users' spatial perception. In turn, spatial perception refers to how the user scans the space while in use.

> "Configuration seems (…) to be what the human mind is good at intuitively, but bad at analytically. We easily recognise configuration without conscious thought, and just as easily use configuration in everyday life without thinking of them, and we do not know it is, we recognise, and we are not conscious of what it is we use and how we use it." (op.cit.)

The concept of configuration exists "when relations between the two spaces are changed according to how we relate one or other (…)" (HILLIER, 1996). In other words, configuration implied that similar shapes could have different arrangements and, consequently, are perceived differently by their users. The image bellows illustrates the concept by comparing three similar "square-shape" house plans with three different openings arrangement. (Figure 12)

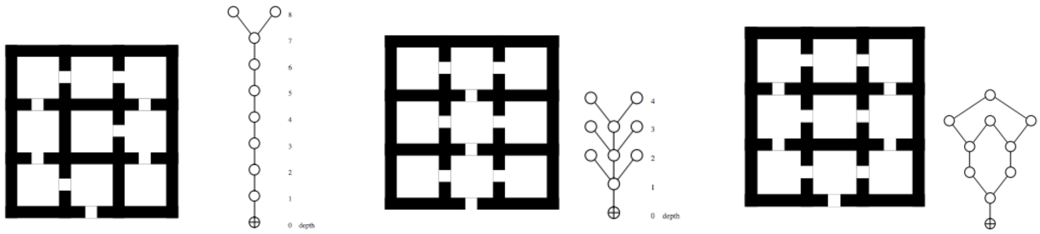


Figure 12. Floorplan layout of three houses and its corresponding graph maps.
Source: Hillier (1996)

However, although the configuration is easily perceived, it is a challenging attribute to quantify and measure, and, therefore, it might also be challenging to reproduce. Due to examine spatial configuration, Hiller and Hanson (1984) used graph maps for spaces representation and measurement. Space Syntax's maps described spaces as nodes and their links as lines, which symbolised physical and visual relationship. In summary:

> "Complex spatial relations, represented as a graph, can be visually simplified by drawing a justified graph. A circle is put at the base representing the root of the graph, and then all circles directly connected to that root. (…) Each graph gives a picture of what the whole layout looks like from that particular space. The key is that a spatial layout not only looks different but is different when seen from different perspectives." (HILLIER, 1996)

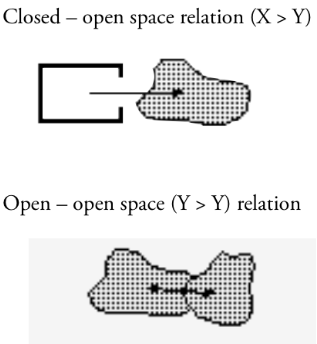
The previous image (Figure 12) compared layouts of three floorplans using graph maps (in the left-hand side of each plan). It shows that even though the overall shape is equivalent, each graph map is singular because the relationship between the rooms (adjacency) is different. The variation influences he user experience when he/she is navigating in the space. In other words, the graphs are one more way to represent the space regarding specifically the relationship within the rooms.

Beyond representing spatial configuration through graph maps, Space Syntax research proposes a variety of methods to measure spatial relations. One of the fundamental ideas is the concept of 'depth', meaning the distance between any pair of spatial elements. (Hillier and

Hanson 1984) The lower the room depth, the more integrated is the space; the higher the room depth, the more isolated is the space. For example, in a dwelling layout with the starting point set in the entrance, **(a)** the hall is a shallow room because it is situated close to the access; while **(b)** the bedroom is broader room, since it is the last room from the entrance. In other words, the lower depths correspond to integrated spaces, and the higher depths correspond to private rooms.

In order to investigate the essential configuration of a city , the Alpha Syntax Model and The Islamic City Model proposed by Hillier (1984, 1996) investigated spontaneous settlements arrangements. Both considered **accessibility** as the major organizing factor, and consequently, their focus was on the observer level (ground floor) resulting in the two-dimensional analysis. Built environment was divided into complementary **built** and **empty** spaces (streets, private and public open spaces). As a result, they defined rules that could describe existing and generate new settlements in a certain level of abstraction. The rules were able to replicate settlements configuration through building's exterior interface requirements and were later programmed as digital generative models by Paul Coates (COATES, 2010) as CA (Celular Automata) systems. Paul Coates' implementations are discussed in detail in Chapter 2.

The image below explains the predefined requirements of alpha syntax based on the relation between open and closed space (Figure 13). The main restriction for this model was that any built space must have at least one accessible face, as Figure 14 illustrates in an example of a generated settlement. The Islamic City model also defines its model regarding the accessibility assumed that there are some predefined global structures for access (main street). Two different open space emerged from this assumption, one 'public' and the other 'private', (Figure 15). The public open space (grey fill) is connected to the main street, associated with local streets and pedestrian paths. The private open space (white fill) is surrounded by houses, associated with patios and leisure areas.



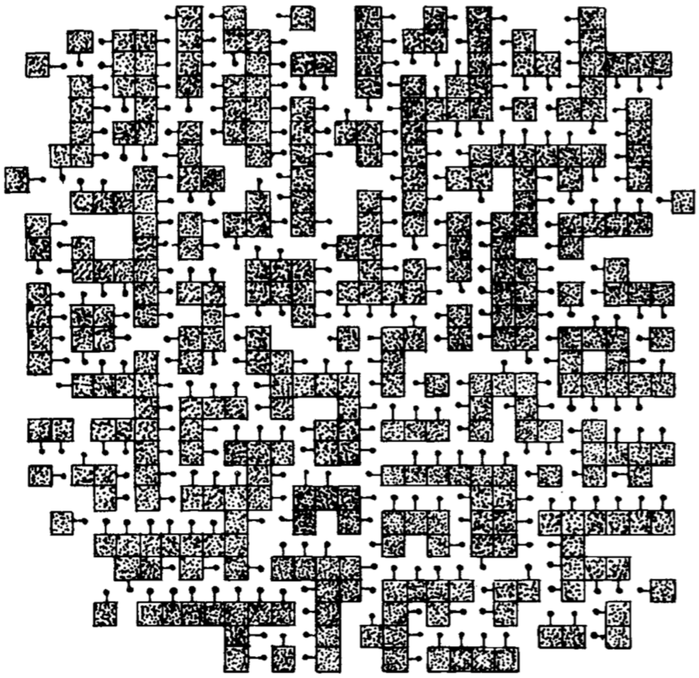


Figure 13. Alpha syntax rule logic: the relationship between closed and open spaces.
Source: Coates (2010).

Figure 14. Alpha syntax settlement: dark areas are the closed spaces and the lines with a point mark their accessibility.
Source: Coates (2010).

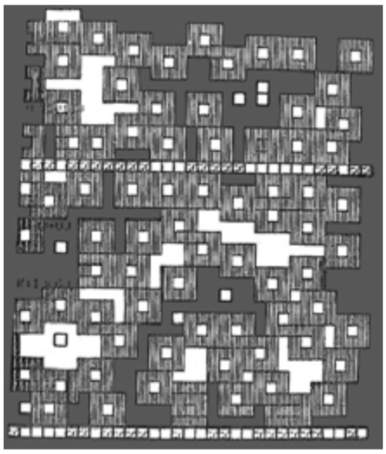


Figure 15. The Islamic City: Reference image (left-hand side). Streets are represented by the array of squares, houses by hatched squares, public open spaces are filled in with white and private open spaces are filled in with grey (right-hand side).
Source: Coates (2010).

The concept of "Built Forms" developed by Philip Steadman (STEADMAN et al. 2000, STEADMAN 2014a) separated 'buildings types' according to its uses (such as housing, hospitals, offices and schools). Each building type was examined aiming to find their generic 'built forms', which was later evaluated regarding a performance indicator. Performance indicators, in turn, comprised energy consumption (STEADMAN and MITCHELL, 2010), visibility (STEADMAN, 2014a), and the ratio of circulation area and the overall area (STEADMAN, 2014a), . Besides broadening the performance indicators types into the analysis, Steadman's works also explored architecture in three-dimensional space, which allows other performance indicators evaluation possible.

Steadman (2014a) suggests that light and ventilation access is the major factor to determine housing overall geometry. Op. cit. describes the housing 'built form' geometry as illustrated in the image below (Figure 16). The chosen variables stand for: (a) d = depth, (b) l = length, (c) 'h' = height, and (d) 'nh' = number of storeys. In his review of more than two hundred housing buildings, Steadman (2014a) demonstrated that the overall housing depth dimensions do not surpass two rooms wide due to day-lit requirements. (Figure 17 and 18) A space that is mostly illuminated by natural light and in which the visual comfort level satisfies its occupants is defined as 'day-lit'. (REINHART and WIENOLD, 2011) In other words, each room in the dwelling requires at least one face with an interface to the exterior, reducing the built form to a narrow band expanding along the length axis. The analysis also concluded that depth was approximately 7 meters, corresponding to two rooms (3 + 3 m) and 1-meter interior circulation (corridor) between them. While this work model also addressed lighting aspects, the cell size adopted in the model is equal to 3,5m (1 room + 0,5m circulation), as explained in Chapter 3.

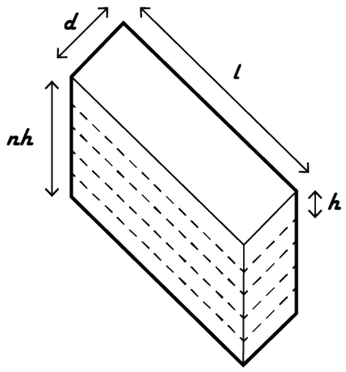


Figure 16. The built form for a housing building, where d = slab depth, l = length, h = unit height, nh = building's height. Source: Steadman (2014a) / The author (2019).

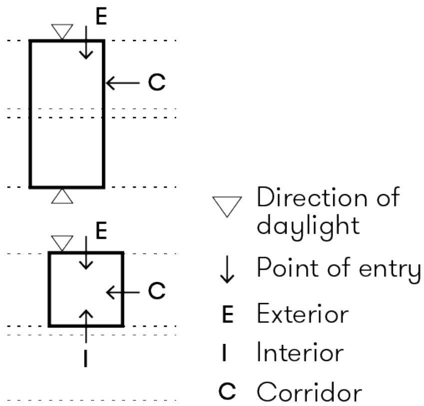


Figure 17. Two arrangements for housing units one with daylight access from 2 sides (top) and the other with daylight from 1 side (bottom). Source: Steadman (2014a)/ The author (2019).

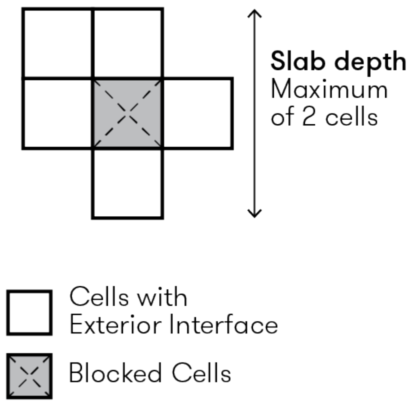


Figure 18. Diagram illustrating the concept that constrains the slab depth into two cells due to its interface with daylight and ventilation. Source: The author (2019).

Moreover, Steadman and Mitchel (2010) proposed a technique of binary coding to describe an 'archetypal building' "where all possible plan arrangements for built forms derivable from the courtyard floors of the archetypal building can be indexed and catalogued using a method of binary encoding." The buildings forms were described regarding its relationship with the exterior interface. There are seven strips running in the 'x' and the 'y'-axis , corresponding in sequence to the space of the different types (side lit, artificially lit and the court). (Fig 19) Let us assign to each strip either a 0 if it is to be removed, or a 1 if it is to be selected. We thus obtain two seven-digit binary strings, in 'x' and 'y'. The binary code describes a dimensionless configuration. Figure 20 illustrates how the encoding method can be used to define a wholly side-lit L-shaped form with the code 0001101 0001101. A dimensioned example of the L-shaped form is illustrated in figure 4(c).

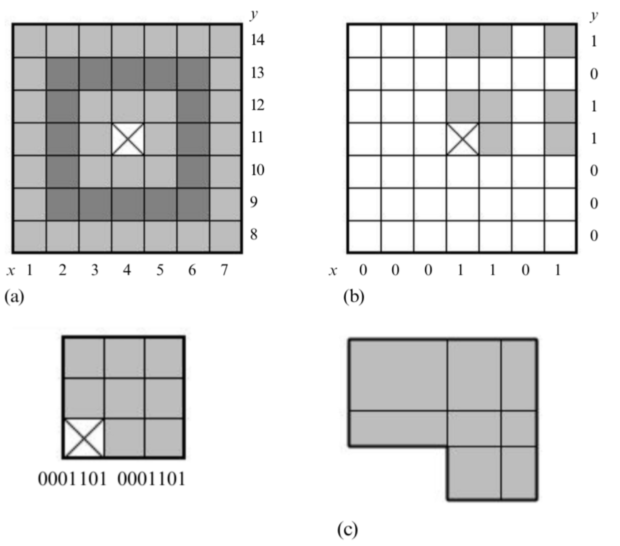


Figure 19. An example of the how a L- shaped building (c) can be derivate from the general morphospace (a). Light grey cells stand for cells with interface with the exterior and darker grey stands for enclosed areas as corridors.
Source: Steadman (2014a).

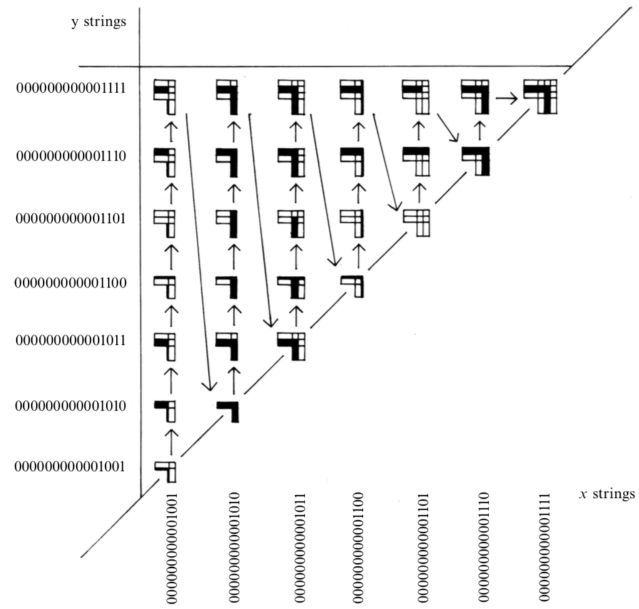


Figure 20. Variations of L-shaped building arranged according to its binary code translation, where 1 stands for a built cell and 0 for voids.
Source: Steadman and Mitchel (2010).

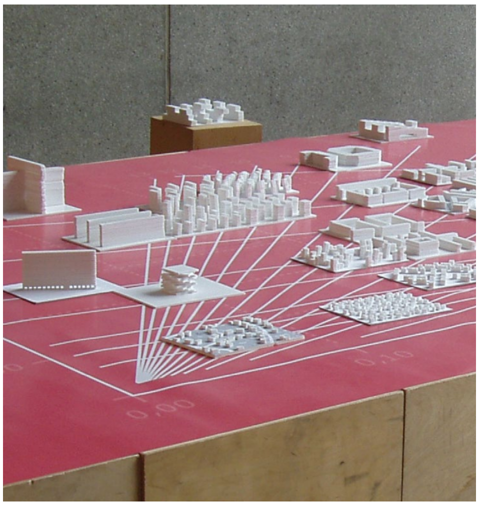
To conclude, Steadman and Mitchel (2010) introduces the concept of '*morphospace*' for architecture investigation, as explained:

> The term '*morphospace*' has gained currency in biology to refer to a means for representing the ranges of actual and possible forms for the bodies or organs of plants or animals. Typically, such a representation locates forms within some coordinate system in which the axes correspond to dimensional parameters that describe the forms. (STEADMAN and MITCHEL 2010).

In summary, he proposed a method for plotting a large variety of built forms across a two-dimensional 'morphospace' of possibilities. The use of 'morphospace' has helped to support design decisions and to compare existing morphologies. Methodologies as the 'morphospace' are practical for the computational design process because their outputs typically offer a variety of design possibilities which require supported decisions.

The Space Mate methodology (BERGHAUSER-PONT and HAUPT, 2010) also explored this sort of data representation and investigated density through quantitative and qualitative attributes. The qualitative attributes addressed to Martin and March' different urban fabric types (court, street and pavilion) and quantitative attributes addressed performance indicators as building potentials, common area and daylight accessibility. Their studies considered density through the relation of **open space and built area** in the tri-dimensional space by associating different density measures. Their (op.cit) model used respectively the following concepts and measurements: (a) coverage (Ground Floor Index, GFI); (b) building intensity (Floor Space Index, FSI); (c) spaciousness (Open Space Ratio, OSR); (d) Building height (Length, L). As a result, the authors proposed the SpaceMate / SpaceMatrix method as a representation for density, which correlates these four measures, as illustrated below, Figure 21 and 22).

Berghauser-Pont and Haupt (2010) work contributed to elucidate the relation between density concepts and quantitative aspects. SpaceMate data communication was also associated with a 'morphospace' (STEADMAN, 2014b), and, this way, can support designers' decisions. They demonstrated that it is possible to associate form, measurement and performance if we consider prevailing indicators as density. It is possible to affirm that Bergahauser-Pont and Haput (2010) have implicitly asked for "**the need for an architectural model of the city**", further contemplated in Bobkova, Marcus and Berghauser-Pont (2017). The level of abstraction evoked by these latter groups of researchers had a crucial contribution to the computation insertion into architecture and design fields. The use of mathematical aspects as topology (HILLER and HANSON, 1984) (ALEXANDER, 1965), geometry abstraction (MARTIN and MARCH, 1972) and the built forms representation based on binary codes (STEADMAN, 2014a) has supported the development of several works in architectural computation and digital design fields and has played a relevant role in the development of this thesis.



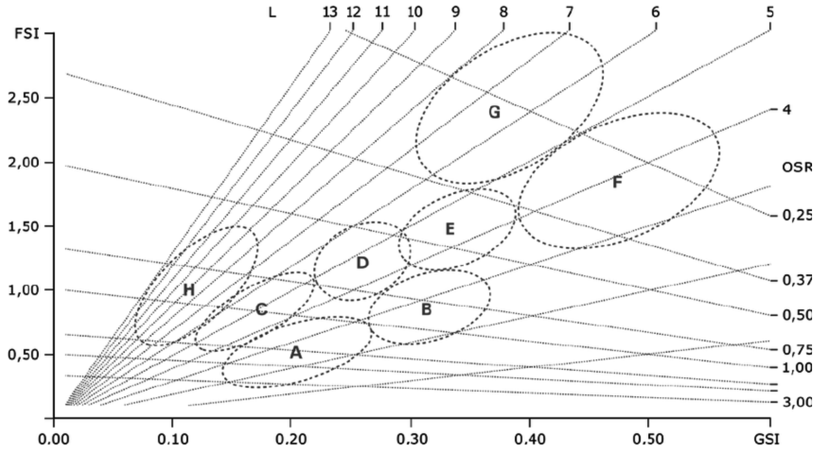


Figure 21. Models of land development typologies spread over the space matrix methodology. Source: Bergahauser-Pont and Haput (2010).

Figure 22. Space Matrix board combining four metrics: FSI, OSR, GSI, L (height). Land development typologies are defined with ellipse representations: **A.** Low-rise spacious strip developments blocks; **B.** Low-rise compact strip developments blocks; **C.** Mid-rise open building blocks; **D.** Mid-rise spacious building blocks; **E.** Mid-rise compact building; **F.** Mid-rise closed building; **G.** Mid-rise super blocks; **H.** High-rise developments.
Source: Bergahauser-Pont and Haput (2010).

The Complexity Theory of the Cities (CTC) and its implications into the proposed model presented in this thesis are discussed as follows. The CTC dated from the late seventies and is recurrently discussed in the present-day literature (PORTUGALLI, 2012) (PORTUGALLI, 2016). Paraphrasing Batty (2013), a major distinction between the theorists' presented beforehand and those based on CTC theory lies in their different world's perspective. According to Batty (2003), "While the previous perspective involves an approach that focuses on understanding 'what is', the current thinking concentrates on 'what should be'". In other words, CTC investigated the city as a *wicked problem*, which essentially does not have one definitive solution but several possible answers. (RITTEL and WEBBER, 1973).

According to Prigogine, the precursor in associating cities to complex systems: "Obviously in a town, in a living system, we have a quite different type of functional order. […] for this type of structure we have to show that non-equilibrium may be a source of order." (1977 apud Portugalli 2016) Prigogine indicated that cities are no stable and fixed entities and had a order in their behaviour. Influenced by his studies and further findings, Peter Allen created the domain of complexity theory of the cities (CTC). From the Complexity theory's perspective, the city is an open and decentralized system, which must be related to an evolutionary process and not to a project. (PORTUGALLI, 2000). As an effect, their contributions shifted the city image from a 'machine' to an 'organism'. This organism is the result of city agents' interactions, mostly associated with people and their behaviour. For these reasons , urban agents' behaviour became the centre of theorists' investigations and simulations (e.g.: city growth, inhabitants circulation, transport).

CTC derivate from the complexity science that is an interdisciplinary field of research. Mitchel (2009) characterised complex systems from three aspects: (a) **collective complex behaviour**, which emphasises that complexity emerges from decentralised iteration among components resulting in unpredictable patterns; (b) the ability for **processing and signalling information** between system components and external environment, and (c) **adaptation**, ability to change behaviour in order to increase the chances of survival through learning or evolutionary processes. These three characteristics are recurrently associated with human behaviour in the city. Recent literature (PORTUGALLI, 2012) (PORTUGALLI, 2016) (BATTY, 2013) discusses the divergences between natural complex systems and cities. Portugalli (2016), for example, claims that there is a relationship between city agents and its artefacts, as stated:

> "Cities are composed of material components and organic components. As a set of material components alone, the city is an artefact: a simple system. However, seen as a set of human components — the urban agents — the city is a complex system. It is thus a hybrid simple-complex system (…)". (PORTUGALLI, 2016).

In accordance with Portugalli statement, Batty (2013) in his book "*New Science of Cities"* discuss the 'physicalism' concept, which refers to the cities physical part, composed by "a geographically space located vocabulary". Batty (2013) states that although 'physicalism' is neither the attractor and motivator for urban development, its vocabulary is the unsurpassed mean to represent, manipulate and design the city.

> "(...) what we mean by the term here [physicalism] is that physical form is the appropriate way to represent cities, in terms of the city's geography, geometry, and associated attributes. It does not exclude the drivers of cities such as agglomeration, decentralization, and globalization, which clearly originate in human behaviours and social structures, but it does focus on what can be immediately observed and hence manipulated through city planning. Nor does it exclude other forms of planning, although we would argue that the manipulation of the city's physical form is still the most obvious, appropriate, and least controversial approach." (BATTY, 2013)

In summary, Batty (2013) and Portugalli (2016) considerations reiterate architects' significance in the urban framework. As a result, they claim for a 'new science of cities' (BATTY, 2013), which might be neither deterministic, nor complex, but **'hybrid'**. In other words, human behaviour must be taken into consideration, however, the object of architects and planners' work is the physical environment.

1.1 Summary and Contributions to the Dissertation' theoretical framework

In the last pages, several theorists' perspectives were presented. In respect to this work, **morphology** major contribution is the urban units' definition and their transformations along time, history, and ideology variables. **Jacobs and Lynch** shed light to inhabitants' importance to city planning. Their work stimulated people's concentration and implied that high density enhanced the city centre's quality. Moreover, Jacobs was one of the first thinkers to introduce the complexity concept into urban context. The 'mathematicians' (Alexander, Martin and March, Hillier and Hanson) claimed for analytic and abstract models to be used in the city investigation. Alexander demonstrated that city's structures are not as linear as planners intended they were and shed light on the use of abstraction to perform an analytical study. **Space Syntax** contributed showing that spatial configuration has a relational bias. More specifically, Alpha Syntax and The Islamic City models explored the settlements arrangements based on built and empty space, which is the same interpretation used in this works. In addition, space syntax adjacency and contiguity concepts were explored during the model design.

Land use and Built forms experimentations showed that indicators, like density, are broader and more sophisticated than people's intuition might suggest. They reinforced the value of controlled experimentations and abstract analysis to evolve the understanding of the built environment. Steadman developments reinforced the role of light into buildings overall geometry. To conclude , the Space Mate Model (Berghauser-Pont and Haupt 2010) developed the concept of density as a wider indicator. Both light and density were considered in this work investigation. Finally, **Complexity Theory of Cities** and its further developments (Batty 2013 and Portugalli 2016) elucidated that even though the city is an unpredictable organism, its artefacts are stable and should keep as the planning focus.

2. Cellular Automata and the Built Environment

Computers are ubiquitous in architectural practices nowadays. Their use has facilitated the design, manufacturing, and construction of new building forms. Still, the use of computers is mostly limited to graphic communication in traditional standards, as technical drawing and perspectives (HERR, 2007). Terzidis (2006) points out that "The problem with this situation is that designers do not take advantage of the computational power of the computer." According to Lawson (1997), early computer-aided design (CAD) researchers envisioned the computer as 'real design tool' (LAWSON, 1997) that would be capable to automatically generate design solutions based on the supplied data. Terzidis (2006) evokes for the development of a 'algorithmic architecture', which "involves the designation of software programs to generate space and form from the rule-based logic inherent in architectural programs, typologies, building code, and language itself." (TERZIDIS, 2006). In summary, the use of computers as 'real design tool' involves **(a)** designing the algorithm (rules), **(b)** adjusting the starting parameters and shapes, **(c)** steering the derivation process, and **(d)** selecting the best form variation. (HERR, 2007).

Terzidis (2006) adds that the process of designing the algorithm is an educational exercise by itself. "Algorithmic design does not eradicate differences but incorporates both computational complexity and creative use of computers." The algorithm design requires a conscious methodological approach of the design problem, which approximates the designer to the wicked nature of architecture and urban plan problems. As stated by Rittel and Webber (1973), "while we define the problem, we solve it." For this reason, the recent literature as well as this work support the idea that the use of the computer in architecture is not only a powerful tool to solve complex problems, but also as a powerful cognitive and learning tool, where the designer develops a deeper understanding of the process.

On the other hand, Negroponte and Groisser (1970) forewarned that for computers to design, they should be programmed to cope with context dependency and missing information. In other words, computers must be programmed to deal with the complexity of design problems. In parallel, according to Herr (2007), the more we learn about the design process sophistication, the greater the authors which shatter "the vision of an intelligent auto-sufficient machine able to design (...)" (HERR, 2007). Cross (2001) reinforced that "[the computer] can be programmed to do a lot of the design work, but under the supervision of a human designer".

Although the topic has been widely discussed in the last 30 years of architecture research, there's no evident concordance in literature. While technology enthusiasts' claim for automated deterministic models, others claim for 'conversational' models, where the user intervenes during the generative process. Although there is not yet a final verdict, a growing body of literature has evaluated and classified the use of computer according to its different degrees of autonomous action, ranging from fully automated process to a step-by-step user-controlled. It reinforces the importance of having awareness to the level of automation while building the algorithm, balancing the algorithm autonomy with evaluation method output.

2.1 Generative Systems: Cellular Automata

Generative systems are one of a variety of paths to use computers to its 'full potential'. Generative systems are a systematic method to obtain a variety of solutions for a specified problem trough similar rules structure. Cellular automata, shape grammar, fractals and genetic algorithms are examples of generative systems able to support the creation of formal configurations appropriate to architecture and urban design.

Generative systems were computerized in different degrees of autonomous actions; fully automated, as the cellular automata, or step-by-step user-controlled generation such as shape grammar. As mentioned, Cellular Automata (CA) is one of a variety of generative systems. CA are systems of cells capable of generating intricate patterns based on rules relating to local cell neighbourhoods (BURKS, 1970) and, for this reason, are classified as "bottom-up" systems. Coates et al. (2006) remarks that the main idea behind bottom-up approaches is that "you can investigate phenomena by starting from its simplest components and simulating their relationships to generate the overall structure." This local behaviour contributed to CA application to simulate urban growth (BATTY, 2005) (BATTY, 2013). The majority of these models considered density as their major growth factor. Areas with high population concentration tended to spread faster than areas with fewer occupants. These models demonstrated high fidelity to cities behaviour in large scale developments, mostly for regional planning (BATTY, 2005). The CA effectiveness to reproduce nonlinear and difficult to predict results popularized its use for urban modelling, and consequently, in the architecture field. (for more information about CA see SANTÉ et al., 2010).

2.2 Cellular Automata definition and applications

Mitchell (1998) defines Cellular automata (CAs) as "decentralized spatially extended systems consisting of large numbers of simple identical components with local connectivity." The identical components, also known as cells, take on a given finite number of states. Cell's state can change according to the transformation rules that each cell executes in relation to its cell neighbourhood (HERR and FORD, 2016). CA are space and time discrete models composed by two components: **cellular space**, also referred as lattice or grid, and **transition rules**. The first component defines spatial configuration, which can be described in one, two or three dimensions; the latter defines and updates the condition of the cells' state over time.

Each cell has a predefined and identical neighbourhood, both for input and output data. Neighbourhoods are defined by its structure configuration and coverage radius. There are no restrictions for neighbourhood configuration, nevertheless the same structure is applied to every cell during the whole iteration period. Two recurrent neighbourhood configurations are named "Von Neumann" and "Moore" (formalized in the equations below – Figure 23); the first comprises only the contiguous cells, while the second comprises the contiguous and the diagonal cells. For radius = 1, Von Neumann neighbourhood comprises the 4 immediate cells in bi-dimensional space, and 6 cells in a three- dimensional space; Moore neighbourhood comprises the 8 cells (4 immediate cells plus 4 diagonal cells) in bi- dimensional space, and 26 cells (6 immediate cells plus 20 diagonal cells) in a three-dimensional space. To exemplify, figure 24 demonstrates both 2d neighbourhood configurations with two different radiuses, and figure 25 demonstrates cellular spaces in two and three dimensions.

$$N_{i,j} = \left\{ (k,l) \in \mathcal{L} \,\middle|\, |k-i| + |l-j| \leq r \right\} \qquad N_{i,j} = \left\{ (k,l) \in \mathcal{L} \,\middle|\, |k-i| \leq r \text{ and } |l-j| \leq r \right\}$$

Figure 23. Mathematical formalization for de Von Neumann and Moore neighbourhood equations.
Source: Weimar (2000).

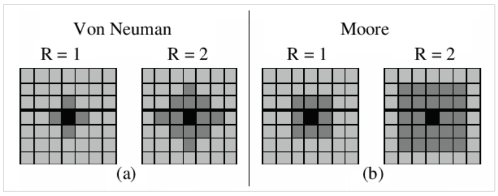


Figure 24. Neighbourhoods described according two different radiuses.
Source: Weimar (2000).

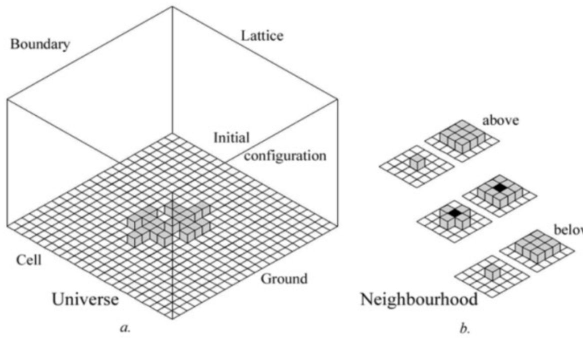


Figure 25. Spatial representation for Von Neumann (7 cells) and Moore (27 cells) neighbourhoods.
Source: Krawczyk (2002).

"Time is also discrete, and the state of a cell at a time slice is a function of the state of a finite number of cells called the neighbourhood at the previous time slice. Every cell exhibits a local behaviour based on a rule(s) applied which in turn is based on values in its neighbourhood. Each time the rules are applied to the whole grid a new generation is produced." (Terzidis, 2006) In other words, the state of a cell in a slice of time (t=1) is an effect of its respective neighbourhood in the previous slice of time (t=0). Whereas cell states can change over time, the components can appear to move along the grid. However, CA cells are fixed in the space and this conclusion is a user perception. Therefore, the model interaction perception is an effect of time passing, and not spatial displacement. The starting time, t= 0, is called initial state. At this slice of time, cells' states are arbitrated as the system's start point.

CA and Form Variability

Terzidis (2006) underlines that "The basic idea behind CA is not to describe a complex system with complex equations, but to let the complexity emerge by interaction of simple individuals following simple rules." Herr and Ford (2016) agree with op. cit. and emphasize that systems simplicity and the potential complex outcomes motivate architect's interest in CA. As said, complexity emerges from several local and simple states transforming over time, and although it might motivate CA use, the potential to generate a variety of results is also an intriguing characteristic._"Such system tends to be surprising and often display complex global forms, which 'emerge' from interaction of the many application of the local rules. [...] cellular automata often imply a more simultaneous parallel approach to decision making." (COATES, 2010). Coates (2010) also highlighted that the variety of forms is attributed due to the **multiplicity of possible combinations of neighbourhood** configurations. Figure 26, for example, illustrates "the eight different ways of having a neighbour" (Coates 2010).

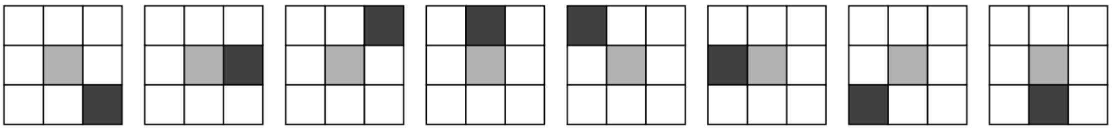


Figure 26. One centred cell with eight possible one-neighbour.
Source: Coates (2010).

Two classical CA application exemplified variability potential based on **rules** and **initial state** variation. Firstly, Wolfram (1983) in 'Elementary Cellular Automata' (ECA) stressed all the possible rules for his unidimensional model. ECA had two possible states for each cell (0 and 1), and neighbourhood configuration depended only on the nearest neighbour states. The evolution of cell can completely be described based on the value of the cell to its left, the value the cell itself, and the value of the cell to its right. Since there are 8 (2 x 2 x 2) possible binary states for the the three cells neighbouring a given cell, there are a total of 256 (2^8) ECA rule sets, which were indexed by an 8-bit binary number (WOLFRAM 1983, 2002). The evolution of a one-dimensional CA can be illustrated by the initial state in the first row, the first generation on the second row, and so on. (Figure 27) (MITCHELL, 1998). The figure 28 shows four rules sets and its application outcomes. In summary, Wolfram (1983) graphically verified a variability of 256 patterns trough the "simplest class of one-dimensional cellular automata" (Wolfram 2002). In other words, the experiment demonstrated that even with a fixed initial state and a limited neighbourhood the minor alteration in the rules had an expressive impact into the resultant patterns, as illustrated in the eight examples of Figure 29.

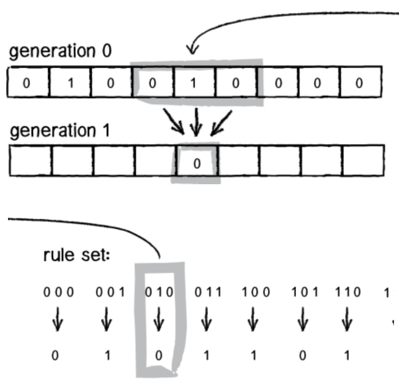


Figure 27. The rule set and its application.
Source: Shiffman (2012).

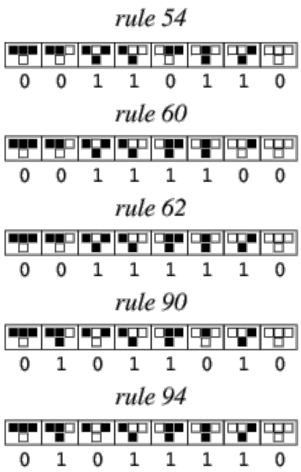


Figure 28. Four rule sets representation.
Source: Wolfram (2002).

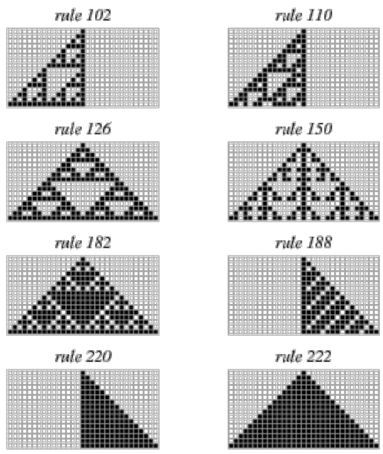


Figure 29. The resultant patterns.
Source: Wolfram (2002).

Secondly, Conway's Game of Life (GARDNER, 1970) model, in turn, increased variability trough the association of one effective rule set and the **initial state diversity**. Game of life was a bi dimensional model with Moore neighbourhood configuration, two possible states dead or alive (0 and 1) and one fixed rule set. The idea behind the model was to create a system able to generate a wide range of results through a simple rule set. (GARDNER, 1970) To conceive this rule set, Conway emulated population cycles (birth, death, survival), which followed the three following prerequisites:

> "**1.** There should be no initial pattern for which there is a simple proof that the population can grow without limit. **2.** There should be initial patterns that apparently do grow without limit. **3.** There should be simple initial patterns that grow and change for a considerable period of time before coming to an end in three possible ways: fading away completely (from overcrowding or becoming too sparse), settling into a stable configuration that remains unchanged thereafter, or entering an oscillating phase in which they repeat an endless cycle of two or more periods" (GARDNER, 1970).

Due to Game of life further developments, the concept of 'birth and death' population rules were widely disseminated, being mostly associated to as CA rules per se. The model has shown that even with a fixed rule set it is possible to generate a wide range of formal results and behaviour.

These two applications also made evident the possibility to catalogue the occurrence of patterns in the CA results. Wolfram has divided up the range of outcomes into four classes: (a) Uniformity: every cell constant (b) Repetition: cells states oscillate in some regular pattern back and forth. (c) Random: appear random and have no easily discernible pattern (d) Complexity: 'organized chaos'. Wolfram's work also demonstrated the relation between computerized and natural patterns. For example, the resultant pattern of the number 30 rule set is straight-forward comparable to the pattern encountered in the shell *conus textile* (Figure 30 and 31). This example evidences how valuable these systems can be for pattern generation.

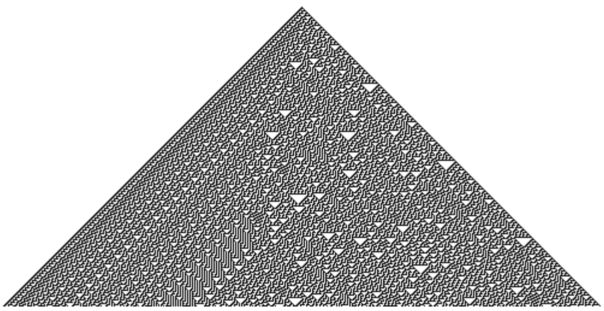


Figure 30. Pattern from number 30 rule set.
Source: Wolfram (2002).

Figure 31. Conus textile shell pattern.
Source: Wikipedia (2018).

According to Terzidis (2006), "While cellular automata (CA) were developed originally to describe organic self-replicating systems, their structure and behaviour were also useful in addressing architectural problems." The author summarizes CA's typical features as autonomy, heterogeneity, and emergence from local interactions which appealed architects and researchers to propose models for architecture based on CA systems. The following subchapter presents and discusses the development of previous CA models in the architecture field.

2.3 Cellular Automata in the Architectural Context

The literature mainstream has considered the use of CA's in the analysis of urban growth due to its capability to represent organic and local behaviour. However, due to simulation goals, scale and the vast amount of processing data, these models were limited to representations in two dimensions. More recently, researchers have introduced three-dimensional CA's systems to the architecture field, which has broadened its' applications. With the added third dimension, CA's generic systems require typical adaptations and modifications when applied to architectural models.

Herr and Ford (2016) named these models as 'CA extended models' and stated that while CA is routinely adapted in architectural design practice, few studies have reviewed their adaptations adequately. These reviews have considered aspects as (a) the transformation rules, (b) the cells' shapes and sizes, (c) the neighbourhood configuration and (d) the models' application as a design tool or an automated form-finding process. This last aspect is related to the level of automation of the model and its uses but doesn't consider the models' objectives and motivations. The authors' review shed light on the importance to associate architecture semantic aspects in CA systems implementation. In other words, CA's entities should be associated to meaningful objects and behaviours when applied to architectural porpoise.

To provide models with architectural meanings, authors (a) redefined **cells size** and **shape** to match with architectural spaces (KRAWCZYK, 2002) (HERR and KVAN, 2007) (FORD, 2013) (KHALILI-ARAGHI and STOUFFS, 2015); (b) associated **cells states to its uses** (KHALILI-ARAGHI and STOUFFS, 2015) (FORD, 2013) or (c) to its **materiality** - empty and built (COATES et al. 1996) (COATES, 2006); and (d) proposed rules in order to **avoid obstruction** (COATES et al.,1996) (WATANABE, 2002). As this work concern is related to context sensibility, form variability, and daylight exposure, the following pages compiles a brief review of ten CA previous models observing these three aspects. This review supports the proposed model development described in Chapter 3.

Context Sensibility

The context concept is defined by Alexander (1965) as "anything in the world that makes demands of the form – including designer, client, user, meaning, aesthetics, environment, and function". The concept of 'context' extends to include user behaviour, culture, and experience, which involves multiple layers of understanding. This work addresses only to the physical integration that embraces how the model perceives and reacts to the existing environment. The work of designers consists in dealing/negotiation between the existing structures and the ones he/she is proposing.

Abdelmohsen (2016) remarks that "one of the challenges continuously facing the use of generative systems in architectural and urban settings is the incorporation of context in the design process." And, although addressing complex real-world contexts is yet undertaking, this challenge is becoming of growing interest (ARIDA, 2004). For this reason, this topic is of most interest for this work. Even though there are only a few examples of implementations considering the context, they are commented as follows.

Coates et al. (1996) addressed context in **'Series D'** proposing 'avoidance rules' that limited growth when obstacles were encountered. In detail, the avoidance rules define a condition for state transition based on a predefined distance between two different states. The following statement defines an avoiding rule, where the centre cell would change from state 0 to state 1: "cell transition to state 1 is not permitted if a cell of state **3 is within a radius of 5** cells in the cell locations **east, west, south and north** of the cell at the centre of attention" (COATES et al., 1996). As seen, the condition to change the state requires a minimum distance of a specific group. In this case, the CA considers not only counting rules, but also examines a wider range of cells. As a result, the model outputs (Figure 32) segregates the states that were designed to avoid each other. Analysing the image, it's possible to see that the state blue and red avoid themselves, resulting in three compact groups (blue, white and red cells).

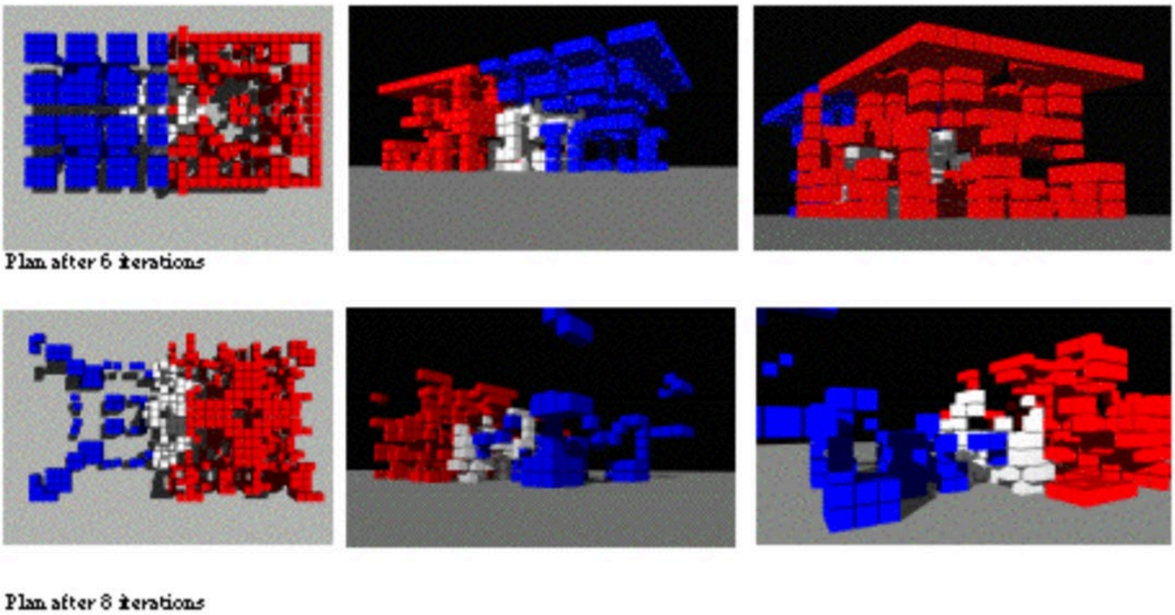


Figure 32. The avoidance rule and its outcomes: segregation between blue and red cells.
Source: Coates et al. (1996).

A second strategy is presented by Ford (2013) thesis project. The author proposes a conversational model that includes a step to incorporate the terrain inclination in the generative process. Rules addressing the sites' surroundings were implemented to respond to CA's inherent limitations while taking context into account. "This allowed not only a more accurate architectural understanding of the CA growth than one generated with no surrounding context, but also influenced the way CA generation was directed as part of the design process." (HERR and FORD, 2016). The growth in the Z axis is then restricted in the axis in accordance with the number of cells within its neighbourhood. The topography is imported from a GIS file converted into cells, as illustrated in the image below (Figure 33). As seen, this restriction rule also provides a better preservation of architectural scale in the model, which contributes to a more accurate result.

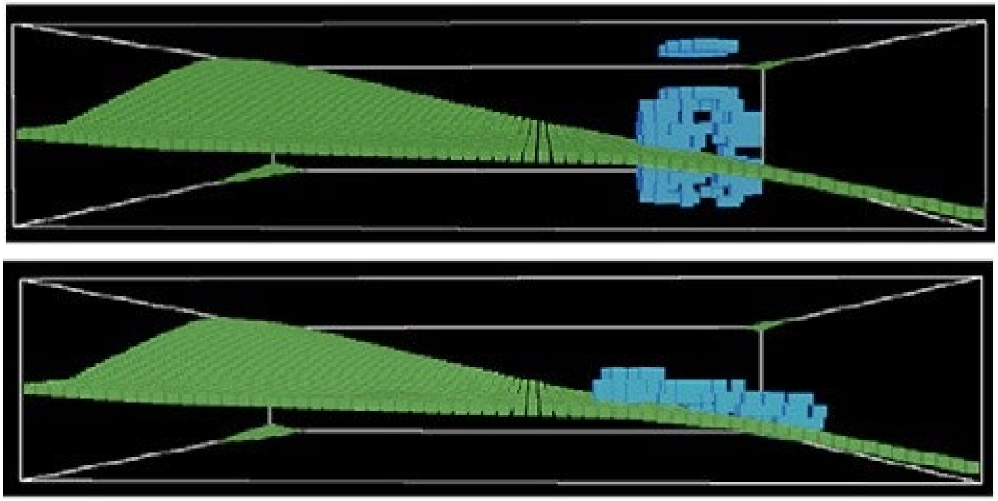


Figure 33. The terrain sensibility in the model: before (top) and after (bottom) the association of topography cells (green).
Source: Ford (2013).

Finally, although there is no mention of how the author differs the topography cells to other cells in the system, Ford (2013) alludes to differentiate the terrain cell as fixed, while the building cells are not. In turn, Coates et al (1996) only considered cells in the systems and, therefore, cannot be understood as part of an existing context. However, the avoidance rules incorporate further restriction beyond the predefined neighbourhood, which indicates a concern around global aspects. In conclusion, both examples presented strategies that override the local rules in favour of the whole. There are global restrictions influencing the final result. This concept is further developed in the proposed model and is discussed in the following chapter.

Form Variability

Form variability is one of the main characteristics of CA systems. The Game of Life and the Elementary Cellular Automata, for example, demonstrated the richness of possibilities that simple rule sets can generate (WOLFRAM, 1983). According to Terzidis (2006) "While cellular automata (CA) were developed originally to describe organic self-replicating systems, their structure and behaviour were also useful in addressing architectural, land-scape, and urban design problems." He also states typical features of CA as: "absence of external control (autonomy), symmetry breaking (loss of freedom/heterogeneity), complexity (multiple concurrent values or objectives)" attracting the use of CA for form exploration.

The main motivation behind Paul Coates et al (1996) experiments was to use CA intending to explore automatic form generation. They believed that "3D CA's allows us to get back to a more rigorous analysis of the basic determinants of form, where the global form of an object not only should not but actually cannot be predetermined on an aesthetic whim". (COATES et al.,1996). Moreover, they suggested that authorless process would evoke a 'real functionalism'. The results would not address the authors' intention, but functional rules that would lead to a final output. Although their concerns did not involve variability, they elaborated formal and aesthetic aspects based on CA systems.

Krawczyk (2002) used CA "as a framework to begin to investigate architecture forms." The author justified that comparably to parametric methods, recursive methods outcomes are usually hard to anticipate and "this offers an interesting and rich platform from which to develop possible architectural patterns." (KRAWCZYK, 2002). However, he has also stated that the pure mathematical translation of a CA included a number of issues that do not consider built reality, such as the lack of connections between cells and architectural scale. In turn, the author proposed a hybrid method that used the CA constructions as a starting point for design association to an interpretive approach with architectural considerations. Essentially, CA interactions provided the cells distribution, and the author determined the best cell shape and scale in order to deal with connections and interior spatiality. The image below

(Figure 34) illustrates three different interpretations of CA outputs. In this case, the author maintained the cell distributions varying the size and shape of cells. Krawczyk (2002) not only addressed form variability supported by CA typical features, but also associated interpretative approaches that enlarged the number of formal possibilities (8^8) .

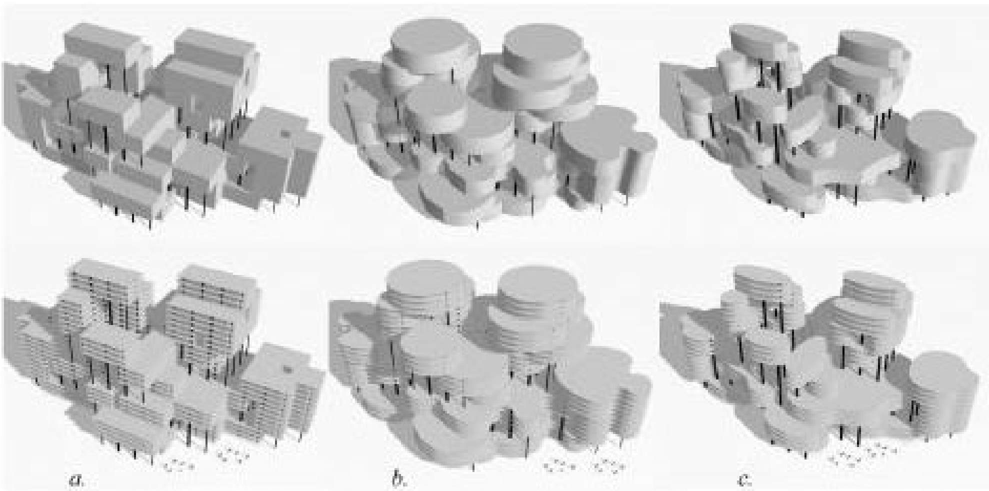


Figure 34. Six interpretations of the same CA output.
Source: Krawczyk (2002).

Form variability was also addressed by Herr and Kvan (2007) and Khalili-Araghi and Stouffs (2015) works, which used CA to generate high density housing. In Herr and Kvan (2007), the authors stated that high density architecture is typically determined by tight economic constraints and building regulations. As a result, even though the outcomes are "efficient in terms of space, the lack of variety in the standard building form leads to monotonous estates." (HERR and KVAN, 2007). To overcome the lack of possibilities, the authors suggested the use of CA associated with 'human interventions'. "To accommodate both generative and traditional design procedures, the implemented cellular automata may be used in phases, with intermittent stages of manual design interventions." (HERR and KVAN, 2007).

CA systems can assemble similar unities in different arrangements based on local and decentralized CA structure. Moreover, they stated that classical CA properties were often changed according to their intended use, increasing its usefulness in architectural design projects. The models' conception included remodelling a completion project designed by Cero9 in 2001. The complex form of an array of a thin 25-storey tower attended the high-density briefing for an urban block for the city of Aomori in northern Japan. The image below (Figure 35) illustrates the project used to extract the model's rules.

Figure 35. The study case ('Soft Metropolism' by Cero 9) used by Herr and Kvan to extract CA main rules. Source: Herr and Kvan (2007).

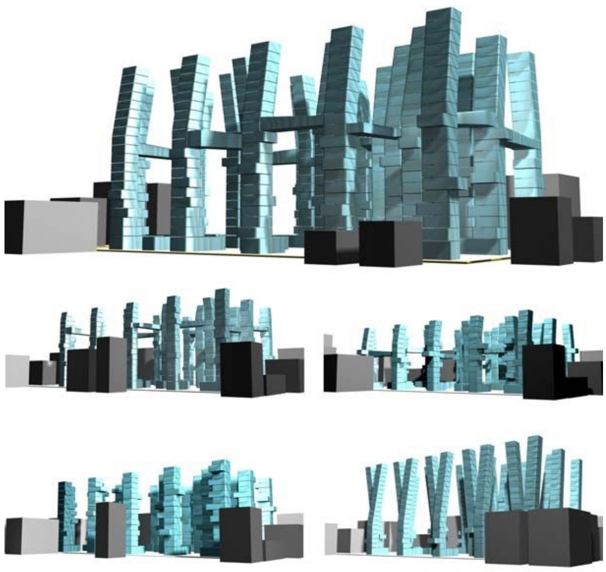


Figure 36. Five experiment outcomes that combines automatic generated tower with user's interventions. Source: Herr and Kvan (2007).

Herr and Kvan (2007) explored CA properties combined with user's interventions. While the CA deterministic behavior contributed to generating variability, the user intervention contributed to attending the architectural brief. On the one hand, manual intervention assured global structures as the tower typology, ground floor use, and commercial distribution. On the other hand, CA iteration has offered a wider range of formal outcomes and inter-connections. Figure 36 illustrates five outcomes, enabling us to see the global structure and its variabilities. This model has demonstrated that overall constraints do contribute to the emergence of typologies, which can be associated with architects 'language' and/or urban rules (as base-and-tower typology). Moreover, the CA contributions indicated the possibility to associate different briefs in the same building, to create a wider variety of views, and to contextualize the new building with the existing surrounding.

Khalili-Araghi and Stouffs (2015) have addressed the monotony of high density housing buildings as a problem. They've stated that "(...) Although mass production of high density housing promises operational performances and production efficiency, the designed forms typically demonstrate less variety, innovation and integration within the context." (KHALILI-ARAGHI and STOUFFS, 2015). The variability of the model is based on **(a)** different apartment briefs (studio, 1 and 2 bedrooms) and one circulation core (Figure 37) addressed as cell's states, **(b)** two sets of rules and **(c)** four sets of neighbourhood patterns. During the iteration process, the circulation units are fixed, while housing units change their state according to the transition rules. The first set of rules analysed the cell's accessibility to the circulation core and the second set of rules addressed daylight. The first set of rules performed on a two-dimensional Moore neighbourhood patterns with two different radiuses (Figure 38). The second set of rules used a horizontal and a vertical configuration to assure that "each unit needed to have proper access to natural light" (KHALILI-ARAGHI and STOUFFS, 2015). The association of these elements (set of rules, variety of cells states and neighbourhoods configuration) resulted in a wide range of possibilities of arrangements, as can be seen in the image below (Figure 39).

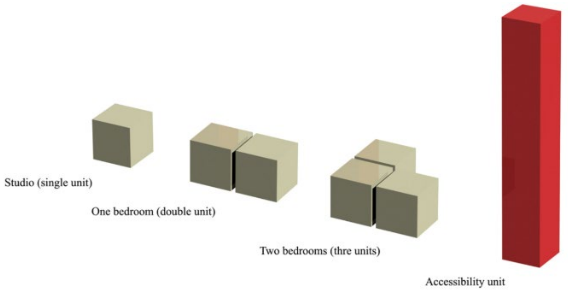


Figure 37. Housing units (studio, one bedroom, two bedrooms) and accessibility unit (red).
Source: Khalili Araghi and Stouffs (2015).

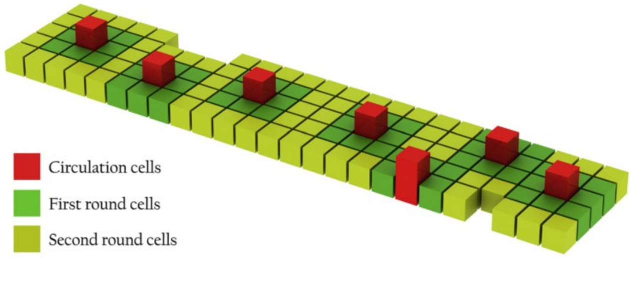


Figure 38. Layout for one floor housing complex, illustrating the restriction of 'two round cells' around the circulation core. (First round in darker green and second round in light green).
Source: Khalili Araghi and Stouffs (2015).

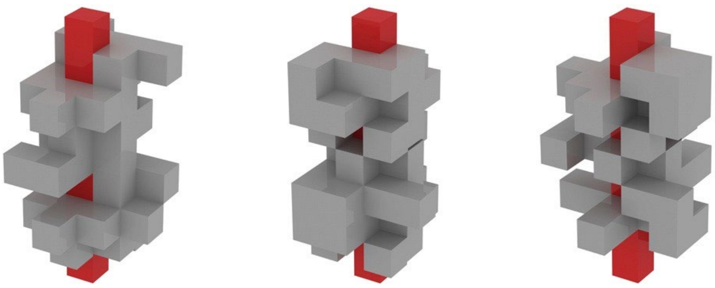


Figure 39. Three different building outcomes respecting the 'two round cells' rule, red cells represent circulation cores and grey cells represent housing units.
Source: Khalili Araghi and Stouffs (2015).

The so far presented examples (KRAWCZYK 2002) (HERR and KVAN 2007) (KHALILI-ARAGHI and STOUFFS, 2015) demonstrate that CA systems have the ability to generate a wide range of formal possibilities not only in a representation level (as in ECA and Game of Life), but also in a architectural purpose search. As seen, architectural briefs composed by similar units, such as housing buildings, can benefit from the use of CA systems during the architectural process. Moreover, all the examples included the user interference during the generative process, mostly related to the model's unpredictability: in other words, the user interference in the generative process can be interpreted as a form of control. The shown examples demonstrated that form variability is not only related to aesthetic outputs, but also reflecting functional aspects such as the building uses, accessibility and the natural light.

Daylight and Exterior Interface

As previously discussed, the exterior interface was widely explored as a major influence on spatial configuration (HILLIER and HANSON, 1984) (STEADMAN, 2014). Several previous authors also incorporated daylight as attribute to set up their CA models. Previous studies demonstrated a correlation between CA outputs and overall 'irregular' geometries due to its local behaviour. The images below (Figure 40, 41 and 42) illustrates three outputs' top views of different models characterized by complex floor plan arrangements. This property is related to the proportion of perimeter length and floor area and can be assessed by the wall-to-floor indicator. The wall-to-floor ratio of a building is calculated by dividing the external wall area by the gross internal floor area. This indicates the proportion of external wall required to enclose a given floor area.

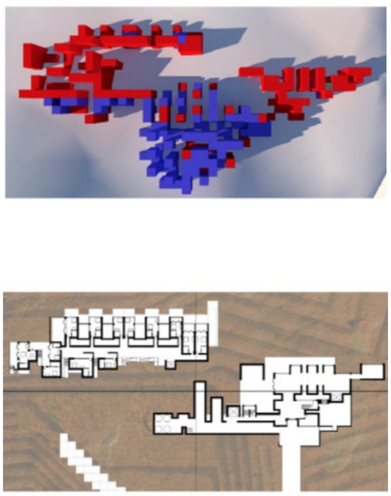


Figure 40. Site plan and ground floor plan originated using CA model. The cells are spread in the terrain following a complex pattern.
Source: Ford (2013).

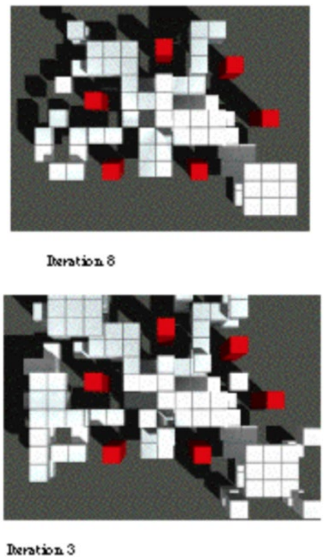


Figure 41. Top view of 2 iterations of CA model with 2 built cells states (white and red).
Source: Coates et al. (1996).

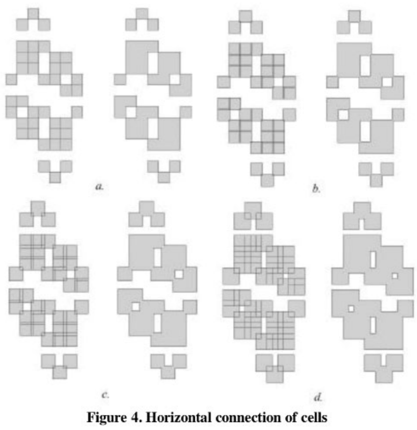


Figure 42. Top-view variations for one CA outcome. The original outcome (top left-hand image) is an example of unorthodox shape generated by CA model.
Source: Krawczyk (2002).

This metric is mostly used to assess the buildings cost efficiency, but it also calls attention to the fact that different configurations influences how the building communicates with the outside. In other words, buildings with higher wall-to-floor ratios offers a wider range of possibilities for windows, leading to a variety of daylight access inside the rooms. The image below (Figure 43) illustrates an equal quantity daylight availability with different light distribution. In this example, floor, window and naturally illuminated surfaces are equivalent. However, even though the sum of illuminated areas is similar, the distribution of daylight is different. For example, the floorplan on the right has four cells completely unexposed to daylight, while in the floorplan in the left, all cells have 50% of their area covered with daylight.

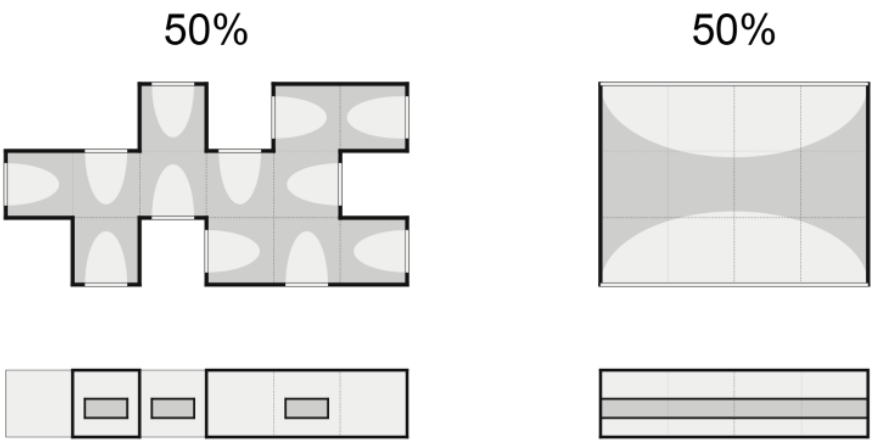


Figure 43. Floor plan and elevation of two buildings with equal window and day-lit areas but distinct arrangement.
Source: The author (2019).

The building occupation and its use also influence the requirements for daylight. (STEADMAN, 2014) The housing typology, for example, is composed by small individual rooms and each of them require access to daylight. Buildings that require an individual distribution of daylight, similarly to the one illustrated in the figure 43, might benefit from CA generative systems. While CA systems local and bottom-up behaviour leads to irregular and autonomous cell arrangements (TERZIDIS, 2006), enabling it to be explored as a strategy to balance daylight distribution.

The **Alpha Syntax** and **The Islamic City** proposed by Hillier and Hanson (1984) introduced the logic for every settlement arrangement based on the relationship between the building and the open space. These models, originally developed for theory exploration, were later programmed by Paul Coates (COATES, 2010) using CA systems. Both algorithm discussed in Coates (2010) used a 'counting' rule that stated: "You can build anywhere as long as you don't block out any existing building's access to the rest of the city." (COATES, 2010). Although there was no explicit relation between these models and daylight, the principle that there should be no obstacle to every cell has built the ground for further works.

Two strategies proposed in Coates et al (1996) considered environmental parameters for generative process. The experiment **'Section D'** of 'Series 1' addressed daylight associating avoidance rules with shadow simulation. As an effect, cells located in shadow areas should change their state to / or remain dead. Following the same approach used for context sensibility, Coates et al (1996) incorporated a logic to the rule set design that considered local and global structures. In other words, although the rules and the system were originally designed as local and bottom-up system, in this case, it also considered the overall shape shadow in the generative process, as is illustrated in the image below. (Figure 44).

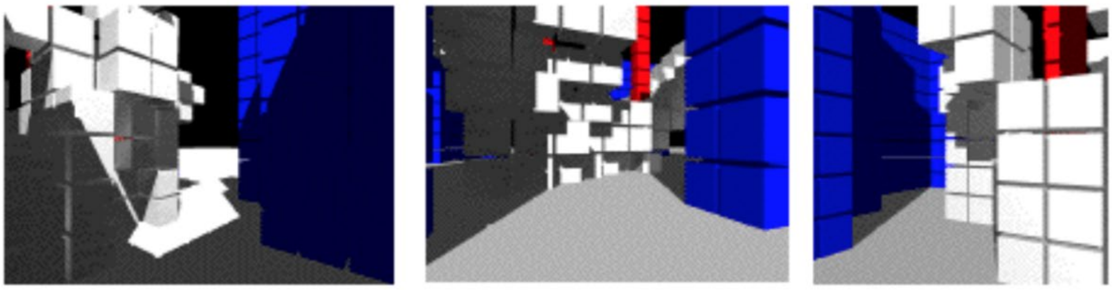


Figure 44. Close –up images for the results in the Coats model with shadow avoidance rules.
Source: The author (2017).

In turn, the **'Sunshade' model'** considered "a three-state cellular automaton [enclosed rooms, balconies and open space] with rules based on both counting and direction, so that the influence of environmental considerations can be explored." (Coates et al 1996). In this experiment, Coates et al. (1996) implemented CA rules aiming to bring light to each cell from the south side, the "sunny side". The system used a neighbourhood configuration of 6 cube region and southern cells were treated differently to the other directions. Sunshade proposed a rule set that considered orientation "with the aim of generating sheltered open spaces" (Coates et al. 1996). The introduction of traditional aspect of natural light and insolation orientation, resulted in narrow buildings, as illustrated in the images below (Figure 45). The enclosed cells are represented in red, while the green slabs represent the balconies.

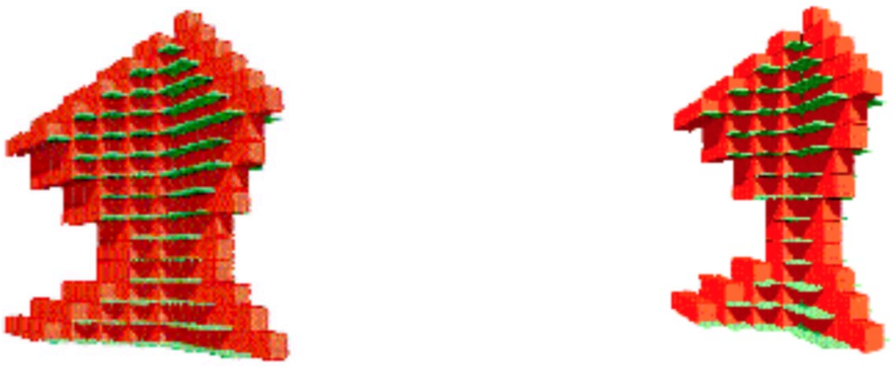


Figure 45. Two outcomes of Sunshade model in which enclosed cells (red) must have an adjacent open cell/ balcony (green).
Source: Coates et al. (1996).

Essentially, Coates et al. in these two experiments presented two different strategies to address environmental influence in CA models. Firstly, the authors associated the shadow simulation with the avoidance rule, which introduced a global sensibility in the model. Secondly, the Sunshade model associated the cell orientation to the transition rule (direction rule) and a specific cell state to benefit the daylight (balcony). It is possible to infer that in the latter model the authors used not only architectural knowledge as the orientation, but also semantic aspects as the balconies to design the algorithm.

Watanabe (2002) **'Sun God City'** also reflected environmental concerns in his adaptation to simulate natural lighting within CA generated shapes. To guarantee cells natural light performance, the model also used insolation simulation to set up the transition rules. Cells states were divided into built and empty. In order to change its state, the cell should obey the predefined 'number of shadow hours' threshold. For example, the user set up a maximum of

"4 hours of shadow", as an effect, to become or remain in the 'built' state, a cell should not overpass four hours of shadow per day.

Sun God City's main objective was to automatically generate cities. This fact influenced the level of simplification. For example, built cells represented housing units with the intention to spread in large areas, as seen in the image below. (Figure 46). The scale and an effective mathematical model to calculate the insolation in the geometry, allowed the **"real time" insolation simulation** and representation. That being said, Watanabe (2002) presented an impressive association of performance and generative model, however, it is important to recall that insolation models are significantly simpler to simulate than daylight models.

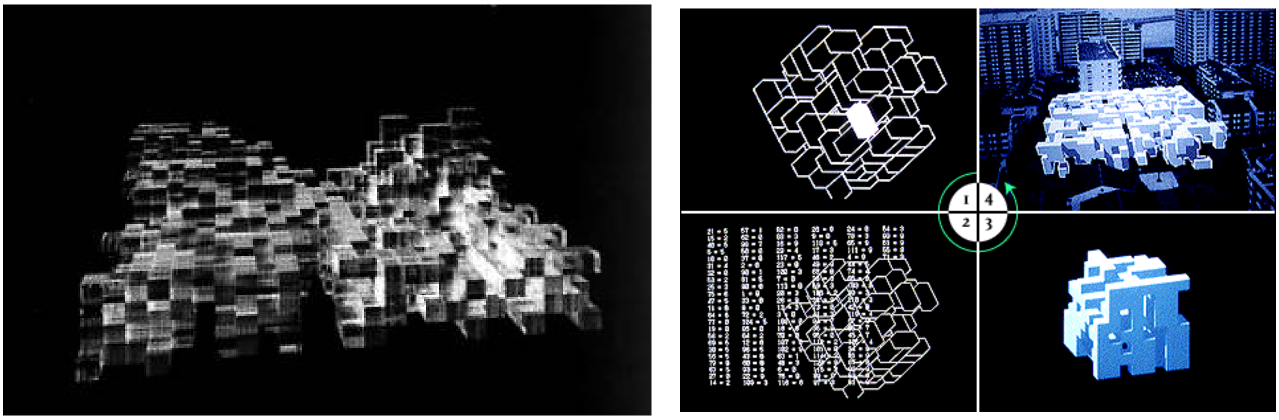


Figure 46. Watanabe Sun God City outcomes.
Source: Watanabe (2002)

Khalili-Araghi and Stouffs (2015) explored the potential of CA "to address density, accessibility and **natural light** in the architectural context." Their model used cells to describe one circulation core and rooms for high density dwellings. To address natural light availability, the authors proposed a specific set of rules to define cells' state according to local and global identification, summarized as follows:

> "Exploring the definition of CA rules for natural light starts from the principle that there should be no obstacle in the way of the sky. Therefore, investigating the natural light state of cells cannot be limited to their first or second round neighbors. What makes a cell receive natural light depends on the states of a string of neighbors all the way until the boundary of the lattice." (KHALILI-ARAGHI and STOUFFS, 2015).

The set of rules proposed by Khalili-Araghi and Stouffs (2015) aimed to ensure that every cell would have an appropriate access to natural light from either a vertical or a horizontal direction. The image below illustrates three options generated in Khalili Araghi and Stouffs (2015) study. Red cells represent the core circulation and are not naturally illuminated, while beige cells represent rooms. (Figure 47) The arrangement of beige cells (housing units) in maximum two round cell's guarantees that every housing cell is close enough to the building's boundary ensure sing the daylight access for a diversity of building sizes.

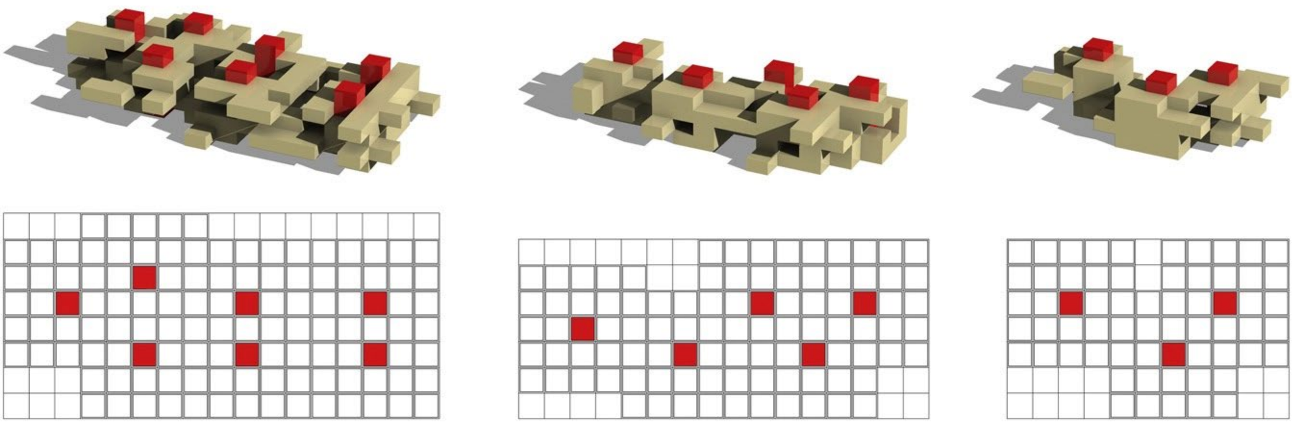


Figure 47. Automatically generated buildings
Source: S. Khalili Araghi, R. Stouffs (2015)

Although the latter rule's set is more sophisticated than the previously presented (COATES et al., 1996) (WATANABE, 2002), the natural light access was guaranteed by prescribed rules without supplementary daylight simulations. In conclusion, CA models' relationship with the environment is understood by the authors (COATES et al., 1996) (WATANABE, 2002) as a relationship with the context. Because of that, they've used similar strategies to address natural light parameters. These three authors explored system's **global properties** to increase the natural light performance, such as the whole building shadow and rules that expanded their radius beyond the neighbourhood configuration. These examples demonstrated the affinity between CA systems to qualitative indicators as daylight performance and reinforces its choice for this work.

Multi-Level Integration

Koenig (2016) has applied multi-level cellular automata systems supported by Humpert (1992) idea that every city could be described based on six patterns (nucleus, cluster, highway man, boom, interlink, and plan). To conceive a model that could generate these six patterns, Koenig proposed a model divided into four specific scales: **(a)** the information level (regional planning), **(b)** site development level (network), **(c)** building level (parcels and building), and **(d)** optimization level.

The site development and building levels used cellular automata as a generative system. The site development stage generated a site population based on the street network. The author associated **(a)** diffusion limited aggregation (DLA) to **(b)** "Free Agents in a Cellular Space" (FACS) to create the six predefined patterns. The FACS associated a CA two-dimensional regular lattice of squares with agents that could move freely across the cellular space and interact with cells. The image below illustrates four generated networks (fixed cells) with different level of aggregation (Fig 48). Although the author associated agents to CA, the cellular space modularity facilitated the translation from urban to the building scale.

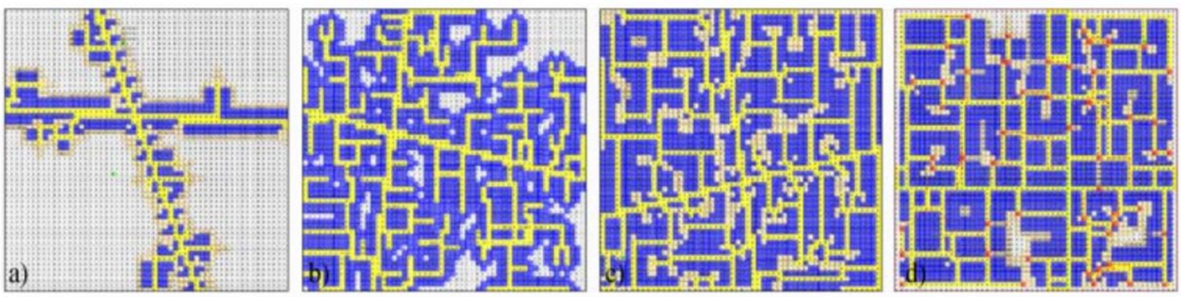


Figure 48. Four generated cities using a regular grid, where yellow cells comprise the streets network and the blue cell's the built areas.
Source: Koenig (2016).

For the building level, CA was applied regarding two major urban parameters. Firstly defining the building footprints in 2d and, secondly, defining building heights in 3d. Koenig (2016) generative model included both public and private areas using four cell states; three for empty areas (green, yellow and red for streets and internal voids) and one for built cells (dark blue) in the image (Figure 49) below. The footprint population were based on counting and voting rules aiming to optimise the neighbourhoods' density. For the three-dimensional scale, the footprint area is extruded according to a predefined number of storeys, as illustrated in image 50.

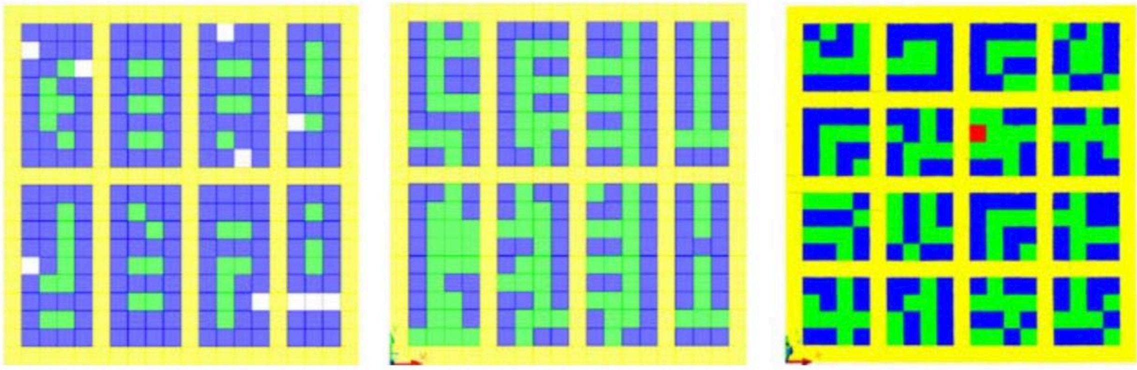


Figure 49. Automated footprint population for different densities. Blue cells are built while green, yellow and red are empty.
Source: Koenig (2016)

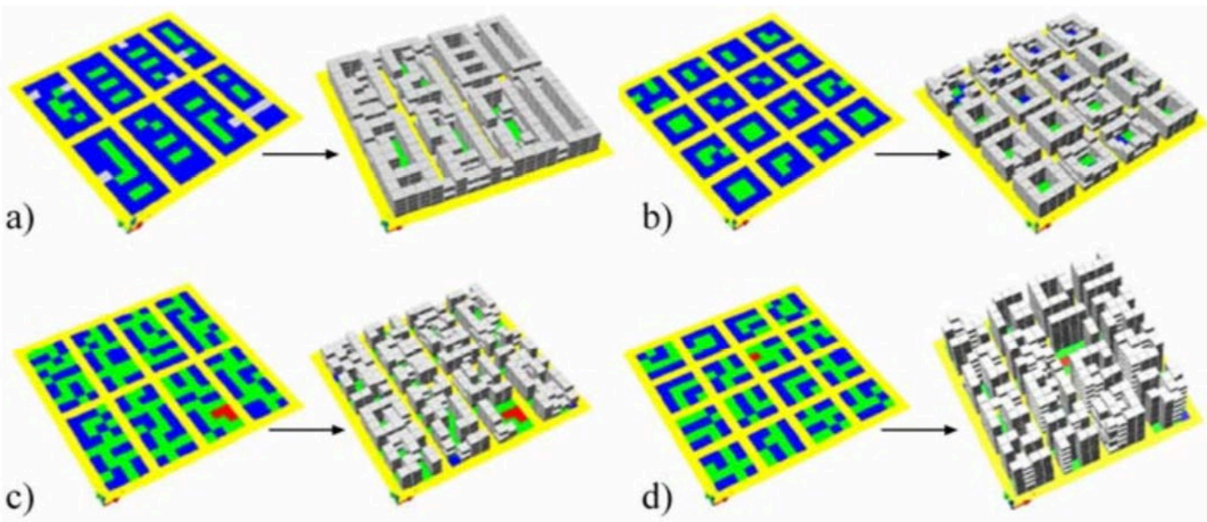


Figure 50. Four generated footprints extruded according a defined number of storeys.
Source: Koenig (2016)

Contributions

Every work presented in the previous pages contributed to the development of a new generative model, which is based on cellular automata (CA) system concerning **(a)** context sensibility, **(b)** daylight availability, and **(c)** form variability in urban and building scale simultaneously. The main contributions are summarized as follows.

Herr and Kvan (2007) evidenced that CA models as form generators with disregard to its context tend to produce fascinating three-dimensional forms, but hardly attend to urban requirements. To overcome this limitation, inspired by Koenig (2016) and Khalili-Araghi and Stouffs (2015), this work suggests the use of **fixed** and **variable cells** states. This state segregation enables the specification of the **urban requirements** (as maximum heights, footprints and morpho-typologies) and **context** considerations in the generative process. Cells States, were also distinguished as **built** and **empty** in the Alpha Syntax models to describe the built environment (HILLIER and HANSON, 1984). While in the original model the relationship between empty and built spaces intended to guarantee the ground floor accessibility (two-dimensional space), the proposed model addresses the exterior interface through a three-dimensional space. **Cell's size**, according to Steadman's (2014) can be depicted from the average depth of day-lit rooms in housing units which is equal to 3,5 m; this is the adopted value for the cells' horizontal dimensions in the proposed generative model.

To configure the **neighbourhood** in the three-dimensional space, the proposed model followed **Coates' Sunshade model** comprising the six immediate cells (Von Neumann Neighbourhood). This configuration not only assures that the built cells can communicate as a continuous indoor space, but also exclude diagonal neighbour cells, which do not interfere in the relationship between the building and its immediate exterior spaces. Also influenced by Alpha Syntax model (HILLIER and HANSON, 1984), the **transformation rules** are set to obtain **(a)** daylight accessibility and **(b)** the spaces contiguity. In other words, they are conceived to avoid cells' overpopulation (no blind cells) and isolation (no flying cells). Rules are based on the 'Game of Life' logic of birth and death **counting rules**, as in the majority of the presented models. While few works demonstrated the impact of initial state, except for Koenig (2016), this work used random seeds to populate the initial state in the model tests. Finally, Koenig's (2016) work reaffirmed that **CA's modularity** facilitated the integration of multi-level models, from site development to building scales. In order to obey overall urban requirements, the proposed model includes three predefined morpho-typologies, based on Martin and March (1972) built forms.

Although the proposed model is constrained to automated generations, its conception enables the **user intervention** in future works. The model requires the specification of inputs such as: the cells size, the global morpho-typology and its attributes (footprint and height), two types of neighbourhoods (Von Neumann and Moore), counting rules threshold, maximum built units (density), daylight simulation parameters, metrics (spatial daylight autonomy and continuous day light) and data representation. The two following tables summarize the previous works contributions and the chosen parameters to conceive the CA model. The first table addresses each model's affinity with context sensibility, form variability, daylight attributes, motivation and contributions to the proposed model. The second table compiles the specifications used in the proposed model.

Table 01 – Presented model's summary

		CS	FV	DL	Motivation	Contributions
1	Alpha Syntax (Hillier and Hanson 1984)			■	Accessibility	Cells State
2	The Islamic City (Hillier and Hanson 1984)			■	New settlements accessibility	Cells State
3	Section D (Coates 1996)	■		■	Authorless form-finding	Avoidance Concept
4	Sunshade (Coates 1996)			■	Form-influenced by light	Neighborhood (6)
5	Sun God City (Watanabe)	■		■	Form-influenced by light	Cells State
6	Krawczyk (2002)		■		Complex geometry into archi.	
7	Koenig (2015)				Urban form pattern generator	Integration
8	Herr and Kvan (2007)		■		Housing Variability	
9	Khalili-Araghi and Stouffs (2015)		■	■	Variability and daylight	Fixed cells
10	Ford (2013)	■			CA based design tool	Context Sensibility

Table 02 – Proposed model parameters.

Attribute	Model Specification	Reference	Motivation
Cell Size	3,5 x 3,5 x 3 m	Steadman	Day-lit Housing Requirements
Cell States	Variable and Fixed	Koenig Khalili-Araghi and Stouffs	Context Urban Requirements
	Empty and Built	Alpha Syntax	Built Environment Description
Neighbourhood	Von Neumann	Coates et al. - Sunshade	Contiguity and Daylight efficiency
Rules	Contiguity	Hillier and Hanson	Housing Requirements
	Exterior Interface	Coates et al. - Sunshade	Daylight efficiency

3. Methodology: A Strategy to create an Interface Between the Urban and Building Scales.

This chapter describes the proposed generative model and the software used for modelling the algorithm. In a broad-spectrum, the challenges to develop this framework included **(a)** the association of a generative model (cellular automata) with a performance model (daylight simulation), **(b)** the specification of strategies to establish the dialogue between different scales (urban and building) and **(c)** the combination of a system intended to generate variability under *global* constraints. In the following, each of the four phases, **(a)** geometry simplification, **(b)** form control and context sensibility set-up, **(c)** form generation based on CA algorithm, and **(d)** daylight autonomy simulation are described in detail.

Modelling and Simulation Environment:

The proposed framework used Rhinoceros 3D for visualization, the plug-in Grasshopper for the algorithm programming and the plug-in Urban Daylight to simulate daylight performance. Rhinoceros is widely used as CAD (Computer Aided Design) software due to its efficiency in complex geometry description and manipulation. It also disposes of an algorithm modelling plug-in based on visual language programming, named Grasshopper (GH). GH has an easy to learn interface and a collaborative community supported by a wide library of predeveloped works. The association of these two factors popularized the use of programming by designers during the design process. For these reasons, the model was conceived with Rhinoceros and Grasshopper.

Grasshopper is based on parameters (geometry primitives and input data) and components, represented by input and output boxes responsible for the algorithm operations (Figure 51 and 52). The user connects the chosen geometries to the components by ‘wires’ resulting in a procedural algorithm. Considering that the algorithm modelling is supported by Rhinoceros, all the geometrical transformations can be simultaneously visualized in the Rhinoceros interface.

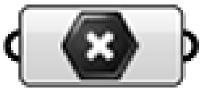


Figure 51. Parameter – Point Geometry.
Source: Grasshopper (2018).

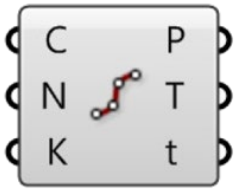


Figure 52. Component – Curve division: inputs are in the left-hand side and outputs are in the right-hand side.
Source: Grasshopper (2018).

To overcome Grasshopper's programming limitations, this work incorporates two Visual Basic (VB) scripts procedures for the Cellular Automata form generation. CA systems require recursive transformations, also known as 'loops' in programming terminologies. "**Recursion** is a term used to describe a process in which the definition of an entity refers to the entity itself." (Terzidis 2006). Conversely, regular users do not have access to looping functions in Grasshopper through conventional means. For this reason, one script sets the simulations area (world size) and, the second, processes the CA iterations.

Visual Basic (VB) is a well-developed programming language accepted in GH environment.GH also accepts scripts from other programming as 'Python' and 'C#'. VB was the chosen language considering the availability of libraries and previous CA works. Each VB script is embodied in a specific GH component. The input variables' values of each procedure are connected in the left side and the outputs of the procedure (transformations outcomes) are accessed in the right side of the component, as demonstrate in the image bellow (Figure 53). For detailed information, see both codes annexed in the appendix section it the end of the text.

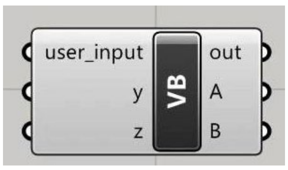


Figure 53. Visual basic component.
Source: Grasshopper (2018).

Finally, the daylight simulation used Urban Daylight' (UD), a plug-in developed to integrate daylight simulation to Grasshopper. 'The plug-in uses a design metric to optimize the set up and simulation time with minor accuracy loss for urban scales' (DOGAN et al. 2012). According to Saratis et al (2012), the plug-in "uses DAYSIM to calculate hourly illuminance levels on discrete facade patches. An impulse-response method is then used to convert outside illumination levels into diffuse light propagation in the interior of a building." (SARATIS, 2012). In other words, the plug-in uses the DAYSIM program with its corresponding software engine Radiance to calculate the illuminance in building's facade and converts the results for the indoor spaces. For this reason, the only required geometry in the simulation process is the building envelope (boundary representation), all the other attributes are set analytically.

UD plug-in simulates building performance using dynamic daylight measures. Recent literature (Reinhart et al. 2006, Dogan et al 2012, Saratisis 2012) advocated for the use of these metrics regarding their level of accuracy. Dynamic daylight performance metrics usually extend over the entire year and consider daily and seasonal variations. The plug-in enables the performance results visualization as **(a)** a value per point displayed in a grid per floor plan, **(b)** the average value per floor, **(c)** the average value per building. The results are rendered in the Rhinoceros interface following a customizable "false-color" graphic scale according to the users' visualization choice. The UD plug-in was chosen as part of the framework due to its reduced time of simulation and level of accuracy, demonstrated by Dogan et al (2012); but also due to the Radiance engine, which is the state of the art in the field.

In summary, **Rhinoceros** and **Grasshopper** are used mainly to import, manipulate and simplify geometries. The **Visual Basic scripts** are used for the CA form generation and the **Urban Daylight** plug-in simulates and plot the results for daylight performance. The image bellow illustrates the overall algorithm in Grasshopper interface, each of the four steps are separated by colours (Figure 54).

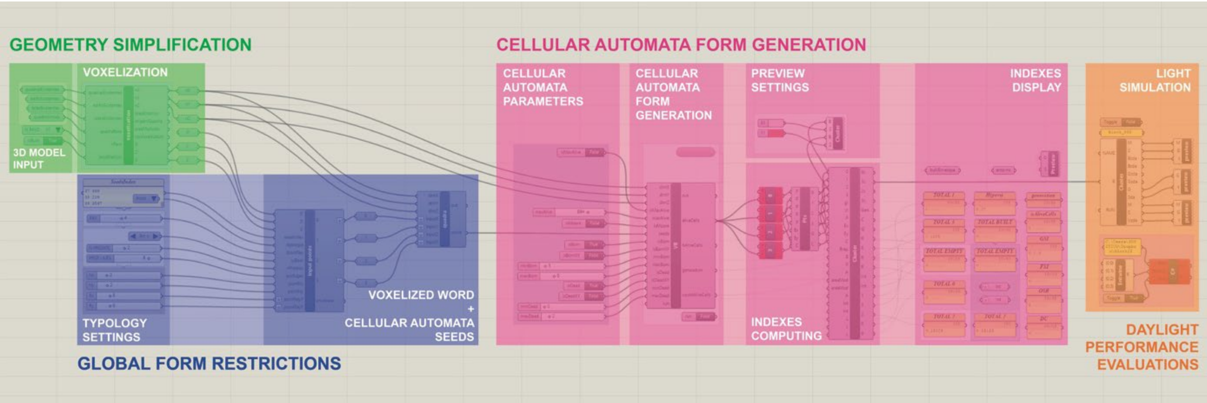


Figure 54. GH algorithm with four steps in Grasshopper.
Source: The author (2019).

Framework:

The proposed framework is divided into four sequential steps, as illustrated in the diagram bellow (Figure 55).

Figure 55. Algorithm step by step workflow.
Source: Zandavali and Turkienicz (2018).

1: Geometry Simplification

The first step main objective is to translate an existing 3D model into a regular 3D grid of cells segregated into empty and built units. This step enables a conventional digital model to attend the CA systems requirements. More specifically, this step automatically converts the existing geometry into a regular grid of cells with specific states. In the output, the cells are divided into two cell types according to their "state": empty or built, which are later translated to the cellular automata systems as dead (0) or alive (1).

The imported 3d model geometry is converted into identic cells for the built environment and for the voids surrounding it. In other words, the model converts boundary volumes (BReps) into points (point cloud). This process is called 'voxelization'. (KAUFMAN, 1987) The voxels used in the model are described by one point and three dimensions. The point is located in the prism centroid, which is described by two coordinates a (x,y,z) referring to its georeferenced position and a second (i,j,k) referring to its position in the model.

Voxels units discretize space into identical cells which are segregated as built and empty cells in analogy to the actual built environment. The geometry simplification step is illustrated in the image bellow (Figure 56). The models on top are the imported 3d models, where is possible to observe minor geometries irregularities. The models in the bottom, in turn, are the outputs of the geometry simplification, which is composed by several identical cubes assemble and described by its centroids and dimensions. As illustrated in the example, it is possible to observe dissimilarities between the original and the simplified models, however, the overall shapes are still noticeable in this scale.

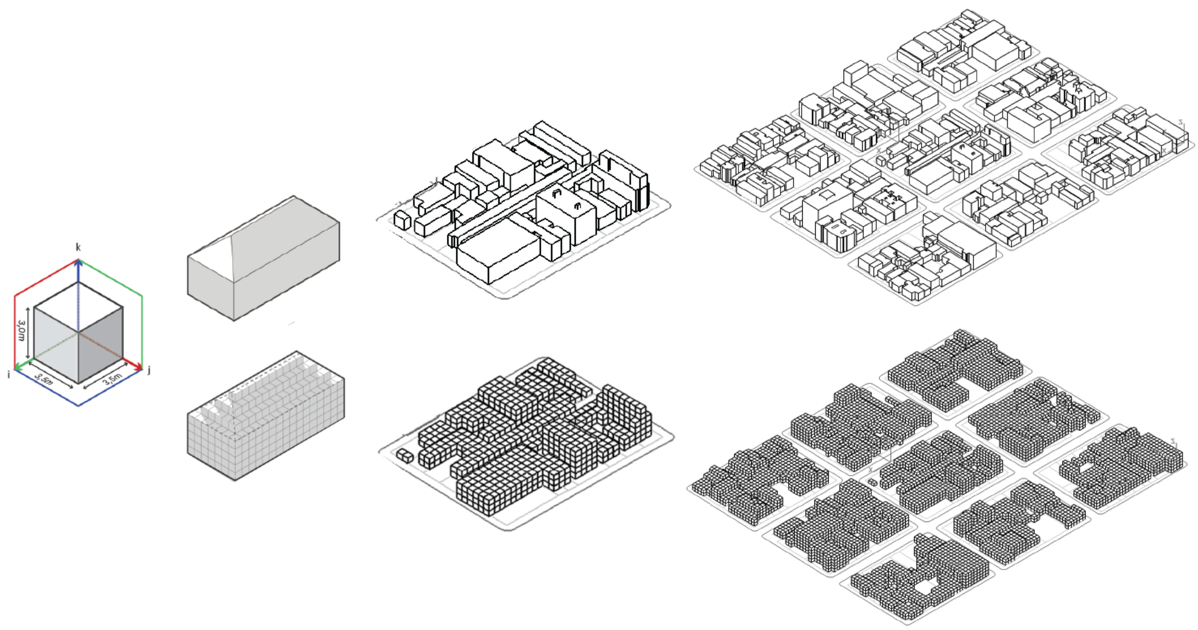


Figure 56. Geometry simplification process.
Source: The Author (2019).

The users' workflow starts with a 3D model file (dwg format) import. The 3D digital model might include curves with the city blocks, plots and building envelope. The user then selects the area to be voxelized, the selection comprises the area where the form generation will take place and its context (e.g. existing buildings and streets). At this moment, the user defines the simulation maximum height and whether the algorithm should include or not existing buildings in the form generation area. This definition impacts whether the model will create completely new buildings or insert new cells in the area considering the existing structure.

After the area is defined, the algorithm sets automatically a new origin in the drawing to the lowest coordinates and rotates the model to facilitate further selections and calculation. This translation only impacts the algorithm calculations without any visual impact. Lastly, the user specifies the cell size, defining consequently the level of geometry simplification. Although the model cells' size is a parametric value, the chosen values for the cells' sizes are defined considering housing activities due to its similar parts aggregation and daylight requirements. For this research, the cells were described with 3,5m by 3,5m by 3m height in analogy to one residential room and a half of the circulation width (STEADMAN, 2014a). (Figure 57)

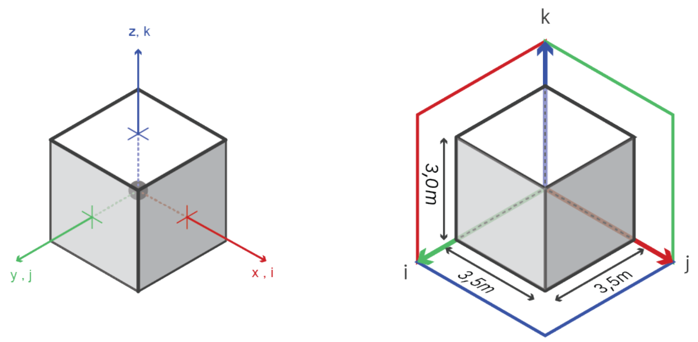


Figure 57. Parametric model for cell's description: centroid and dimensions.
Source: The author (2019).

After the parameters are set, the user calls a function (toggle button on / off) to starts the simplification process. Next, the algorithm generates a three-dimensional array of points (point cloud). The distance between each of the points is equal to the cells dimension. The array comprises all the selected area in the model with a starting point located in the lower left corner (x and y) in the 'ground level'. The point cloud is, then, linked to the imported building envelopes. The intersection of points and building BReps defines the cells states as built or empty. The cells included within the buildings' envelopes are assumed as built (1), and the cells located outside the buildings envelopes are defined as empty (0). Each point in the cloud point has at this moment a state information, which will be considered during CA generation form.

To conclude, the step-by-step of geometry simplification can be described as follows:

Input: City area 3d model

1) File import;
2) Simulation area selection;
3) Simulation height definition;
4) include existing buildings in the form generation area?
5) Models' translation and rotation;
6) Cell size definition;
7) Start the simplification;
8) Point cloud generation;
9) Intersection between buildings BReps and 3Dpoints;
10) Attribute points a value 0 or 1;

Output: Array of 3d points with an attributed value (0 or 1).

2: Form Control and Context Sensibility

Steps two and three complement each other. While the third step main goal is to generate interesting building forms to attend contiguity and exterior interface requirements, the second step's goal is to assure that generated buildings follow urban requirements and address their immediate context. To associate these two divergent goals (form variability and control), this research combines bottom-up systems (CA) with top-down global restrictions (urban requirements). Although the strategies are divergent, the inclusion of context sensibility and form control is understood in this work as an evolution to the existing CA models recurrently criticized for its disconnection with existing structures and practical requirements (HERR and KVAN, 2007).

To address the global restrictions for the form generation process, this work used fixed and variable cells. The inclusion of fixed states in step two enables the model to detect pre-existing buildings, to obey urban restrictions (maximum heights, setbacks and footprint) and to follow predefined 'morpho- typologies' (court, street and pavilion). Table 3 summarizes the two opposed concepts (bottom-up variability and top-down urban controls) and how each of these relates to the design scales, to the actual objects in the built environment and to cell states. Both fixed and variables cells can be either built or empty cells, resulting in four different states within the system. The cells' disaggregation into four states not only guarantees that the generated buildings attend to urban requirements, but also enables the model's application in areas with existing buildings aiming to densify or to redesign block's shapes. In this case, the CA algorithm fills eventual gaps between the existing buildings, compensate different heights and redesign the block morphology.

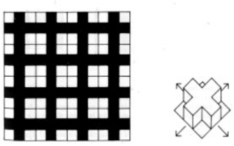
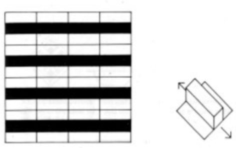
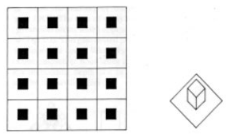
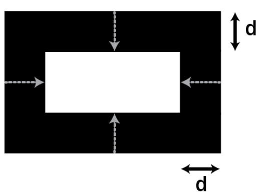
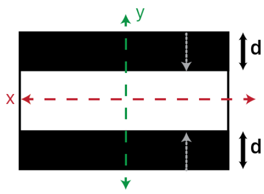
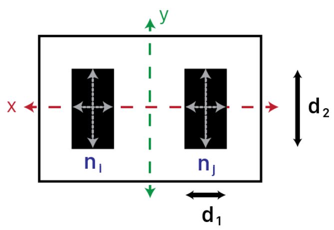
Table 03 – Top-down and bottom up strategies included in the model.

	Urban Control		**Form Variability**	
Aim	Control		Variability	
Approach	Top-down		Bottom-up	
Design Scale	Urban		Building	
Semantic equivalence	Existing Buildings Public Space Urban Bulk		New buildings closed spaces New buildings open spaces	
Model's Cell type	Fixed		Variable	
	Built	Empty	Built	Empty
	3	2	1	0

Although for the model, the cells are not segregated, we didactically separate the cell according to their location: inside or outside the 'study area'. The cells outside the study area are the context without any direct influence the form generation. The cells inside the study area the immediate 'neighbours' and are counted in the form generation process. Outside the study unit, **fixed built cells** represent neighbours' buildings, while **fixed empty cells** represent all the open spaces as streets, squares and backyards. Inside the study area, the **fixed empty cells** determine the block morphology and urban requirements as maximum height, alignment and footprint. Finally, the **variable cells**, which may change their state from 'empty' to 'built' throughout building generation, are located inside the block. **Variable built cells** represent the new buildings indoor spaces, while **variable empty** cells represent outdoor spaces as terraces and balconies.

After a few experiments with the model, the results demonstrated that the model required a top-down strategy to define the buildings' footprint. That been said, in addition to the system of fixed and variable cells, this work used three morpho-typologies: **(a)** court, **(b)** street and **(c)** pavilion (MARTIN and MARCH, 1972). The chosen morpho-typologies were previously used in urban density studies (BERGHAUSER-PONT and HAUPT, 2009) due to the variety of possible the outcomes. Each morpho-typology has specific geometry characteristics, for example, the 'court' type configures an enclosed occupation, the 'street' type configures a longitudinal distribution and the 'pavilion' type a vertical population. Since the user can specify the maximum height, coverage and intensity the three typologies can be easy tested in a variety of cities respecting their urban code. These three block morpho-typologies work as urban bulks for the algorithm defining the overall boundaries constraining the new buildings generation volume. Table 4 illustrates their geometry description and the required parameters to describe these boundaries in the algorithm.

Table 04 – Morpho-typologies parametric model description.

Court	Street	Pavilion
 Source: Martin and March (1972).	 Source: Martin and March (1972).	 Source: Martin and March (1972).
 Source: The author (2019).	 Source: The author (2019).	 Source: The author (2019).

Parameters		
• Height • Depth	• Height • Depth • Axis (x or y)	• Height • Depth • Axis (x or y) • Number of Building

Every cell is initially assigned as an empty or built according to the site situation. The definition of the morpho-typology bulk adds static and variable states for the cells according to where they are situated. The cell's final value combines a value for static/variable to a value for built/empty, as illustrated in the diagram of figure 58 and table 5.

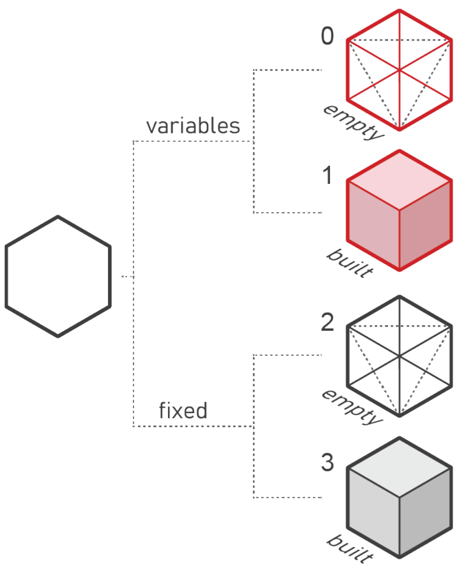


Figure 58. Cell's states diagram.
Source: The author (2019).

Table 05 – Cell's state combination.

State	1^n	2^n	Value
Empty + Variable	0	0	0
Built + Variable	1	0	1
Empty + Fixed	0	2	2
Built + Fixed	1	2	3

Step two workflow starts with the user defining the urban unit to be simulated and selecting the original curve shape in the Rhinoceros interface. In this case, the chosen unit is the block. Then, the user defines the maximum height for the system simulation. The algorithm then extrudes the selected curve to the maximum height, the points inside shape are then associated with the simulation area. After the simulation is set, the user sets the parameters to define the morpho-typology bulk. First, the user starts choosing one of the three types. Then, for–the 'court' type, the user sets the bulk height (h) and the slab depth (d). For the 'street' type, the user sets the bulk height (h), the axis the bulk will be oriented (in this case, x for the longitudinal and y for transversal) and the slab depth (d). For the 'pavilion' type, the user sets the bulk height (h), the number of towers to be considered in the block (n), the predominant axis to divide the land (in this case, x for the longitudinal and y for transversal) and, finally defines two dimensions (d_1 and d_2) to describe each tower footprint. All the parameters are specified in cells units, where the horizontal dimensions are equal to 3,5 meters and each floor height is equal to 3 meters.

Once all the parameters are set, the algorithm automatically executes geometric operations following the block boundaries and the maximum height to create bulk boundary representation ('BRep'). Next, the bulk BReps intercepts the cloud point to attribute the states values. At this moment, all the points within the bulk are defined as 'variable empty' cells. In case of the simulation also includes the existing buildings, these cells are discounted, and their states remain as 'fixed built'.

Lastly, the user defines the cells to carry the 'variable built' state in the first generation, also known as 'initial state'. These cells are the first ones to influence in their neighbours' states. While the initial state has not demonstrated major impact in the form generation, the 'variable built' cells are randomly defined within all the cells inside the urban bulk. To conclude, the step-by-step of 'Form Control and Context Sensibility' can be described as follows:

Input: Array of 3d points with an attributed value (0 or 1)

1) Define block
2) maximum height
3) Intersection block + height and points
4) Define morpho-typology
5) Set parameters (depth, height, axis and number of buildings)
6) Fixed and Variable State Attribution
7) Define Initial State

Output: Array of 3d points with an attributed value (0, 1, 2, 3)

3: Form generation

Step three aims to automatically generate buildings based on rules operated by a CA system. Moreover, this step also aims to create a wide variety of building geometries with **(a)** similar densities (square footage) and **(b)** daylight performances to attend predefined parameters. To guarantee that the CA system outcomes would result in feasible architecture buildings, the model adopted transformation rules based on the **contiguity** between cells ('no flying cells') and the **interface** with the exterior ('minimum blind cells'). The form generation input is the four-state point cloud from the previous step. During the CA iteration, cells may change their states from **'variable empty'** to **'variable built'**, and vice versa, until the system is stopped by the user. The context and the global restrictions remain fixed while the building is generated. Figure 59 illustrates a generated block with the four state cells differed by colour. While the grey cells are fixed (dark grey for buildings and transparent light grey for voids) the red cell are variables and change their state during the generation process (dark red are the new built cells and light rose are the resultant voids).

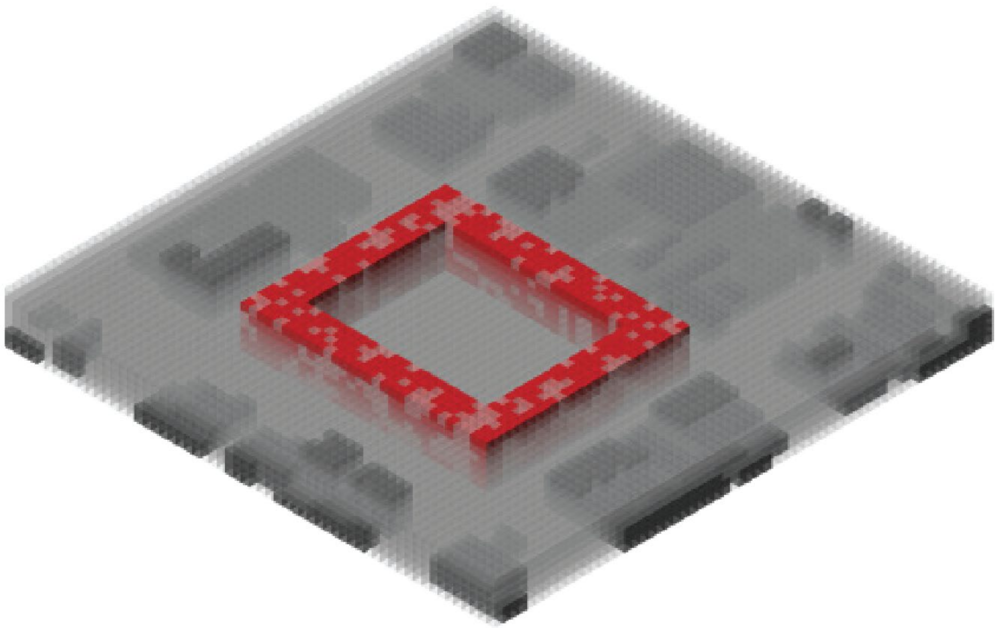


Figure 59 – The final state for a generated block. Red cells iterate their state (empty/built) along the form generation process while grey cells remain static.
Source: The author (2019).

As every CA system, this model requires three inputs: (a) an initial state, (b) a set of transition rules and (c) the neighbourhood configuration. The diagram (Figure 60) describes two different time frames in a simulation and illustrates the input and output of form generation step. The first frame is the initial state (or the 'starting point); the second is the final state, the moment when the user stopped the iteration (the result). The grey cells are fixed, the dark ones represent the existing buildings and the ones in light grey represent the empty areas, such as the streets or the proposed urban bulk that assures the block morphology. The red cells are variable; the dark red ones represent the built cells, and the light red ones represent the empty spaces. The empty variable cells range from a large majority on hold to change their state to private out door spaces. The built variable cells (dark red), in turn, on the initial state are arbitrary inputs, and in the final step they represent the new buildings.

The **initial state**, also known as 'seeds', is a predefined (arbitrary) state that defines the system starting point (time = 0). For this model, the initial state comprises the variables cells (built and empty). After several experiments, the author observed that the initial state influence was minimal[1] to the outcome and, for this reason, the 'built' seeds were randomly assigned. The model supports two different 3D **neighborhoods'** configurations of radius equal to '1' (for more information see chapter 2). The first is the 'Von Neumann' neighbourhood that comprises the six adjacent cells; and the second 'Moore' neighbourhood that comprises twenty-six cells, the adjacent and diagonal cells, like a 3d Game of Life configuration.

[1] Differently to the Game of Life (discussed in the previous chapter) the initial state was minimal, probably due to an association of factors: (a) the defined minimum and maximum range, (b) the third dimension and (c) the numbers of iterations.

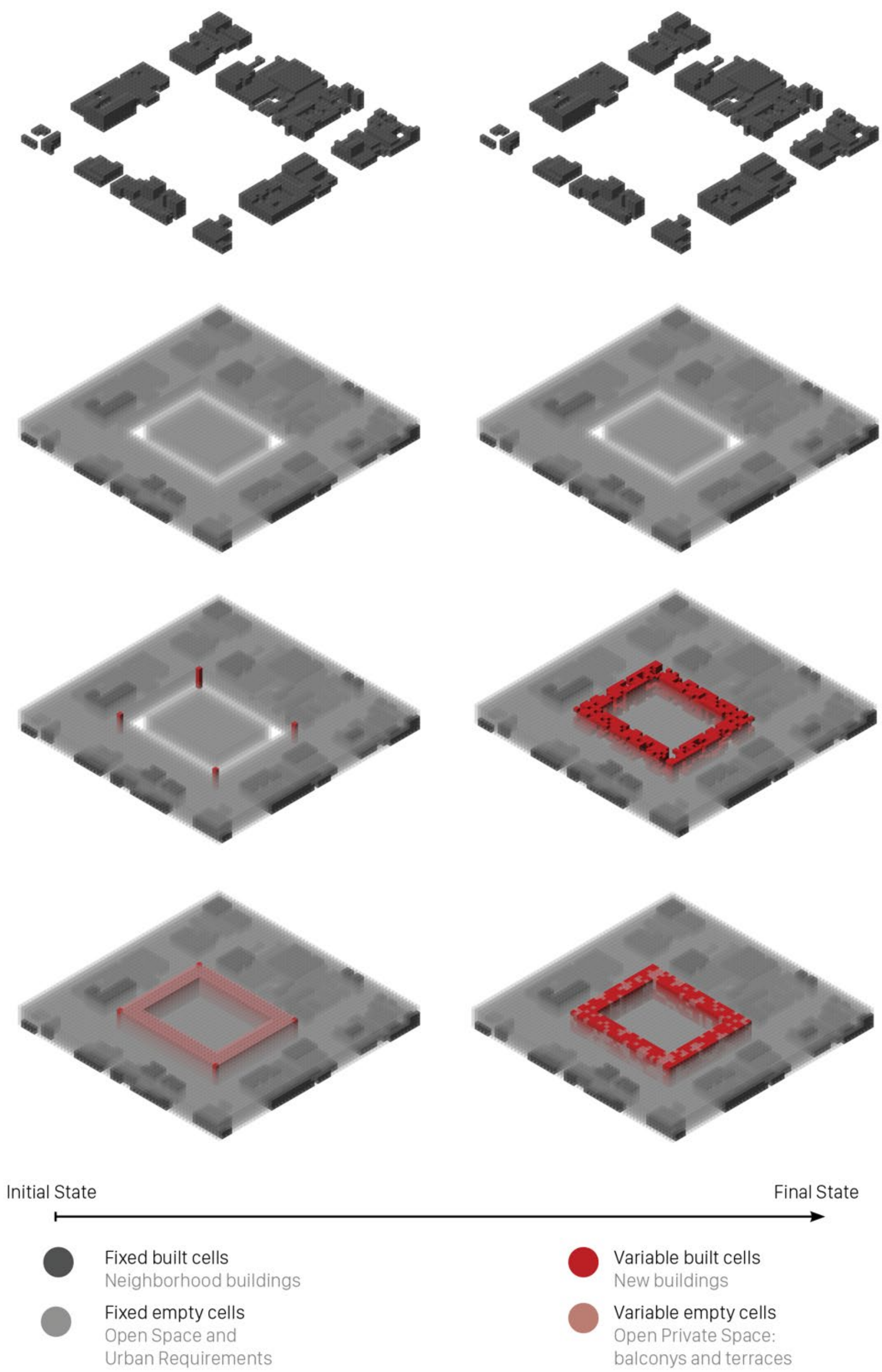


Figure 60. Initial (left-hand side) and final state (right-hand side) of a block generated with AC model. Cells' colour stands for its states, which are represented in additive layers from top to bottom. Source: The author (2019).

The neighbourhood configuration influences the computational processing time and the number of possible combinations per cell. While this research aims for contiguity between cells, the experiments used **Von Neumann** configuration to reduce the number of flying (as also demonstrated by Coates 1999). The diagram bellows illustrates the cell in the centre and its respective neighbour per axis (Figure 61). Each neighbour is identified by the central cell coordinate + / - 1 in each axis: (i: **+1** front, **-1** back), (j: **+1** left, **- 1** right.) (+k: **+1** up, **-1** down).

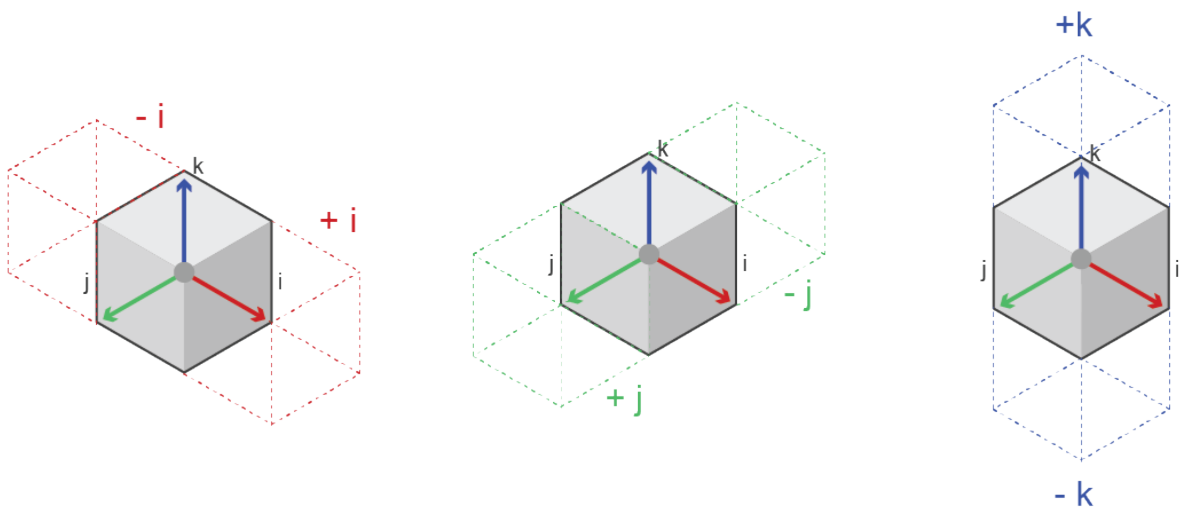


Figure 61. The System Neighbourhood Configuration – Von Neumann
Source: The author (2019).

The process of modelling the ideal rule set required several experiments and observation. The proposed **rule set** follows the Game of Life **counting** method, also known as **Birth** and **Death** rules. The concept behind the rule design was to assure that every cell would not have its neighbourhood overpopulated (exterior interface) nor will remain isolated (contiguity). In other words, every cell might have at least one built neighbour in any face to guarantee the internal contiguity and at least one empty neighbour in the vertical faces (where you can open a window) to guarantee light and ventilation access to the room. The diagram illustrates five possibilities of a built cell (in grey) varying from one to five neighbours.

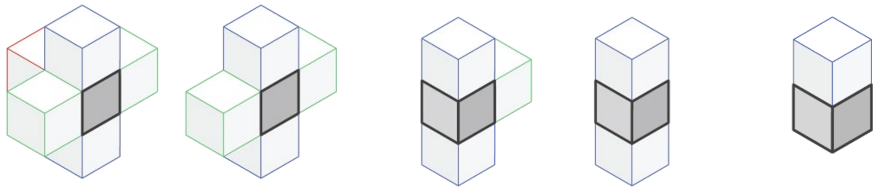


Figure 62. Five 'valid' neighbourhood for one cell, preserving one face with exterior interface.
Source: The author (2019).

During the iteration process, the system counts the number of alive cells and verifies whether the cell state should change or not. The user can define the minimum and maximum threshold to make a cell alive (built) or dead (empty). After the experimentation and observation of different rule sets, this research opts for a fixed range based on contiguity and exterior interface goals, described in the Table 06:

Table 06 – Transformation rules threshold.

Rule	Minimum	Maximum
Born	1	5
Dead	0	2

Considering that the experiment compares buildings with similar densities, the system also has an option to limit the maximum number of cells. The user sets the maximum square footage defining the maximum number of alive cells (e.g. 1000 cells = 1225 sqm). After all the parameters are set, the user initializes the iteration process through a toggle button (star/stop) button and press it again to pause or stop the iteration.

The algorithm developed for the CA system used a Visual Basic Script imbedded in the Grasshopper component. The component, which is also the interface to set up the initial parameters, is illustrated in image bellow (Figure 63). In the right side of the component are located the system inputs and parameters: the initial state (dimX, dimY, dimZ), the rules range (isBorn, isDead, minBorn, maxBorn, minDead, maxDead), the neighbourhood configuration (isMoore: true for Moore and false for Von Neumann), maximum number of cells (maxAlive) and the start/stop button (run). The outputs are in the right side of the component and comprises the new list of points and the generation count. While the generation process uses the same initial state and parameters, it is possible to replicate an outcome by keeping track of the generation number.

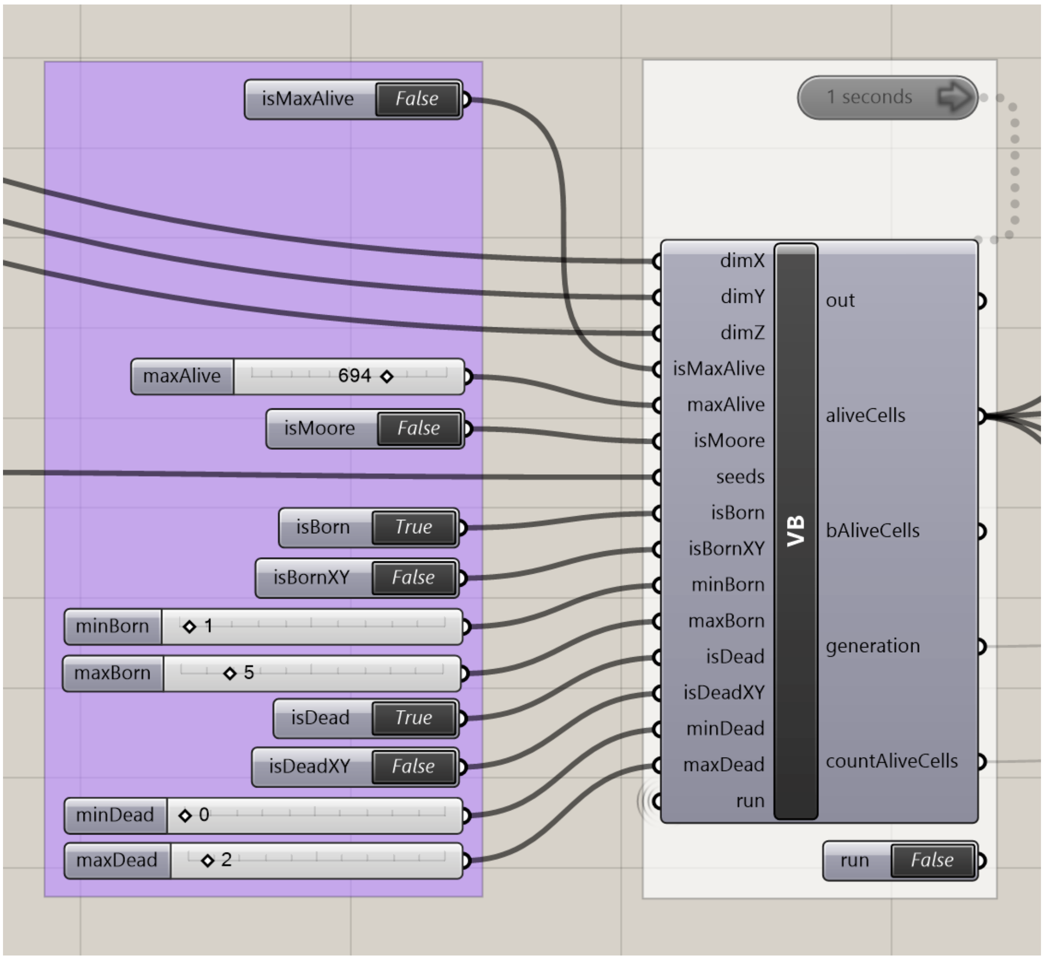


Figure 63 – The Form Generation Interface in Grasshopper.
Source: The Author (2019).

While the iteration is happening, the process is visualized in the Rhinoceros screen and density indicators can be tracked in the Grasshopper interface. To track the density performance, the model also disposes of functions to calculate and display indexes for coverage (Ground Floor Index - GSI), intensity (Floor Spatial Index - FSI), spaciousness (Open Space Ratio - OSR), building height (Number of floors) and the total number of dwelling units (6 built cells = 1 dwelling unit). The outcomes for this step are the new built cells, which can be part of a consolidated area or a brand-new block. Figure 64 illustrates two examples of outcomes with equivalent simulation parameters, one considering the existing buildings (in red) and the other as a whole new building population.

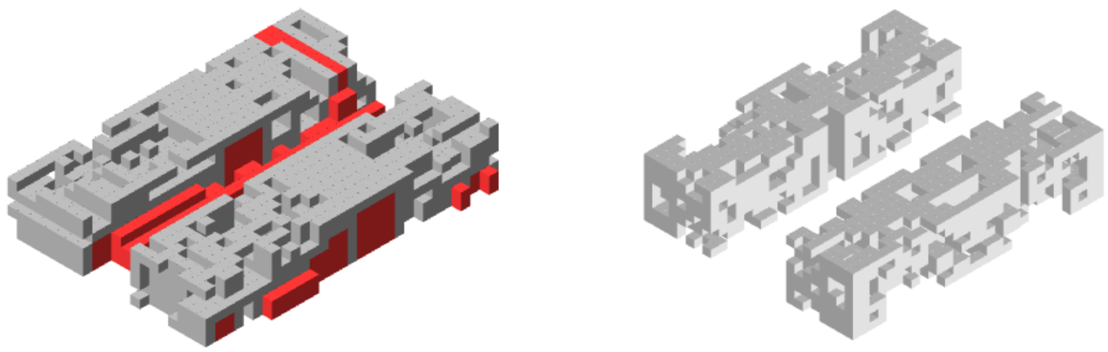


Figure 64. Form Generation Outputs – Typology Street with and without the existing buildings.
Source: The author (2019).

As previously said, the model enables the user to follow the iteration process in the rhinoceros's interface. Figure 65 illustrates the growth process for the outcome in Figure 64, in which it is evident the sensibility to the existing context. The number below the image refers to the generation count, ranging from the initial to the final state.

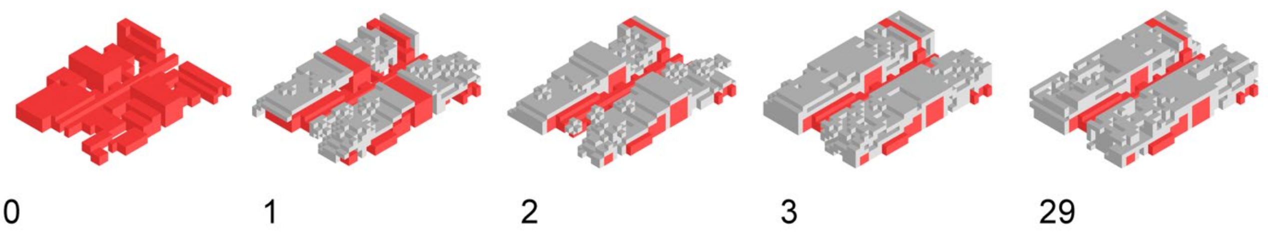


Figure 65. Form Generation process – From the Initial State to the 29th generation.
Source: The author (2019).

The 'Form Generation' workflow can be described as follows:

Input: Array of 3d points with an attributed value (0, 1, 2, 3)
1) Neighbourhood definition
2) Rules range definition
3) Maximum Alive Definition
4) Run it!
5) Follow the behaviour in the Rhino
6) Stop it!

Output: New building Geometry + Density Indicators

4: Daylight Evaluation

The last step, Daylight Evaluation, aims to simulate the generated building daylight performance using 'Urban Daylight' (UD) plug-in. Based on hourly illuminance profiles, the program calculates daylight autonomy considering the building envelope with predefined simulation parameters. First, the user set up the simulation requirements, run it and, then, display the results in the Rhinoceros's interface and collect the indexes in a 'Comma – Separated – List' compatible with softwares as Microsfot Office Excel. To evaluate the daylight performance, this work compares the simulation results through two daylight metric methodologies based on hourly illuminance profiles: Spatial Daylight Autonomy ($sDA_{[300lux]\,[50\%]}$) and Continuous Daylight Autonomy (cDA).

To simulate the building's performance, the Urban Daylight plug-in requires geometric and analytical data. The geometric parameters comprise the building under evaluation and its context, which impacts the final performance. (Figure 66) First, the model merges all the generated cells into few solid geometries as the buildings' envelopes. The building geometry is connected to the "Builder" component, where the user specifies building's information as: floor height, façade openings through window wall ratio (WWR %) and requirements for the daylight simulation metric. The surrounding buildings are connected to the "Shading Surfaces" component. Figure 66 illustrates the volumetric geometries and the result of this step.

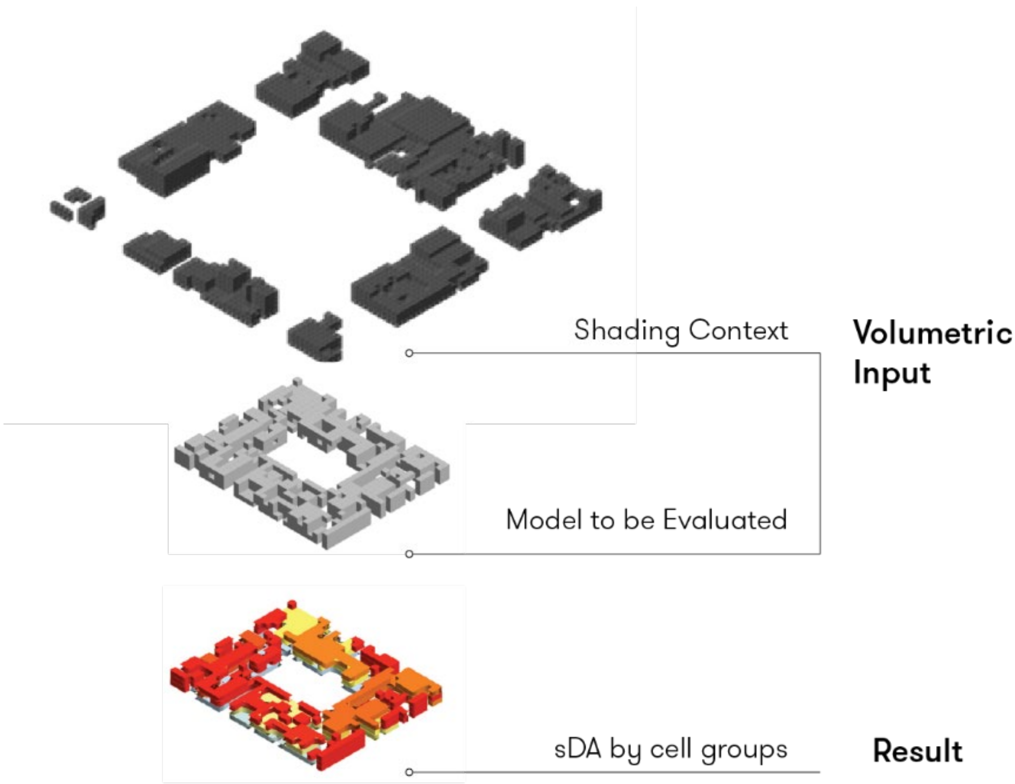


Figure 66. Form Generation Outputs – Typology Street with and without the existing buildings (in red). Source: The author (2019).

Before running the simulation, the user specifies the simulation and radiation parameters and uploads the climate data (local weather file). The simulation parameters report the simulation units (lux) and time frame (in hours). The radiance parameters, in turn, report to the 'Radiance' dynamic simulation algorithm specification (bounces, divisions, super-samples, resolution, accuracy). This step specification set up varies according to the simulation goals and architecture scale. For this reason, this works followed previous works with similar scale to define the test cases' specification, in the detail in the next chapter.

Once the simulation is completed, the results can be displayed by the Rhinoceros interface. 'UD' enables four metrics calculations concerning **(a)** sensor points, **(b)** floor, **(c)** building and **(d)** group. The simulations are based on hourly illuminance profiles that are calculated for two metrics, the continuous daylight autonomy and the spatial daylight autonomy. The results are displayed for both metrics according to false-color scale defined by the user. In this work, the simulation results are displayed according to the floor coefficients that are graphically represented from blue to red colors, corresponding to a 0 to 1 range value (0 to 100%). This research also evaluates the overall group coefficients to compare the whole block performance. The following image (Figure 67) exemplifies the daylight simulation results for the typology street. In the left-hand side are input models with and without the existing buildings in red. The second and third columns refer to the results for Continuous Daylight Autonomy (cDA) and Spatial Daylight Autonomy respectively.

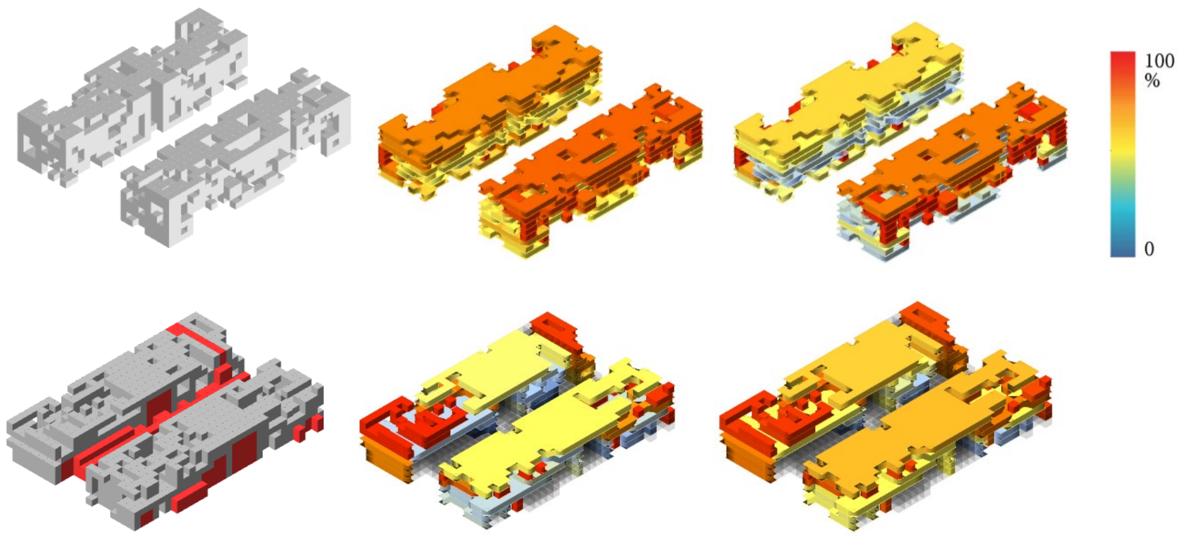


Figure 67. Daylight results for Typology Street with and without the existing buildings (red cells).
Source: The author (2019).

Summary:

In summary the proposed model framework starts with the voxelization process that simplifies the model geometry into a regular grid, followed by the definition of fixed and variable attributes to assure context and urban restrictions. Next, the CA model generates new buildings with the aim of assure daylight access and cells contiguity; and, lastly, the daylight simulation evaluates generated models' performance. The tables in the sequence, summarizes (Table 07) the relationship between the model set up and the strategies envisioned and, (Table 08) each step objectives, inputs, and outputs.

Table 07. Correlation between the model setting, space attributes and the chosen strategies.

Step	Model Setting	Space Attributes	Strategy
Geometry Simplification	World size	Study area and context	Voxelization
	Cell size	Room	Level of Abstraction Day-lit Space
Form Control and Context Sensibility	Fixed cells	Streets, neighbour buildings	Context
		Urban Bulk: Footprint / Coverage Maximum Height	Block/Building Morphology
Form Generation	Max Alive	Floor Spatial Index	Intensity
	Rules Born	Contiguity	No flying cell
	Rules Death	Exterior interaction	No blind cell

Table 08. Model's methodology summarized.

	Geometry Simplification	Form Control and Context Sensibility	Form Generation	Daylight Simulation
Obj.:	• Simplify exiting model into a regular grid	Define urban and context restrictions.	Assure: • Form Variability • FSI (density) • Contiguity • Exterior interface	• Simulate daylight autonomy
Input:	• 3d Model (curves) • Cell Size • Simulation Area	• Point Cloud World (0,1) • Typology definition + parameters	• Fixed and Variable World (0,1,2,3) • Initial State (seeds) • Max alive (density) • Born/Death Rules	• New Building • Simulation Parameters (Window ration, weather file, occupancy, obstruction and evaluation method)
Output:	• Point Cloud World (0,1)	• Fixed and Variable World (0,1,2,3) • Initial State • Footprint and Height Setting	• New Building • Density indicators (FSI, GSI, Height, OSR)	• Daylight results (sDA and cDA) • Daylight results graphic representation

4. Case Study: Auto-Generated Block

4.1 Experiment

The experiment's main goal was to verify the model's potential to generate new buildings with similar density to buildings designed according to the existing urban regulations and compare the daylight performance of both cases. To test the proposed model, two case studies were developed using an existing city block in Porto Alegre, the Brazilian southernmost state capital. In the first case study, totally new buildings were generated for two different FSI values following three morpho-typologies of urban blocks. The generations were evaluated and compared, with respect to daylight accessibility, to the existent fabric. The second case study generated new buildings while maintaining existing ones to redesign the block's peripheral shape. The original buildings floor space was added to the new buildings floor space as to configure the maximum FSI for two urban blocks morpho-typologies.

Site Selection

The selected block is part of a Porto Alegre's regular street grid system currently undergoing a process of renewal. To select the block three different criteria were used: **(a)** to have a regular shape to enable an easy visual comparison with neighbouring blocks, **(b)** to be part of consolidated areas undergoing transformations and **(c)** to have buildings with historical preservation interest.

The block, situated in the 4th district of Porto Alegre's municipality, fulfilled the three partite criteria. The neighbourhood display a orthogonal grid featuring blocks with regular dimensions (around 100m length x 80m depth). The 4th district, historically associated to the industrial activity (today partially moved to the city's periphery) is now predominantly constituted by lightweight commercial activities and residential units. As a result, buildings with different uses and from different periods cohabit the same area. The area is currently undergoing a renewal process whereby multi-storey buildings are gradually occupying lots previously occupied by one-two storey buildings. The renovation, until recently a piecemeal process, is currently being reformulated for a new and faster growth pace led by a Master Plan commissioned by Porto Alegre's municipality (NTU, 2017).

Figure 68, an aerial photo of the 4th district with the selected block in red, clearly shows the orthogonal street configuration. For example, on the upper left-hand part of the image, most of the streets obey an orthogonal pattern. Different land uses can be depicted from the shown image: in the left and top areas most of the blocks are occupied by large one-to-two storey buildings characterizing industrial activities; in the centre and bottom of the image, several plots characterize small commercial buildings and/or multi-storey dwelling units.

Figure 68. The aerial photo of the region where the chosen block (red square) is located.
Source: The Author (2019).

The chosen block (in red, Figures 68 and 70) is part of the Navegantes neighbourhood, one of the five neighbourhoods constituting the 4^{th} district of Porto Alegre. Figure 69 illustrates the block surrounded by França Avenue to the north, Pará street in the east, Cairú street in the south and Amazonas Avenue in the west. The block has a rectangular shape totalizing 9.187,5m^2 area subdivided into 16 plots. Figure 69 displays the selected block and plots of different dimensions and proportions. Filled shapes represent the existing building footprints (in red for the simulation block and in grey for the neighbours' blocks). The variety of buildings shapes and gaps between these sheds light on the discontinuity problem raised in the introduction of this work: while plot 16 is occupied by one large single storey building, plot 11 has a much smaller footprint divided into two buildings. Another evidence of Porto Alegre's discontinuity is the variation of setbacks and featured in the studied block where plots with no frontal setback (plot 16) mingle with varied setback distances (plot 6, 7, 8) in the same road due to different planning regulations.

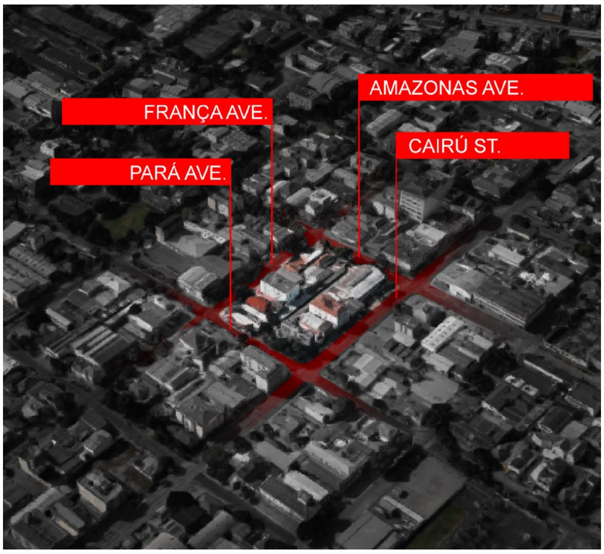


Figure 69. The situation map for the sample block surrounded by similar regular shaped blocks.
Source: The Author (2019).

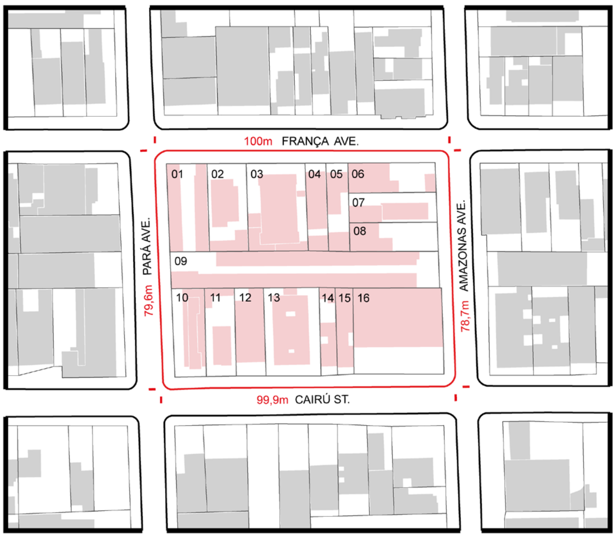


Figure 70. The floor plan for the sample block (in red in the middle) surrounded by nine facing blocks. Although the blocks have regular shapes, the building footprints show a random footprint.
Source: Zandavali and Turkienicz (2018).

Model's Set Up

To set-up the models before the study cases simulations, the author considered the **(a)** density parameters applied to the area according to the urban code, **(b)** the surrounding context, **(c)** the parameters that define the geometric boundaries for each morpho-typology and **(d)** daylight simulation parameters.

Both case studies considered Porto Alegre's zoning **density indexes** as a proxy to the model's applicability to actual urban regulation's requirements. Table 09 summarizes the four density indexes presented in the zoning guidelines: Floor Space Index (FSI) related to land use intensity, Ground Floor index (GSI) related to the building coverage (also known as footprint), the dwelling average size that enables to estimate the number of people living in the area, and the buildings maximum heights (H). Whereas the zoning guidelines allocate indexes for FSI, GSI and dwelling units by region, it defines maximum heights according environmental aspects related to the facing street width and setbacks.

Porto Alegre's zoning guidelines also use setbacks to establish volumetric constraints. The plan associates side-setbacks to the building height to ensure daylight access and ventilation to neighbouring buildings. This work proposes an alternative method to ensure natural daylight access and, therefore, simulations are set without following mandatory setbacks regulations.

Both FSI thresholds were tested in the simulations. The first, 1.3 FSI, is an ordinary index for the area that can be bonus incremented by investors up to 3.0. Both tests used the maximum building height value allowed by the municipality as a reference to limit the height of the urban block. New buildings variable-built cells (maximum alive cells parameter in the model) were limited to match the FSI indexes. **FSI 1.3** constrained the number of cells to a maximum of **1075** and the **FSI 3.0** to a maximum of **2325** cells. The coverage index (GSI) and the height limit were used to define the urban block geometrical parameters along with the chosen morpho-typologies, whereas the FSI index defined the maximum of built cells to be generated during the CA simulation.

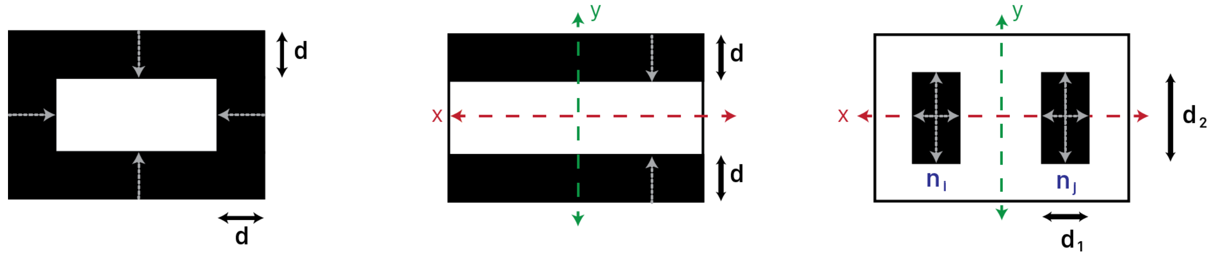
Table 09 – Zoning guidelines for density indexes.

Parameter	Value
Floor Space Index (max)	1.3 and 3.0
Ground Space Index (max)	75%
Dwelling size (average)	75m2 (6 cells)
Heights	12.5 m (4 cells) 52 m (17 cells)
Setbacks for Towers	3m (min.) 18% of the total height (smaller than 27m) 20% of the total height (from 27 to 42m) 25% of the total height (bigger than 42m)

Due to goal correspondence to Saratis et al. (2012), the **simulation context** is set as a 3 x 3 block array. The simulation block is in the centre of a polygon constituted by another eight blocks (the four facing blocks and the four in the diagonal). The model automatically converts (step one, see chapter 3) the existing 3D model of the existing buildings and non-built spaces into a 3D grid composed of empty and built cells for the simulation block and its context. The simplification converted the simulation's block polygon into 25 cells (87.5m) by 30 cells (105m) totalizing 750 cells (9.187,5m2) area – the cell size is 3.5 x 3.5m.

Table 10 – Geometric boundaries setup parameters.

Morpho-typologies Setup



Court FSI: 1.3	Street: FSI 1.3	Pavilion: FSI 1.3
Height = 4 cells Depth = 8 cells	Height = 4 cells Depth = 8 (8 x 31) cells Div. Axis = Y	Height = 8 cells D1 x D2 = 8 x 16 cells Div. Axis = X Num. of Buildings: 2
Court FSI: 3.0	**Street: FSI 3.0**	**Pavilion: FSI 3.0**
Height = 8 cells Depth = 8 cells	Height = 8 cells Depth = 8 (8 x 31) cells Div. Axis = Y	Height = 17 cells D1 x D2 = 8 x 16 cells Div. Axis = X Num. of Buildings: 2

The specification of values for the **geometric boundaries** aims to conform the presented urban requirements of Porto Alegre's municipality according to a chosen morpho-typology. The three morpho-typologies are set to follow the GSI index (defined by the boundary 'depths' – See table 10) and the maximum height (defined by the boundary 'height' – see table 10). Additionally, 'street' typology includes a division axis that defines the direction of the buildings in the block – in this case, it defines whether are they aligned with the shorter or longer side of the block. The 'pavilion' typology requires specification on the number of towers and the axis to divide the land. Table 10 illustrates each of the parameters and summarizes the values used for each morpho-typology (court, street and pavilion) for FSI 1.3 and 3.0 in the study cases.

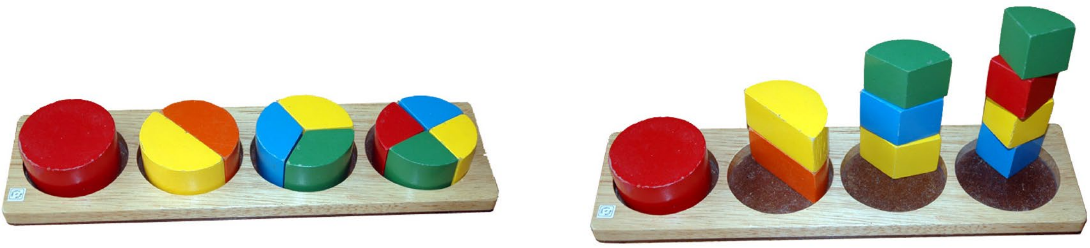
The model's set up for the **daylight simulations** requires inputs for geometric and analytical parameters. The geometric parameters include the generated building envelope and the surrounding context building envelopes. The context used for the simulations included the eight surrounding blocks. Other geometric parameters as the floor- to -floor distance and the openings area are described analytically in the Urban Daylight plug-in. The floor-floor distance is set to an average of 3m (the cell's height) and the façade window wall ratio to 50%. The analytical simulation parameters are listed in Table 11. This work used previous works as references to define each of the simulation set-up values (SARATIS et al. 2012, DOGRAN et al. 2017).

Table 11 – Daylight simulation parameters setup.

Parameter	Setting
Ambient Bounces (AB)	3
Ambient Divisions (AD)	1024
Ambient Super-Samples (AS)	512
Ambiente Resolution (AR)	256
Ambient Accuracy (AA)	0.2
Occupancy Hours	8AM – 6PM
Sampling Distance Inside	0.5m
Blind trigger point	20,00lux
Façade windown to wall ratio	50%
Glazing Type	Tvis 50%, 100% diffusion
Weather data set	Porto Alegre

Measuring Density – Metrics and Indicators

Five indicators were adopted to evaluate density aspects: **(1)** Height (H, meters or floors), **(2)** Ground Floor Index (GSI), **(3)** Open Space Ratio (OSR), **(4)** Floor Spatial Index (FSI), **(5)** Dwelling density (dwellings per hectare, dw/ha). Height indicator, for example, impacts the urban form and is visually perceived by the inhabitants. GSI and OSR relate to the building's footprint regarding built and void space respectively. FSI and dwelling density, in turn, relates to the land use intensity and, consequently, to population concentration. Although each indicator reflects one density aspect, they are interdependent. Figure 71 illustrates the correlation between FSI, GSI, OSR and H. In the left-hand side, the four solutions are identical for the three indicators. In the right-hand side of the image, the four solutions are identical in terms of FSI but differ in GSI, ORS and H.



Height	1	1	1	1	1	2	3	4
GSI	1	1	1	1	1	0.5	0.67	0.25
OSR	0	0	0	0	0	0.5	0.33	0.75
FSI	1	1	1	1	1	1	1	1

Figure 71. Density Indicators: correlated variation of height, coverage (GSI, OSR) and intensity (FSI). Source: Berghauser-Pont and Haupt (2009).

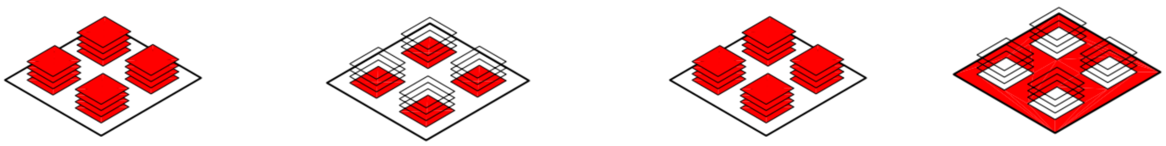
Table 12 explains Bergahauser-Pont and Haupt (2009) calculation method for each density indicator. According to their method, FSI and GSI are the basic indicators, while OSR and H derivates from them. "**FSI** reflects the building intensity independently of the programmatic composition" (op. cit.) and is the result of the Gross Floor area divided by the Land area. "**GSI**, or coverage, demonstrates the relationship between built and non-built space" (op cit.) and is calculated dividing the Footprint area by Land area. The values usually range from 0 to 1 or 0 to 100%, which stands for the ratio of the land occupied the ground floor. The height index measures either the number of storeys or the distance between the ground floor to the highest point in the building. In the first case, a predefined value is assigned for the floor-to-floor distance (equals to 3m in this study) or is a relation between FSI and GSI. The **OSR** index relates to the open space in the ground floor, therefore is the inverse of GSI in relation to the FSI. Berghauser-Pont and Haupt (2009) explain these two indexes:

> "The average number of storeys (**H**) can be arrived at by ascertaining the intensity and coverage or, FSI and GSI. If more floor area is developed in a certain area, without changing the footprint, H will increase. If the building height should remain constant, then FSI and GSI have to increase.[..] The variable **OSR**, or spaciousness is a measure of the amount of non-built space at a ground level per square metre of gross floor area. This figure metric provides an indication of the pressure on non-built space. If more floor area is developed in an area (with the same footprint), the OSR decreases and the number of people who will use the non-built space increases. (BERGHAUSER-PONT and HAUPT 2009).

The calculation for the dwelling density relates the number of housing units for one hectare, which indicates the populational concentration. Porto Alegre's urban code specifies that one house unit in the case study area is equal to 70 m^2 (6 cells = 1 house unit). The calculation of the dwelling unit concentration comprises the division of the Gross Floor Area divided by the Housing Unit Area divided by One Hectare.

Table 12 – Equations for 'Building Intensity', 'Coverage', 'Height' and 'Spaciouness' calculation:

Equation 1: Building Intensity (FSI)	**Equation 2:** Coverage (GSI)	**Equation 3:** Building Height (H)	**Equation 4:** Spaciousness (OSR)
FSI = F /A where F = gross floor area (m^2) A = area of land (m^2)	**GSI = B /A** where B = footprint of (m2) A = area of land (m2)	**H = FSI / GSI**	**OSR =(1-GSI) / FSI**



Source: Berghouser-Pont and Haupt (2009).

Measuring Daylight – Metrics and Indicators

The simulation's metrics calculated in the UD plug-in are the Continuous Daylight Autonomy and Spatial Daylight Autonomy (cDA and $sDA_{[300lux][50\%]}$) metrics, which are both a refinement of Daylight Autonomy's (DA) metric. DA is defined as the percentage of the occupied hours that a sensor point meets the minimum illuminance requirement during a year. (REINHART and WALKENHORST, 2001). Usually, the percentage of hours equals to 50% of the day time. While DA metrics computes only values above the defined threshold (Figure 72 – Credit Computation Diagram), in the Continuous Daylight Autonomy, partial credit is attributed when the daylight illuminance lies below the minimum illuminance level (ROGERS 2006) (Figure 73 – Credit Computation Diagram). For example, say a certain interior grid point has 150 lux due to daylight at a given time step, DA_{300} would give it 0 credit for that time step whereas cDA_{300} would give it 150/300 = 0.5 credit for that time step. This metric endorses the idea that to illuminate a space, even a partial contribution of daylight is still beneficial. (Reinhart et al, 2006).

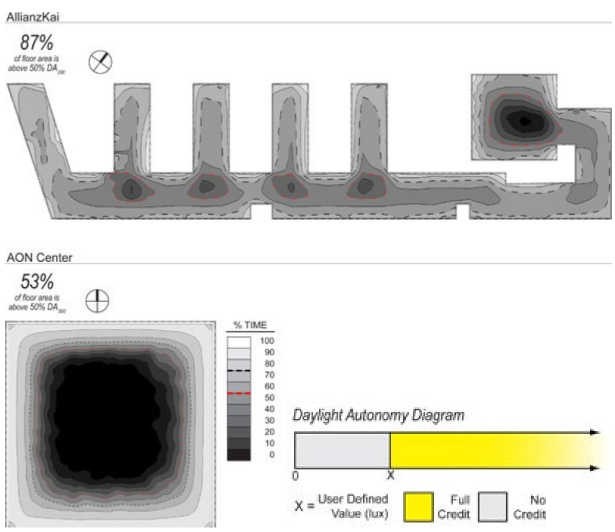


Figure 72. DA simulation for Allianz Kai floorplan and AON Center and Credit Calculation Diagram. Source: New Building Institute (2019a).

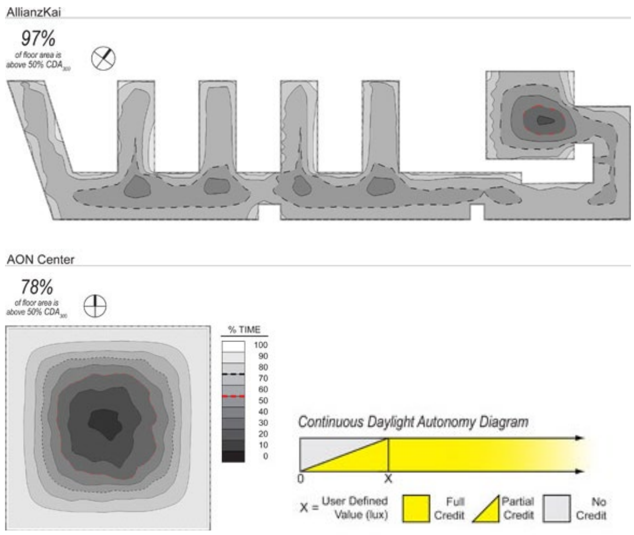


Figure 73. cDA simulation for Allianz Kai floorplan and AON Center and Credit Calculation Diagram. Source: New Building Institute (2019b).

Reinhart and Walkenhorst (2001) defined daylight autonomy as the percentage of the occupied time in a full year that a given point (sensor) meets the minimum illuminance requirement. The graphical values (0 to 100) represent the percentage of the floor area that exceeds the minimum illuminance requirement for at least 50% of the time. Figure 72 and Figure 73 displays DA and cDA results for the same buildings. The graphic representation shows that DA metric is more conservative expressed by an abrupt colour change, while in cDA the colour transition is gradual. Therefore, for the same threshold, the calculated index for cDA is higher than the DA.

Spatial Daylight Autonomy (sDA) was more recently presented in the Lightning Measurement protocol LM-83 and adopted by US Green Building Council's for daylighting credits in its LEED V4 Green Building Rating System since 2014. According to the LM-83, a point in a building can be considered to be "daylit" if at least half of the occupied time (50%, from 8h-18h) the work plane illuminance at the sensor is above 300lux ($sDA_{[300lux][50\%]}$) (IESNA 2012) . While both metrics states the amount of daylit area in the building, the higher sDA and cDA values are, the better. The results for sDA and cDA are also presented using graphic representation indicating the location of well-lit and dark areas.

Density and Daylight – Conflicting Metrics

According to Steadman and Mitchel (2010), architects design based on a conservative argument that the higher the density, the worse is the building daylight performance. However, as demonstrated in previous publications, the building geometry (BERGHAUSER-PONT and HAUPT 2009, STEADMAN 2014) influences the daylight performance confronting the argument that higher densities will necessarily lead to poorer daylight quality. (MARTIN and MARTCH 1975) This research confronts two aspects (qualitative/daylight and quantitative/density) regarding (a) the overall geometry, (b) the aggregation of the cells (discontinuity of the form) and (c) its relationship with the open space, referred here as 'porosity'. The following experiment's goal is to confront density and daylight performance to assess the aggregated impact of these three aspects (morpho-typology, discontinuity and porosity).

4.2 Experiments and Results

This section presents two case studies evaluated according to density and daylight indicators discussed in section 4.1. The experiments first evaluated the existent situation at the block and, then, generated two new occupations for the chosen area according to the existing urban regulations. The situation and these two scenarios' results were taken as baselines, which is later compared against the case study outcomes.

The **Case Study One's** goal is to apply the proposed methodology in the development of new areas. Following this strategy, it generates totally new buildings with FSI 1.3 and 3.0 for 'court', 'street' and 'pavilion' boundaries. **Case Study Two** applies the proposed methodology to densify existing areas reshaping the block as it adds new buildings to the existing fabric to a limit of FSI 3.0 configured to 'court' and 'street' boundaries. In addition to the experiment's results presented in this chapter, Appendix I gathers the results and parameters used in the tests for each Case Study.

Baseline:

First, the experiment converted the existing fabric and two scenarios into 3D cells using the 'Geometry Simplification' step and simulated their daylight performance to obtain the comparison baselines. Figure 74 illustrates the resultant geometry and the simulation results for the existing fabric and hypothetical scenarios.

The 3D model is represented in grey followed by the daylight simulation for Continuous Daylight Autonomy (cDA) in the middle and Spatial Daylight Autonomy (sDa) on the right-hand side. The simulation results were displayed according to the average value per floor, ranging from dark blue (0%) to red (100%). For the sDA, the colour represents the percentage of the floor's area that was autonomously illuminated (minimum 300 lux) for at least 50% of the occupation time (8 am to 6 pm). For the cDA, the colour follows the same logic, attributing partial credits to values below the minimum illuminance (300 lux). Table 13 summarises the density indexes for the block and the block average value for cDA and sDA.

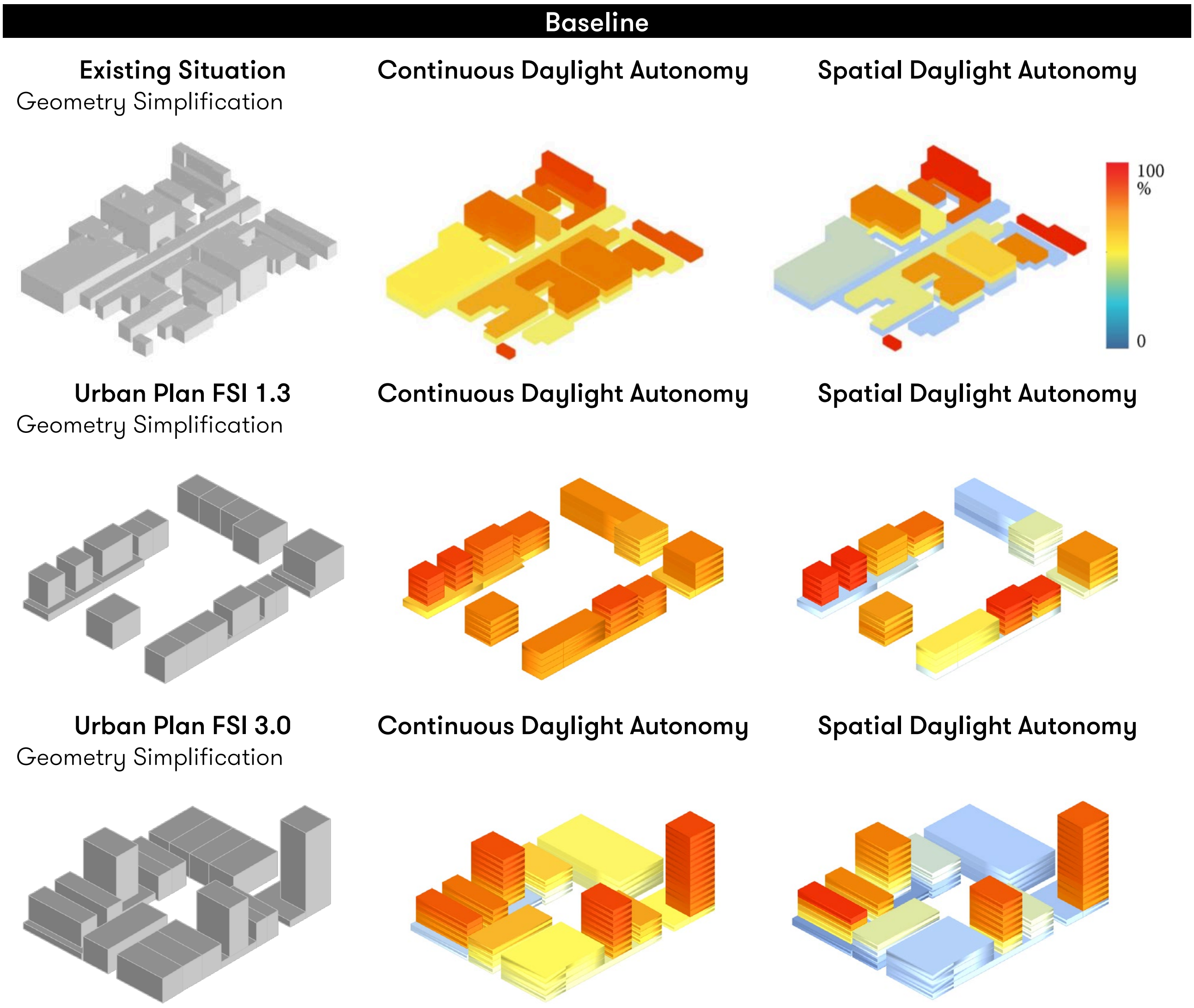


Figure 74. Building forms, cDA and sDA results for the existing fabric and for the designed buildings according to the urban regulations FSI 1.3 and 3.0 scenario.
Source: The Author (2019).

The first row in Figure 74 comprises the results for existing fabric, the second row for the buildings designed according to urban regulations and FSI = 1,3 and the third row for the buildings designed according to urban regulations and FSI = 3.0. The scenarios for the present urban regulation followed the volumetric rules specified in the plan (for more information check Table 9, page 81). Since there are virtually infinite possible scenarios, the proposed baselines follow three main strategies: **(a)** to reach the maximum density FSI indicator (1.3 and 3.0), **(b)** to reach maximum height while **(c)** have a minimum slab dimension of nine meters. These parameters would ensure top densities with reasonable dimensions (slabs> 9m) and to enable a larger possible daylight exposure proportional to the building's height and setbacks. In other words, the baseline generated buildings are the 'best' daylight performance version for high-density occupation according to present urban regulations.

Table 13 – Density indicators and simulations results for the baselines.

Parameter	Actual	Plan 1.3	Plan 3.0
Height	6 floors	5 fl.	14 fl.
FSI	1,29 1005 cells	1,30 1012 cells	3,01 2338 cells
Dwelling Unities	167 un.	168 un.	389 un.
GSI	411 cells 0.53 (53%)	584 cells 0.75 (75%)	584 cells 75%
cDA	59%	73%	54%
sDA	42%	57%	37%

While daylight autonomy metrics is usually applied for regularly occupied spaces, a disclaimer has to be issued at this point. Regularly occupied areas refer to rooms where users stay for long periods developing tasks which exclude horizontal and vertical circulation areas and garages, for example. As the daylight results presented in the case studies do not distinguish space use, the result is an average value for the whole floor (which include circulation cores – not regularly occupied spaces). Hence, it can be assumed that the regularly occupied spaces would have a better performance than the overall average daylight values.

Case Study One: Development of New Areas.

Floor Spatial Index = 1.3

The first test comprises the automated generation of new buildings for FSI 1.3. This value stands for the maximum value defined by the urban regulation code (without acquisition of bonus area). Figure 75 illustrates the existing fabric, the baseline for FSI 1.3 and three options for each morpho-typology, first for 'court', second for the 'street' and last for the 'pavilion/tower' morpho-typologies. The image compares the generated geometry (grey cells in the left-hand side) and the results for the daylight simulation per floor (cDA and sDA). The colour-false scales ranges from 0% (blue) to 100% (red).

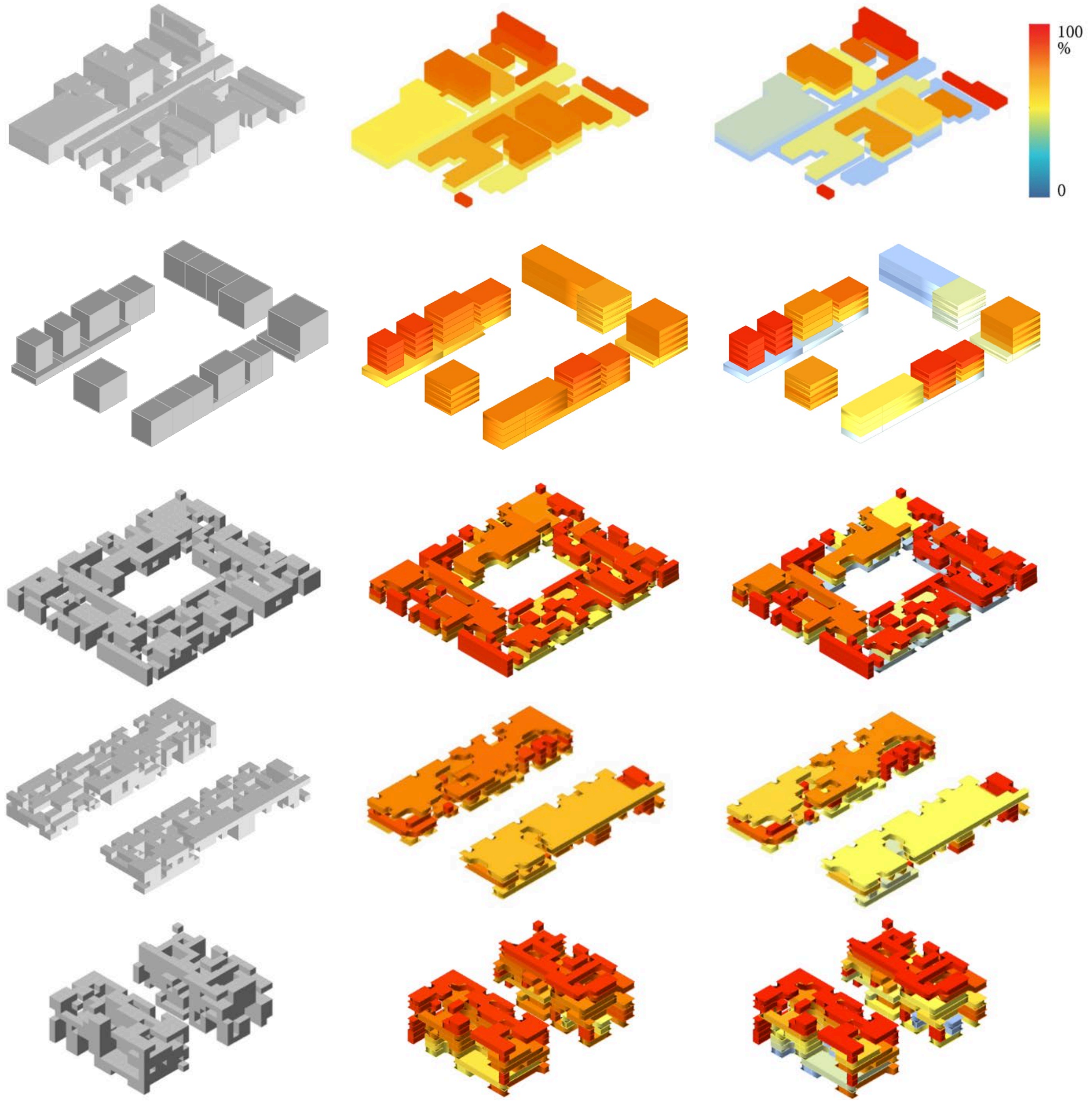


Figure 75. Building forms, cDA and sDA results for the existing fabric, the baseline FSI 1.3 and generated buildings with FSI 1.3 for three morpho-typologies.
Source: The Author (2019).

Table 14 compares the density and daylight performances for the existing fabric, baseline 1.3 and the three morphologies in test one. The results have shown that, for the same FSI limit, every attempt has a superior daylight performance (cDA and sDA) than existing fabric. The baseline 1.3 has similar, but not superior, performance compared to the three morpho-typologies. These values are an average for the entire block and are assured by the large void in the interior of the block. Considering the floor average values, illustrated in Figure 75, the cDA assessment has demonstrated a homogenous daylight distribution, while sDA assessment showed a variation between the lower and higher levels. In other words, sDA metric is stricter and demonstrated that in the existing fabric and the baseline 1.3 most of the cells have a weak daylight autonomy when concentrated in the lower levels (in light blue on the top line of Figure 75). In the baseline 1,3 the lower buildings (12m) without setback (typology *'divisa'*) at the upper left side of the sDA image, illustrates one of the urban regulation drawbacks.

Table 14 – Simulations results for the existing fabric, the baseline FSI 1.3 and generated buildings with FSI 1.3 for three morpho-typologies.

Parameter	Actual	Plan 1.3	Court 1.3	Street 1.3	Pavilion 1.3
Height	6 fl.	5 fl.	3 fl.	4 fl.	8 fl.
FSI	1,29 1005 cells	1,30 1012 cells	1,30 1005 cells	1,28 995 cells	1,39 1080 cells
Dwelling Unity	167 un.	168 un.	167 un.	165 un.	180 un.
GSI	411 cells 0.53 (53%)	584 cells 0.75 (75%)	640 cells 0.83 (83%)	480 cells 0.64 (64%)	256 cells 0.33 (33%)
OSR	0,36	0,19	0,13	0.27	0.48
cDA	59%	73%	74%	72%	73%
sDA	42%	57%	64%	58%	62%

As expected, cells also had worse performance in the lower levels than in the upper levels in the generated buildings, less expressive however than the existing fabric and the baseline FSI 1.3 lower levels (Figure 75). Results show that, this variation is more evident in court and pavilion morphologies due to the buildings **'self-shedding'**. Thus, while in the court typo-morphology the central 'patio' between the buildings is smaller (15 cells x 9 cells), in the street morpho-typology the buildings are separated by a wider open space (31 cells x 9 cells) preventing the building's impact over its neighbours. In the pavilion type, the difference of performance in the lower and higher levels is aggravated by the heights of the towers (8 versus 4 cells) separated horizontally by seven cells (as listed in Table 10 of this chapter).

Figure 76 compares the actual scenario with the court type outcome. In the left-hand side it compares the overall geometry resultant of the geometry simplification, in which the contrast of building heights is evident. In the right-hand-side, an image from the area and a render help the reader to speculate how new buildings generated using the proposed methodology would look like in place.

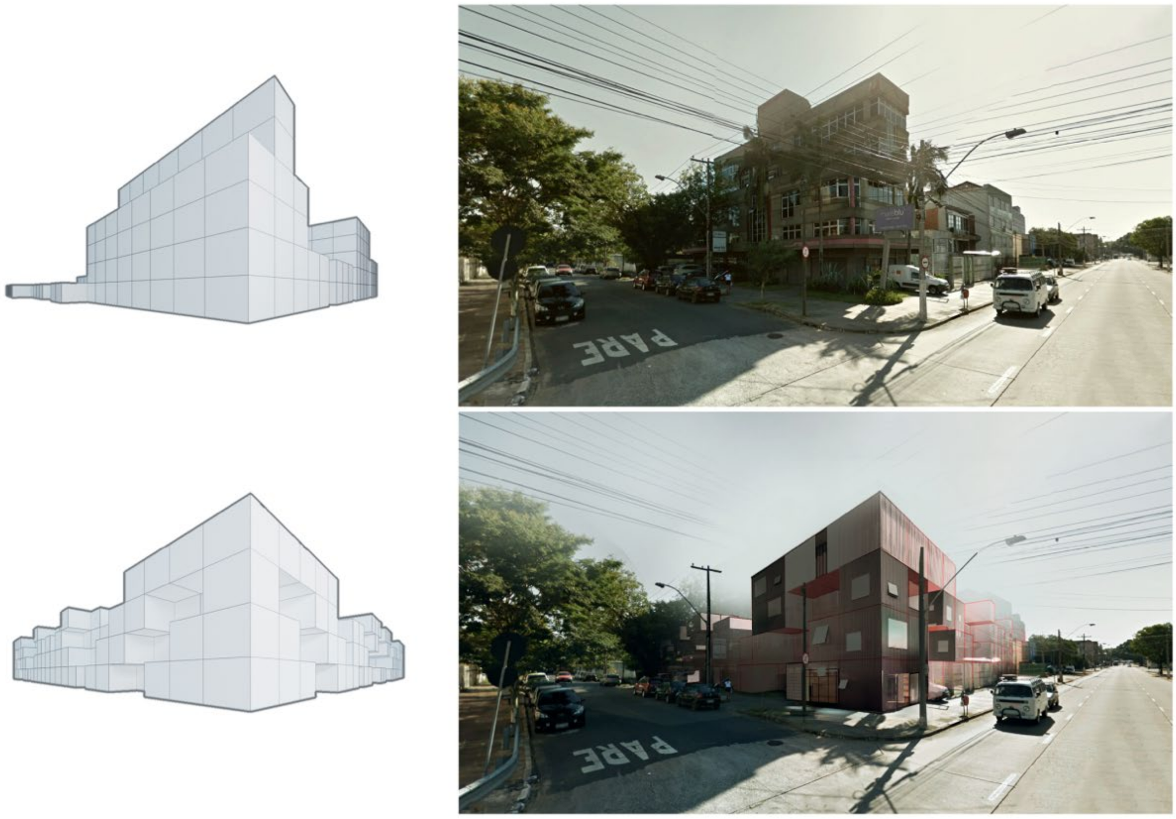


Figure 76. Built form of an existent block (upper left-hand side) and a picture of the actual situation in 2017 (upper right-hand side) versus the built form for an auto-generated block for morpho-typology court (lower left-hand side) and a render of a speculative construction on site (lower right-hand side).
Source: The Author (2019).

Case Study One: Development of New Areas.

Floor Spatial Index = 3.0

To evaluated whether the proposed model would be able to support higher densities scenarios, the three morpho typologies were simulated for the maximum FSI 3.0. This FSI value could be reached if investors acquire FSI bonuses made available by the Municipality for this area. Figure 77 displays the overall shape (grey cells) and daylight simulation results for the baseline 3.0 and for the three morpho-typologies. Table 15 summarizes the density indicators and daylight performance results.

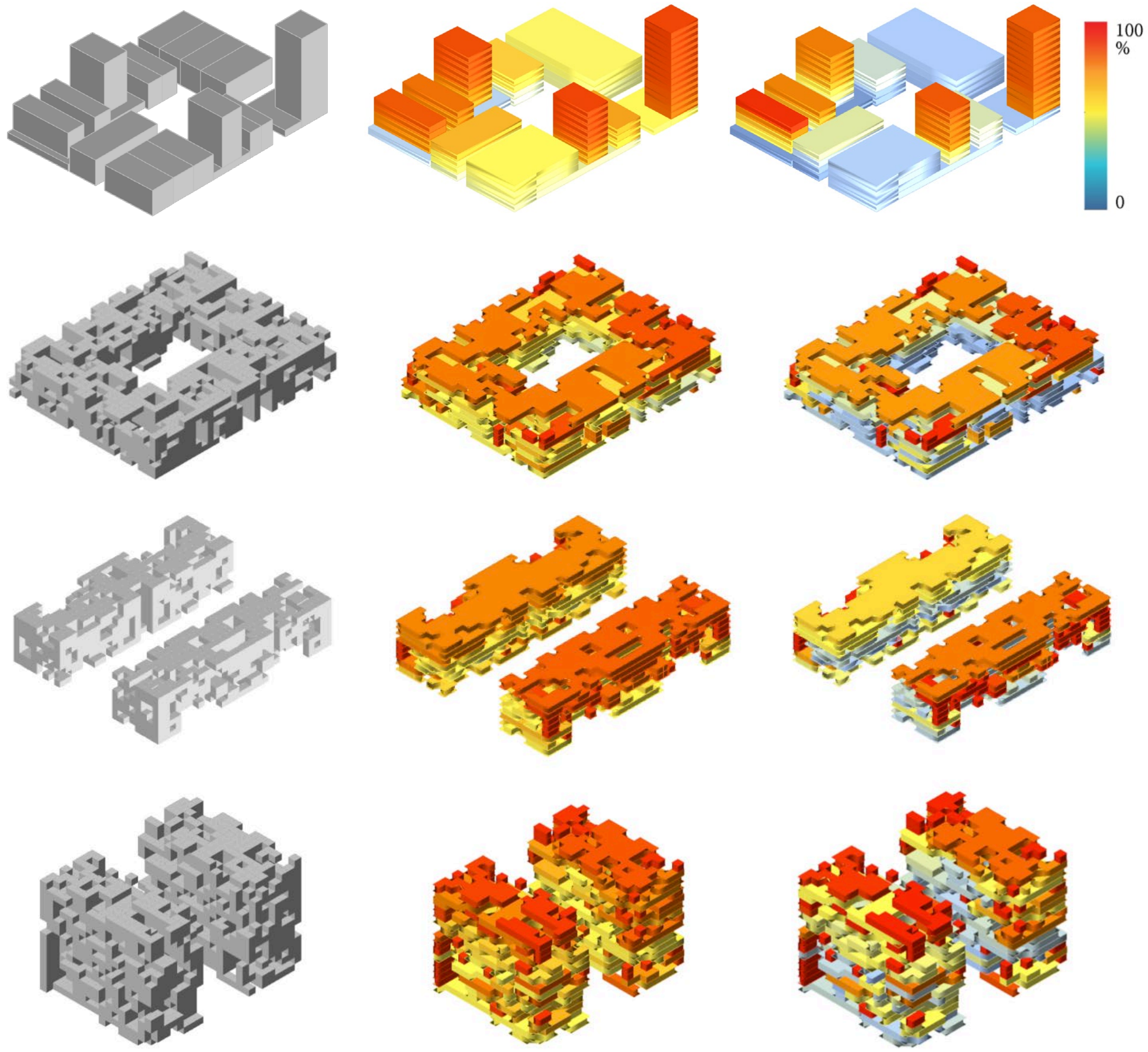


Figure 77. Building forms, cDA and sDA results for the existing fabric, the baseline FSI 3.0 and generated buildings for three morpho-typologies with FSI 3.0.
Source: The Author (2019).

The daylight simulation results (Table 15) demonstrated that for the FSI 3.0, street and tower morpho-typologies had achieved superior daylight performance than in the existing fabric and the baseline 3.0. When different densities are compared, 1.3 in the existing fabric against 3.0 in the generated buildings, the court morpho-typology displays an inferior performance than in the existing fabric. However, while the simulations used more than twice the number of cells (1005 in the existing versus 2375 in the court) this fact does not prevent the model to generate buildings according to daylight requirements. The baseline for the present urban regulations lowered its performance for the higher density scenario. In this case, its performance is inferior to every auto-generated block (cDA and sDA). Since the block's interior void is reduced and the setbacks increased, this result confirms the ineffectiveness of lateral and back setbacks as a measure to guarantee daylight availability. Moreover, in this example, sDA value per building ranges from 19% to 68% highlighting a heterogeneous light distribution within the block.

Table 15 – Simulations results for the existing fabric, the baseline FSI 3.0 and generated buildings for three morpho-typologies with FSI 3.0.

Parameter	Actual	Plan 3.0	Court 3.0	Street 3.0	Pavillion 3.0
Height	6 fl.	14 fl.	7 fl.	8 fl.	17 fl.
FSI	1,29 1005 cells	3,01 2338	3,06 2375 cells	2,90 2244 cells	3,09 2393 cells
Dwelling Unities	167 un.	389 un.	395 un.	374 un.	398 un.
GSI	411 cells 53%	584 cells 75%	640 cells 83%	480 cells 64%	256 cells 33%
OSR	0,36	0,083	0,06	0,12	0,22
cDA	59%	54%	58%	65%	63%
sDA	42%	37%	40%	48%	47%

For FSI 3.0 court morpho-typology has a poorer daylight availability than street and pavilion morphology. This result shows the impact of the geometry on its performance, since the building is higher (7 floors), and block's interior void remains with the same area. The 'height' effect, in turn, is not as expressive for the street (8 floors) and pavilion (17 floors) morpho-typology, whose open also remain the same.

The range of daylight accessibility values between the higher and lower levels are also more evident in higher densities. First-floor's daylight autonomy in baseline 3.0 decrease is evident compared to the baseline 1.3. The difference between the baseline 3.0 and the morpho-typologies also more evident in this experiment than in the previous one. The results per block (Table 15) and per floor (Figure 77) shows that the present urban regulation pitfalls intensify in higher densities scenarios. The relation between the plot width and the proportional set-back that limits the building's vertical growth aggravates the daylight performance reduction. Lower floors in the court and pavilion morpho-typologies are also poorer illuminated than in the street (light blue cells in Figure 77). This effect is aggravated by the building's height and confirm the buildings **'self-shedding'** impact on their performance per floor.

Comparing Typologies: Geometry matters

The results (Table 14 and 15, Figure 76 and 77) have shown that the proposed model was able to automatically generate buildings with higher daylight performance than the existing situation and present urban plan scenarios. Table 16 compares the density indicators and daylight performance results for the three morpho-typologies. The comparison within the morpho-typology demonstrate that the pavilion type displays high daylight performances for both FSI 1.3 and 3.0, while court performance was higher for lower densities (FSI 1.3) and street performance was higher for higher densities (FSI 3.0). These results regard an average value for the whole block, while Figure 76 and 77 displays the results per floor. Results per floor shown that the street morpho-typology light distribution within the first and last floor for FSI 1.3 and 3.0 is more homogenous than court and pavilion.

Table 16 – Density indicators and daylight performance for morpho-typology comparison.

Parameter	Court 1.3	Street 1.3	Pavilion 1.3	Court 3.0	Street 3.0	Pavilion 3.0
Height	3 floors	4 floors	8 floors	7 floors	8 floors	17 floors
Slab Depth	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
Bulk Volume	1920 cells	1920 cells	2048 cells	4480 cells	3840 cells	4352 cells
Built	1005 cells (52%)	995 cells (52%)	1080 cells (53%)	2375 cells (53%)	2244 cells (58%)	2393 cells (55%)
FSI	1,30	1,33	1,39	3,06	2,90	3,09
GSI	83% (640 cells)	64% (480 cells)	33% (256 cells)	83% (640 cells)	64% (480 cells)	33% (256 cells)
OSR	0,13	0,27	0,48	0,06	0,12	0,22
cDA	74%	72%	73%	58%	65%	63%
sDA	64%	58%	62%	40%	48%	47%

cDA and sDA simulation results show and inexpressive correlation with density indicators, as GSI and OSR, in both experiments (Table 16). This fact reinforces the impact of the morpho-typology geometry despite the traditional density indicators. For example, the building heights and the configuration of the open space in the morpho-typologies are evident in daylight results per floor. In the previous experiment, the slab depth was constrained to a unique value (8 cells) to limit its impact in the daylight simulation result. Nevertheless, its influence is illustrated in Figure 78 in which the court morpho-typology for FSI 1.3 and 3.0 have 8 and 5 cells depth. The results call attention to the improvement in cDA and sDA for higher densities with narrower. These examples confirm the impact of volumetric constraints but require wider investigation (discussed in the next chapter).

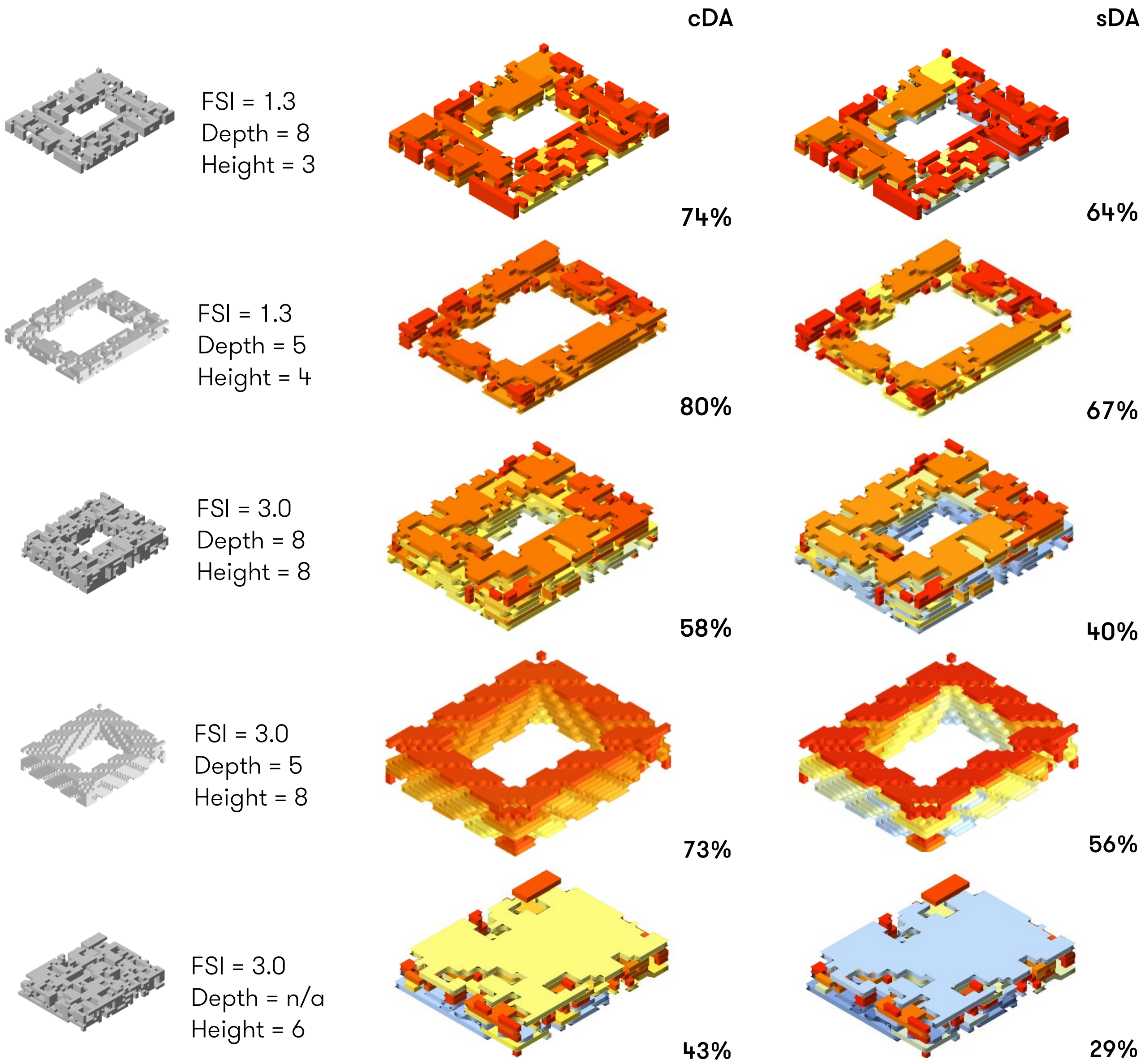


Figure 78. Court morpho-typology simulation results for FSI 1,3 and 3,0 and 5, 8, and 25 cells depth.
Source: The Author (2019).

Case Study Two: Redesigning the block

Floor Spatial Index = 3.0

In the second Case Study, the block is reshaped for 3.0 FSI considering the existing fabric. The court and street morpho- typologies were used as references to reshape the block's periphery. Newly generated cells filled gaps (a) between buildings and (b) equalizing heights and gaps within the existing buildings. The model defines the existing fabric as 'fixed-built' cells for the 'form generation' step. This way, the newly built cells do not overlap the older buildings but will take their state into account for the birth/death counting rules. In other words, the model is **sensitive to its context** and can be used to densify existent areas. Figure 78 illustrates the growth progression of new cells from their initial state (0) to the final state for 'court' and 'street' morpho-typologies (from the left to right-hand side). The frame sequence shows that while existing buildings cells (red) remain static, new ones (grey) grow on top of the existent ones. The cell's growth obeys the boundary constraints defined by the morpho-typology bulk and birth and death rules.

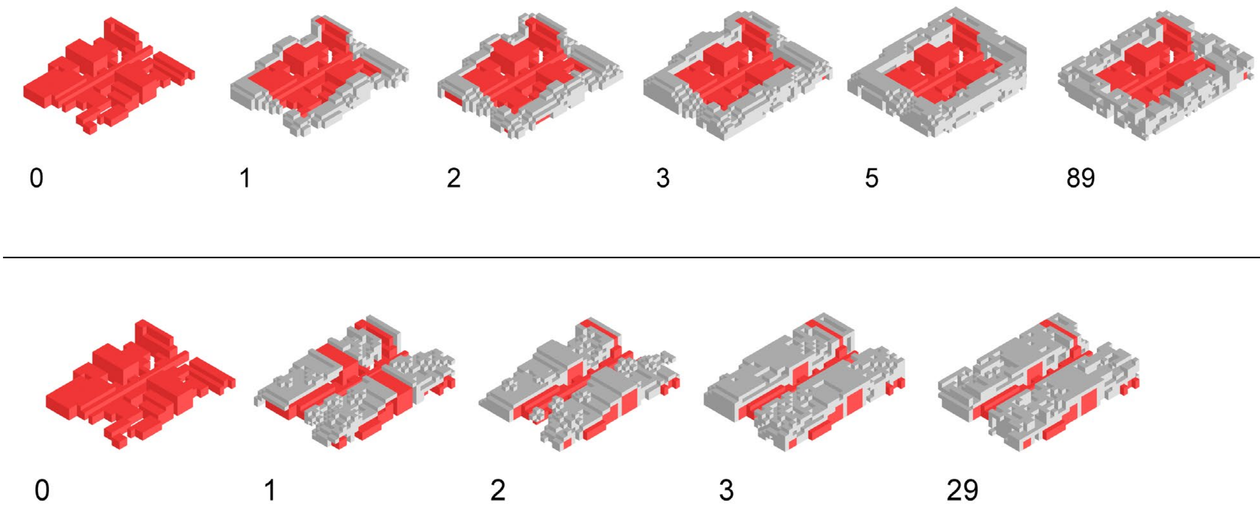


Figure 79. Progression from the initial to the final state for court (upper) and street (lower) morpho-typology. Source: The Author (2019).

The process of 'redesigning' a block is not necessarily related to preserving the historical buildings. This case study focusses on testing the model capacity to densify areas, despite of following any preservation regulation. For the specific case of Porto Alegre, the historical preservation system has three preservation categories: **(a)** 'Compatibilização', **(b)** 'Estruturação' and **(c)** 'Tombada'. For the first two cases, additions can be incorporated to the original building upon the municipality approval.

The results are illustrated in Figure 80, where existing buildings are represented in red and the newly generated cells are in grey. In the middle and in right-hand side columns the images display the daylight performance results for the new buildings with indexes cDA and sDA ranging from 0 (dark blue) to 100% (red). Table 17 summarises density indicators and daylight performance results for the existing situation, the baseline for the FSI 3.0 and the court and street morpho-typology block redesign.

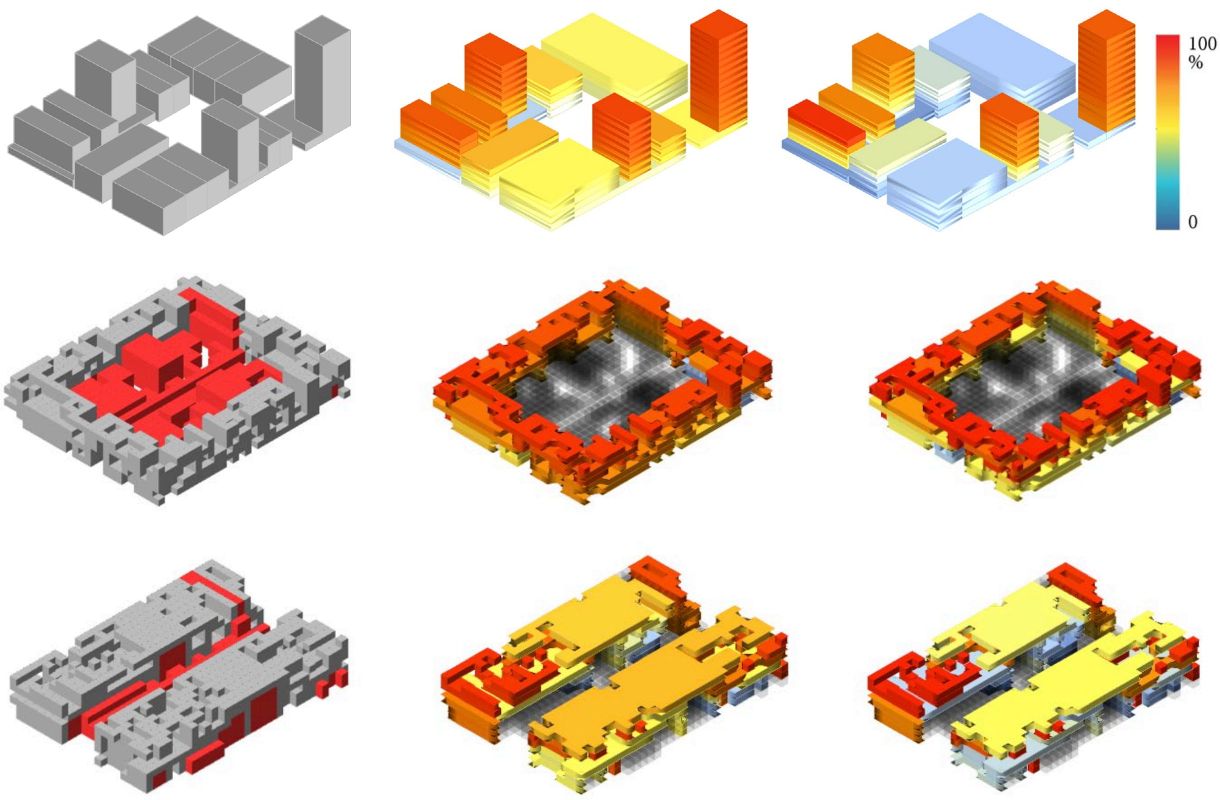


Figure 80. Building forms and cDA and sDA results for the baseline FSI 3.0 and the redesigned buildings for court and street morpho-typologies.
Source: The Author (2019).

In both cases, the final state configures a new block shape, showing the model's potential to redesign areas considering visual ambience as well. If accepted the additions (the case of **(a)** 'Compatibilização' and, 'Estruturação') were made, the daylight simulation demonstrated that general daylight values would be proportionally higher for the whole fabric than in the baseline reference. These results confirm that the proposed model can support renewal design projects and could be used to densify areas with existing structure with guaranteed daylight performance. However, since the sample is specific – takes into consideration a unique block configuration - one should expand the test to a larger sample.

Table 17 –. Simulations results for the existing fabric, the present urban plan and generated buildings for the redesign with FSI 3.0.

Parameter	Actual	Plan 3.0	Court + Actual = 3.0	Street + Actual = 3.0
Height	6 fl.	14 fl.	6 fl.	6 fl.
FSI	1,29 1005 cells	3,01 2338 cells	3,15 2445 cells	3,30 2561 cells
Dwelling Unities	167 un.	389 un.	407 un.	426 un.
GSI	411 cells 53%	584 cells 75%	659 cells 85%	605 cells 76%
OSR	0,36	0,13	0,048	0,072
cDA	59%	54%	68%	46%
sDA	42%	37%	76%	57%

5. Integrating Models:
Recalling geometry into urban scale models

Discussion:

The set objective of this dissertation had been to design a configurational model able to integrate urban, building and performance data to produce automated information on building's daylight access. While urban scale assessments tend to, predominantly, involve abstract models, the automatic assessment of the reciprocal influences between urban and building scales require the spatial representation and the computational generation of 3D attributes. The integration of performance models to building and urban models was a crucial step towards the creation of an optimized framework developed in 'Urban Daylight' plug-in by Dogan et al (2012).

In this research, an integrated model bridges the three models (urban, building and performance models) under the 'Built Form' concept. When working within this framework, the challenge was to define the level of accuracy required to relate **density** to **daylight** performance. In this research, the concept of Built Form was explored to the extent it elegantly captured the essential information of built and void spaces. This research can be understood as a contribution to existing analytical urban and architectural models, shedding light on methods dealing with geometrical aspects of the relation between architecture urbanism.

The limitations found along this research include: (a) resolution of the cell size in relation to the plot dimensions, (b) extensive performance simulation time, and (c) lack of interaction in the generative process. The first refers to the size of the cell, 3,5m x 3,5m x 3 m, in relation to the plot widths ranging from 7 to 33m. Although a seven meters wide plot would fit 2 cells, the whole block simulation can shift to the subdivision starting point resulting in a loss of accuracy in the geometry simplification. Since the case studies did not include the plot subdivision as data, it did not affect the research main results. Second, although the UD's plug-in drastically reduces the daylight performance simulation time, the daylight simulation for CA generated blocks lasted between 30 minutes to 1-hour. The simulation time could be diminished through the reduction of the complexity of the simulated geometry and its replacement by the bulk geometry, as 'simulation twins'. Or even, reducing the resolution level of definition, opting for static methods (IVERSEN 2013) that could be integrated into Game Engines software (Unity or Unreal) able to render the daylight at live speed. Finally, since the user defines the rule's threshold for the CA growth beforehand, he/she can't interfere in the form generation. Therefore, the system outcome could be oversimplified to a massing study to be further refined to the design level.

Conclusion:

The question posed in the introduction of this research inquires whether it is possible to automatically generate urban fabrics with (a) architectural control over the public space and, simultaneously, (b) stimulate building form flexibility and (c) to control building's access to natural light. The experiments presented in Chapter 4 have shown that it is possible to increase the top-down control over the urban fabric using morpho-typologies bulks and the bottom-up development of individual buildings using CA generative system, improving each building's access to natural light. The results confirm that for conservative density indexes (FSI 1.3) the proposed model displays a higher daylight performance than the existing situation and a similar daylight performance (yet superior) to the scenario with building generated according to the present urban regulation. For higher density scenarios (FSI 3.0) the difference enlarges, as Street and Pavilion morpho-typologies display sDA 10% superior to the buildings generated according to the existing plan for the entire block average. Table 18 summarises the Continuous Daylight Autonomy (cDA) and Spatial Daylight Autonomy (sDA) block average value for FSI 1.3 and FSI 3.0.

Table 18 – Density indicators and daylight performance for morpho-typology comparison.

Parameter	Existing 1.3	Plan 1.3	Court 1.3	Street 1.3	Pavilion 1.3	Plan 3.0	Court 3.0	Street 3.0	Pavilion 1.3
FSI	1,29	1,30	1,30	1,33	1,39	3,01	3,06	2,90	3,09
cDA	59%	73%	74%	72%	73%	54%	58%	65%	63%
sDA	42%	57%	64%	58%	62%	37%	40%	48%	47%

The existing situation's lack of natural light highlights the overall impact that different plans provoked in the same region demonstrating that the periodical replacement of plans at each 20 -30 years is harmful to the buildings' daylight performance. Although the block's cDA and sDA average performance were superior to the existing situation for the present urban regulation (FSI 1.3 and FSI 3.0), individual buildings and their lower floor levels have shown a worse performance when compared to the existing situation due to the setbacks' impact in high densities. For example, narrow plots (narrower than 11m wide) are generally constrained to a low-rise typology due to a compulsory 3 meters setback above the second floor. Figure 82 illustrates the daylight results for the generated buildings according to the existing urban rules, where plots 6,7,8 displayed worse performances than wider plots such as 3, 13 and 16. These results illustrate a recurring situation in Porto Alegre and confirm the impact of the plot geometry into the urban form with negative impact in the daylight performance.

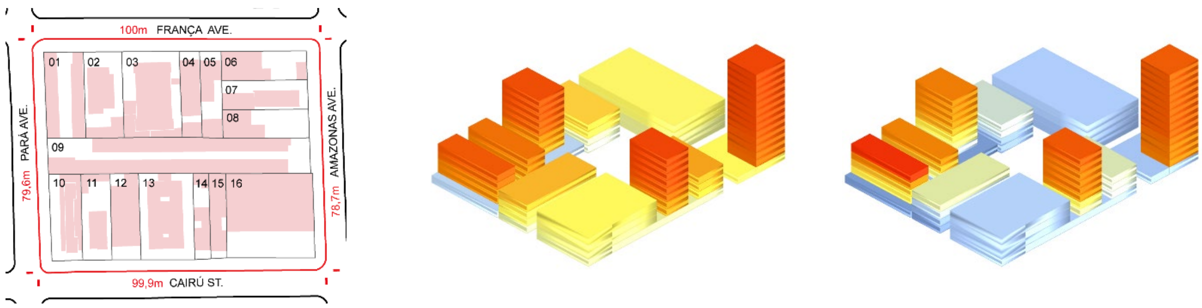


Figure 81. Map of the existing plot subdivision, Continuous Daylight Autonomy and Spatial Daylight autonomy results for the buildings generated according to the present urban regulation and FSI 3.0.
Source: The author (2019).

Urban Form Control

Top-down volumetric restrictions linked to automated generative systems might help to reduce the existent discontinuity of the open space configuration. The randomness provoked by the Porto Alegre's existing urban rules can be replaced by a rather more disciplined structure due to the morpho-typologies volumetric constraints. Figure 83 illustrates the built forms for the existing situation and the court morpho-typology for FSI 1.3, in which the height and setbacks discontinuity is evident for the first case. Despite the slight level of randomness in the automatically generated example, the overall block shape is well defined due to maximum height and frontal setback continuity. The other cases also endorse that block **morpho-types** strategies are an effective alternative to address the continuity of the **public space**. The results have demonstrated that empty spaces may play different roles in **environmental**, **aesthetic and functional** aspects.

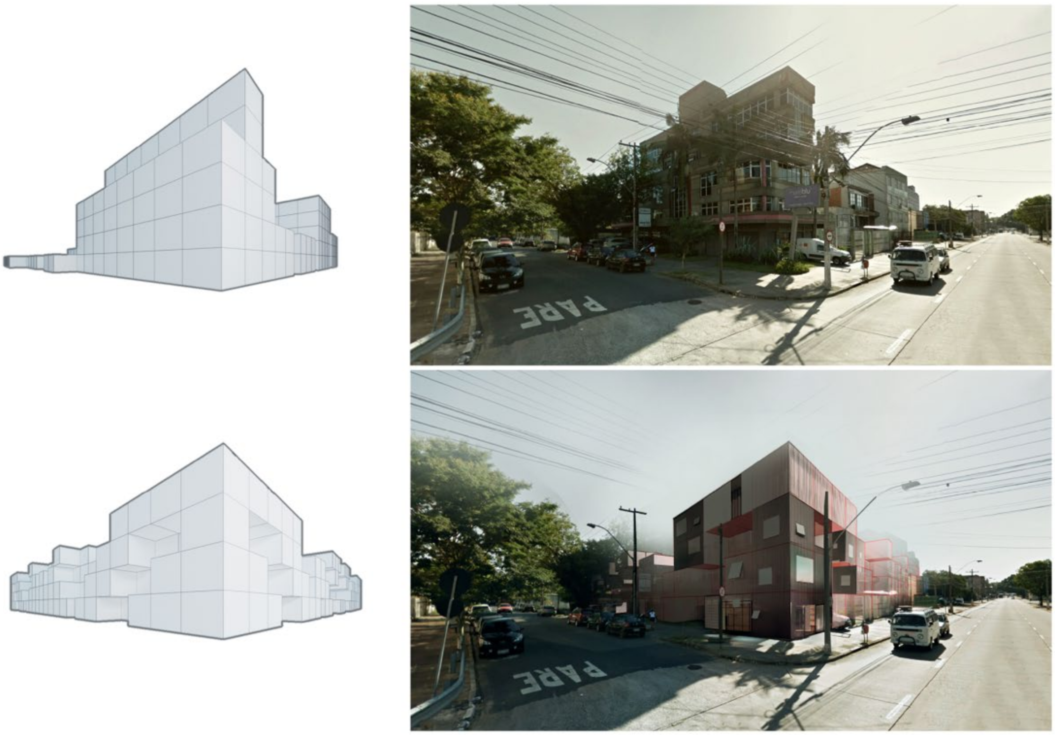


Figure 82. The built form of an existent block (upper left-hand side) and a picture of the actual situation in 2017 (upper right-hand side) versus the built form for an auto-generated block for the morpho-typology court (lower left-hand side) and a render of a speculative construction on site (lower right-hand side).
Source: The Author (2019).

The generated configurations have shown a higher spatial quality for both **public and private realms**. Court and Street morpho-typologies, for example, extended the potential of the interior of the block to be used as private leisure area in the first case or as a pedestrian area in the second case, increasing the potential articulation with the ground floor. In the tower typologies, cells which remained empty inside the building bulk could be directly linked to private built areas, offering space for terraces and balconies. These speculations reinforce the idea that morphological aspects not only contribute to improving environmental performances but, if well explored, do enhance the city's form and use.

Building Variability

The auto-generated blocks clearly demarcated public and private spaces: while public spaces are "designed" by the morpho-typology strategy through fixed empty cells, private empty spaces are defined by the algorithm's birth and death rules. Table 19 quantifies the empty spaces for each morpho-typology and the percentage represented by private and public spaces for the entire simulation volume ('World Size') and for each morpho-typology's bulk volume. The index presented in the fourth line refers to the ***porosity*** or the private empty spaces percentage inside the building bulk. Differently to other density indicators regarding voids, like Open Space Ratio (OSR – explored in BERHAUSER-PONT and HAUPT 2009), the 'porosity index' refers to the private empty space inside building bulks.

Table 19 – Empty spaces and daylight performance for the court, street and pavilion morpho-typologies.

Parameter	Court 1.3	Street 1.3	Pavilion 1.3	Court 3.0	Street 3.0	Pavilion 3.0
World Size	2325	3000	6200	5425	6000	13175
Bulk Volume	1920 cells 43%	1920 cells 33%	2048 cells 17%	4480 cells 44%	3840 cells 37%	4352 cells 18%
Empty + Private	915	925	968	2105	1596	1959
Porosity Index	48%	48%	47%	47%	42%	45%
Empty+ Public	405	1080	4152	945	2160	8823
OSR	0,13	0,27	0,48	0,06	0,12	0,22
cDA	74%	72%	73%	58%	65%	63%
sDA	64%	58%	62%	40%	48%	47%

In the examples generated by the CA algorithm, the porosity index varied from 42 – 48% with the minimum void size at 3,5 by 3,5 meters. There is no evident connection (see table 19), between higher porosity and better daylight performance (higher cDA and sDA). On the other hand, the street type FSI 3.0 had the highest sDA and the smallest porosity index. As Porto Alegre's existent urban regulations constrain designers to predefined volumetric solutions, a porosity index could be more appropriate to add building form flexibility and simultaneously ensure a higher quality of daylight performances. We can conclude that building's porosity may well be more effective than the current setbacks strategies and could constitute a proxy for further urban design regulations.

Designing with Voids:

This research shed light over the necessity, for urban indexes, to not only address density parameters but observe some important aspects of built space configuration, such as natural light availability and design freedom. As for daylight performance, we concluded that building porosity indexes were more effective than existent setback rules. Results also showed the advantage of clustering the block's voids as shown in the court morpho-typology as opposed to voids dispersion via setback rules. Design strategies, such as urban block morpho typologies, can be understood as effective strategies to address the required continuity of the public space. The association of urban block morpho typologies to the building's porosity concept has emulated flexible and diverse building forms. The process of designing urban rules is a design exercise, involving not only environmental parameters but geometrical and configurational metrics as well. In this research, geometry and configuration data were included in the 'Built Forms' concept, thus able to support designers' decisions in performative urban planning rule design processes

Future Works:

Two main research lines can be devised for future work development: **(a)** models' integration and **(b)** the investigation of the 'porosity ratio'.

In the first case, other environmental performance models (energy, thermal, ventilation, etc) could be easily associated trough Rhinoceros 3d and Grasshopper *plug-ins*, thus enlarging the range of variables under scrutiny and criteria. Two other possible criteria are related to construction feasibility and costs - due to its cellular aggregation mode, CA models relates to a modular construction system and thus could be directly linked to prefabricated systems. Prefabrication can be used to build complex shapes and CA models can contribute to introduce variability to highly standardized buildings systems.

The investigation of the ‘porosity index’ is another possible path to be examined and tested. It could involve specifying the ideal ratio between built and void private areas and size for an “adequate” open space. Its effectiveness should be evaluated for criteria as ventilation and visibility (privacy). Further research regarding the porosity index should include a variety of climates and densities to validate its relevance for urban rules design.

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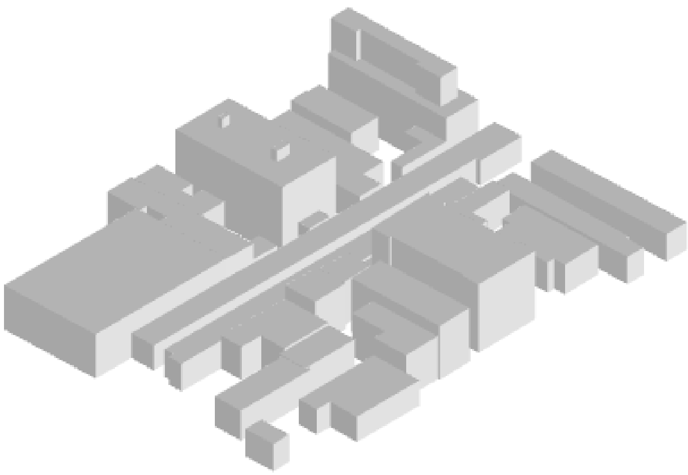
APPENDIX

000 EXT



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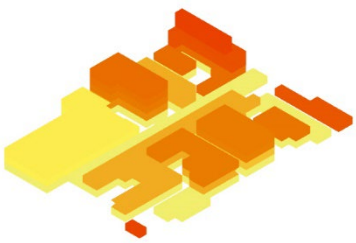

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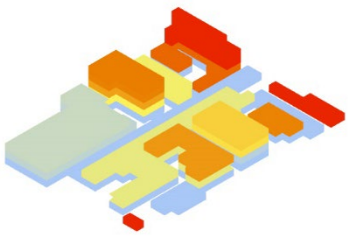

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Nº buildings:	n/a		
Dim.:	n/a		
Total bulk:	4.500 cells		
Form Generation			
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Rules:		min	max
Birth:		-	-
Death:		-	-
Max alive:	-		
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GSI:	53%		
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OSR:	0,36		
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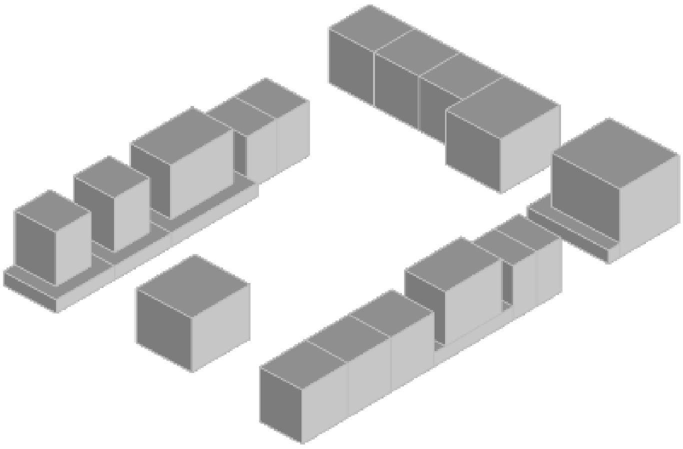

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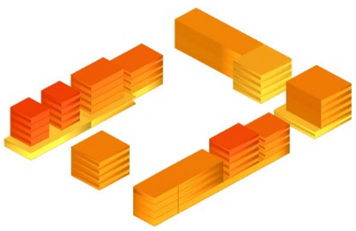

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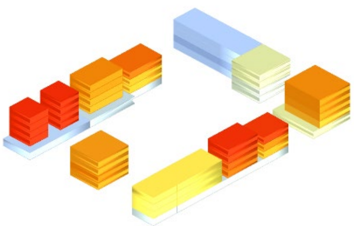

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N^0 buildings:	n/a	
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Form Generation		
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Rules:	min	max
Birth:		
Death:		
Max alive:	-	
Density Indicators		
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	New:	1012 cells
	Existent:	0
Total Empty:	2863 cells	
	Private:	2863
	Public:	0
FSI:	1,30	
GSI:	75%	
Height:	5 floors	
OSR:	0,19	
Dwelling Un.:	168 un.	
Simulation Parameters		
Occupancy:	8am – 6pm	
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cDA:	0,73	

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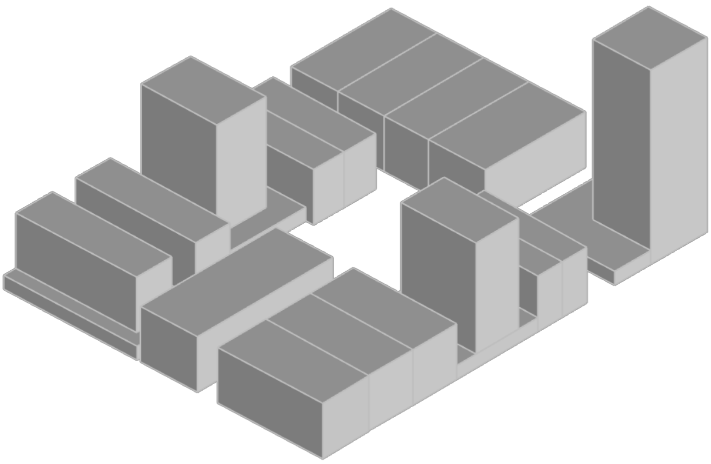

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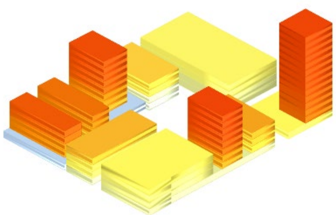

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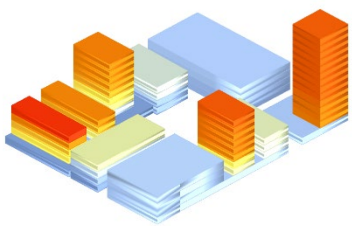

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Nº buildings:	n/a
Dim.:	n/a
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Form Generation	
Generation:	
Rules:	min / max
Birth:	
Death:	
Max alive:	
Density Indicators	
Total Built:	2338 cells (100.241,75m^3)
	New: 2338
	Existent: 0
Total Empty:	8512 cells
	Private: 8512 cells
	Public: 0
FSI:	3.01
GSI:	75%
Height:	14 floors
OSR:	0,083
Dwelling Un.:	389 un.
Simulation Parameters	
Occupancy:	8am – 6pm
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Context:	N
Daylight Simulation Results	
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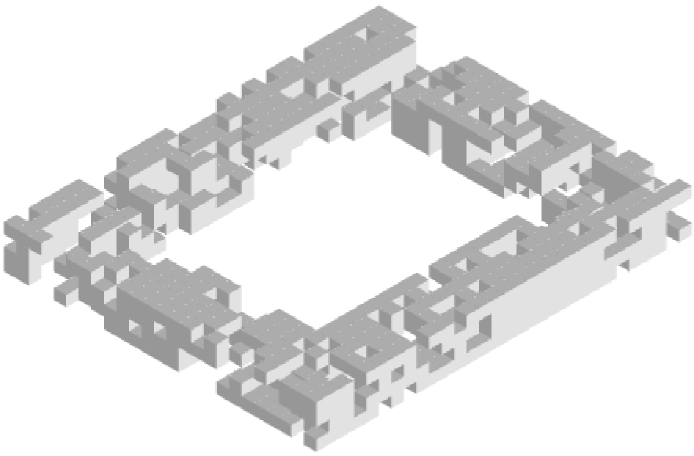
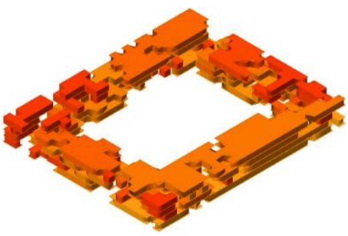
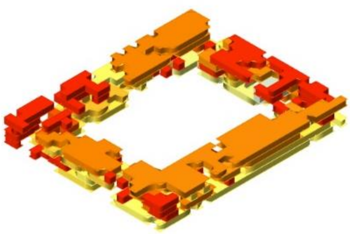
cDA:	0,54

005 B39_965_C2



cDA	sDA
	

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R. influence:	1 cell		
H. max.:	4 floors		
Context and Urban Restrictions			
Typology:	Block		
Nº buildings:	1 (x=1, y=1)		
Dim.:	5 cells (D)		
Total bulk:	1800 cells		
Form Generation			
Generation:	39		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	965 cells (35463.75m³)		
	New:	995 cells	
	Existent:	0	
Total Empty:	2035 cells		
	Private:	835 cells	
	Public:	1200 cells	
FSI:	1,29		
GSI:	60%		
Height:	4 floors		
OSR:	0,310		
Dwelling Un.:	160,83 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	N		
Daylight Simulation Results			
sDA:	0,67		
cDA:	0,80		

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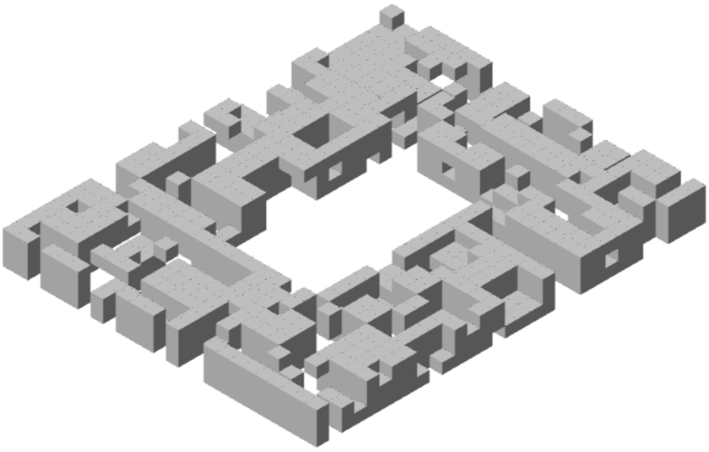

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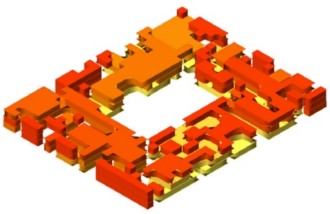

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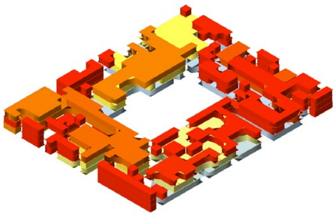

Geometry Simplification			
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Cell size:	3,5; 3,5; 3 m		
R. influence:	1 cell		
H. max.:	3 floors		
Context and Urban Restrictions			
Typology:	Block		
Nº buildings:	1 (x=1, y=1)		
Dim.:	8 cells (D)		
Total bulk:	1920 cells		
Form Generation			
Generation:	64		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	1005 cells (36933,75m³)		
	New:	1005 cells	
	Existent:	0	
Total Empty:	1320 cells		
	Private:	915 cells	
	Public:	405 cells	
FSI:	1,30		
GSI:	83%		
Height:	3 floors		
OSR:	0,13		
Dwelling Un.:	167,5 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	N		
Daylight Simulation Results			
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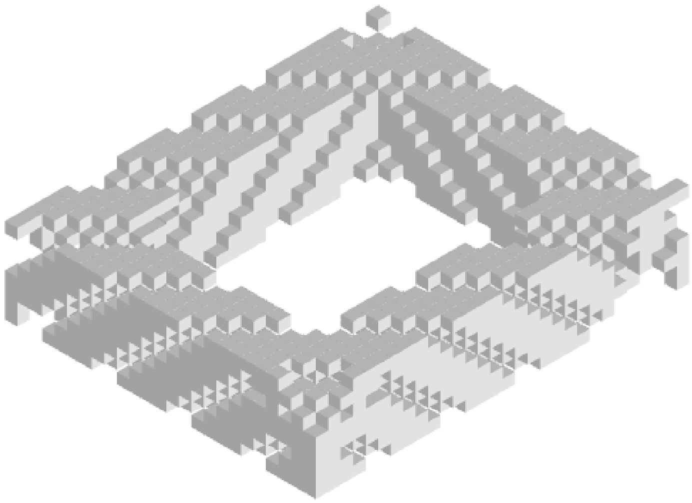
006 B33_2212_C2



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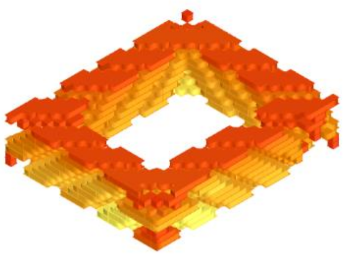

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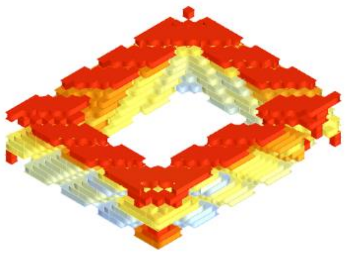

Geometry Simplification			
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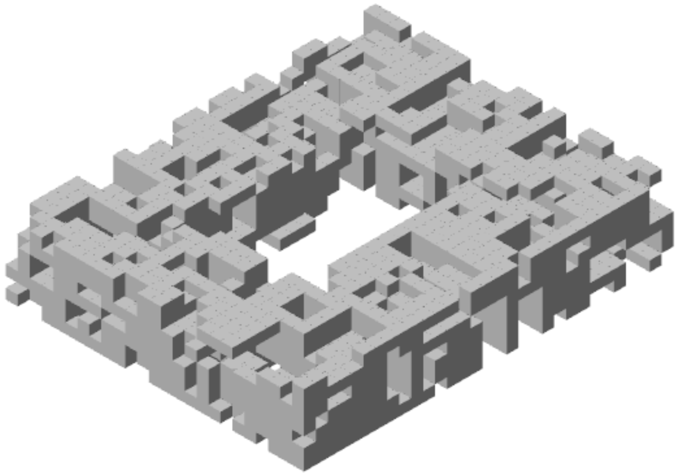
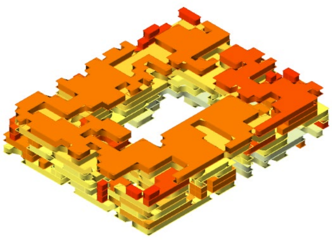
R. influence:	1 cell		
H. max.:	8 floors		
Context and Urban Restrictions			
Typology:	Block		
N⁰ buildings:	1 (x=1, y=1)		
Dim.:	5 cells (D)		
Total bulk:	3600 cells		
Form Generation			
Generation:	33		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	2212 cells (81291m³)		
	New:	2212 cells	
	Existent:	0	
Total Empty:	3788 cells		
	Private:	1388 cells	
	Public:	2400 cells	
FSI:	2,95		
GSI:	60%		
Height:	8 floors		
OSR:	0,136		
Dwelling Un.:	368,66		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	N		
Daylight Simulation Results			
sDA:	0,56		
cDA:	0,73		

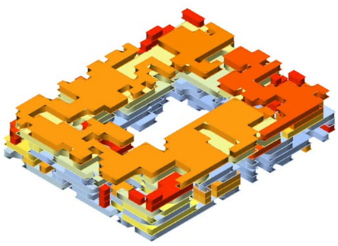
037 B33_2375_R3



cDA

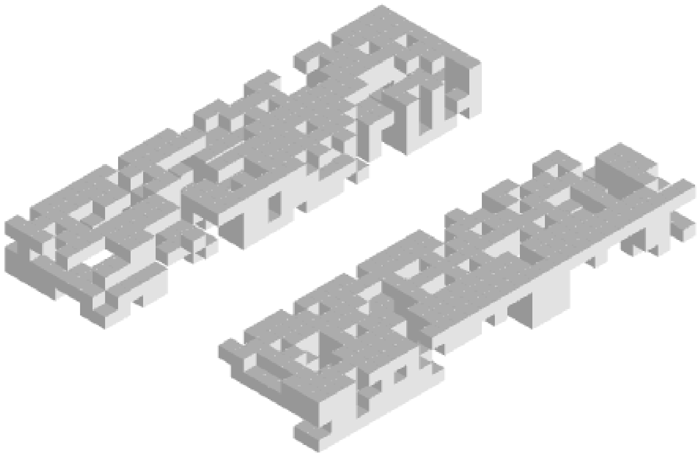


sDA

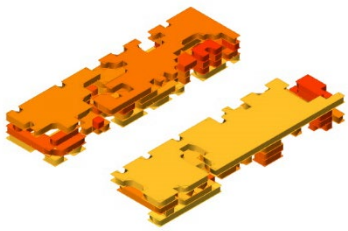


Geometry Simplification			
Block dim.:	31 x 25 cells		
Cell size:	3,5; 3,5; 3 m		
R. influence:	1 cell		
H. max.:	7 floors		
Context and Urban Restrictions			
Typology:	Block		
Nº buildings:	1 (x=1, y=1)		
Dim.:	8 cells (D)		
Total bulk:	4480 cells		
Form Generation			
Generation:	33		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	2375 cells (87281,25m³)		
	New:	2375 cells	
	Existent:	0	
Total Empty:	3355 cells		
	Private:	2105 cells	
	Public:	945 cells	
FSI:	3,06		
GSI:	83%		
Height:	7 floors		
OSR:	0,064		
Dwelling Un.:	395,83 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	N		
Daylight Simulation Results			
sDA:	0,40		
cDA:	0,58		

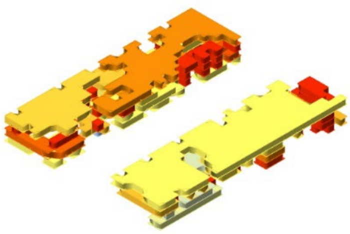
004 S33_995_C2



cDA

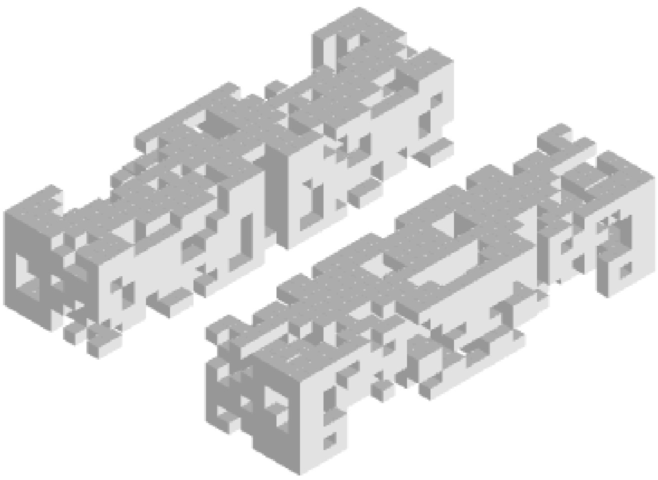


sDA

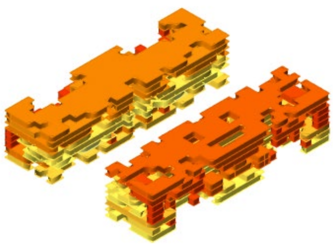


Geometry Simplification	
Block dim.:	30 x 25 cells
Cell size:	3,5; 3,5; 3 m
R. influence:	1 cell
H. max.:	4 floors
Context and Urban Restrictions	
Typology:	Stripe
N⁰ buildings:	2 (x=1, y=2)
Dim.:	30 x 8 cells
Total bulk:	1920 cells
Form Generation	
Generation:	33
Rules:	min / max
Birth:	Y 1 / 5
Death:	Y 0 / 2
Max alive:	Y -
Density Indicators	
Total Built:	995 cells (36566.25m³)
	New: 995 cells
	Existent: 0
Total Empty:	2005 cells
	Private: 925 cells
	Public: 1080 cells
FSI:	1,29
GSI:	64%
Height:	4 floors
OSR:	0,271
Dwelling Un.:	165,83 un.
Simulation Parameters	
Occupancy:	8am – 6pm
Location:	Porto Alegre
Context:	N
Daylight Simulation Results	
sDA:	0,58
cDA:	0,72

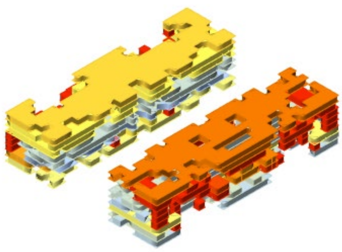
003 S69_2244_C2



cDA

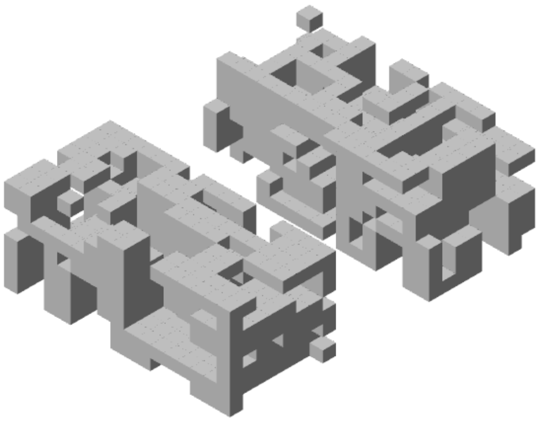


sDA

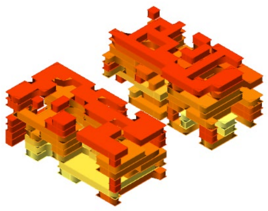


Geometry Simplification		
Block dim.:	30 x 25 cells	
Cell size:	3,5; 3,5; 3 m	
R. influence:	1 cell	
H. max.:	8 floors	
Context and Urban Restrictions		
Typology:	Stripe	
Nº buildings:	2 (x=1, y=2)	
Dim.:	30 x 8 cells	
Total bulk:	3840 cells	
Form Generation		
Generation:	69	
Rules:	min	max
Birth: Y	1	5
Death: Y	0	2
Max alive: Y	-	
Density Indicators		
Total Built:	2244 cells (82467m³)	
	New:	2244
	Existent:	0
Total Empty:	3756 cells	
	Private:	1596 cells
	Public:	2160 cells
FSI:	2,90	
GSI:	64%	
Height:	8 floors	
OSR:	0,120	
Dwelling Un.:	374 un.	
Simulation Parameters		
Occupancy:	8am – 6pm	
Location:	Porto Alegre	
Context:	N	
Daylight Simulation Results		
sDA:	0,48	
cDA:	0,65	

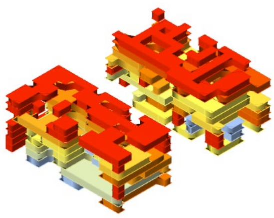
039 P90_1080_R3



cDA

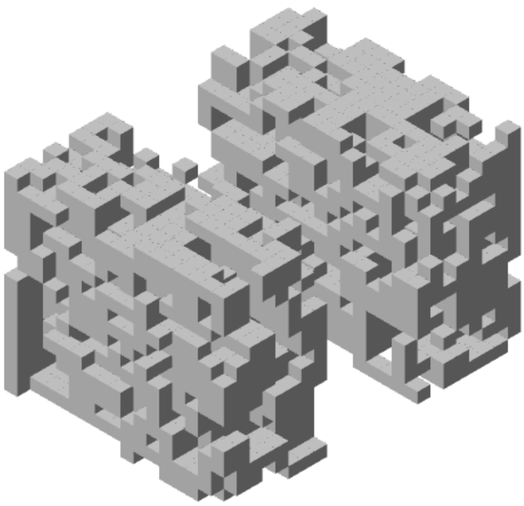


sDA

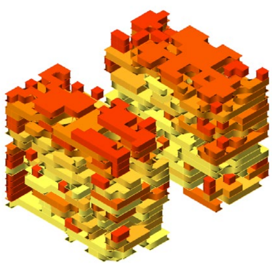


Geometry Simplification		
Block dim.:	31 x 25 cells	
Cell size:	3,5; 3,5; 3 m	
R. influence:	1 cell	
H. max.:	8 floors	
Context and Urban Restrictions		
Typology:	Point	
Nº buildings:	2 (x=2, y=1)	
Dim.:	8 x 16 cells	
Total bulk:	2048 cells	
Form Generation		
Generation:	90	
Rules:	min	max
Birth:	Y 1	5
Death:	Y 0	2
Max alive:	Y -	
Density Indicators		
Total Built:	1080 cells (39690m³)	
	New:	1080 cells
	Existent:	0
Total Empty:	5120 cells	
	Private:	968 cells
	Public:	4152 cells
FSI:	1,39	
GSI:	33%	
Height:	8 floors	
OSR:	0,477	
Dwelling Un.:	180 un.	
Simulation Parameters		
Occupancy:	8am – 6pm	
Location:	Porto Alegre	
Context:	N	
Daylight Simulation Results		
sDA:	0,62	
cDA:	0,73	

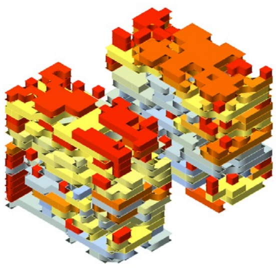
040 P17_2393_R3



cDA

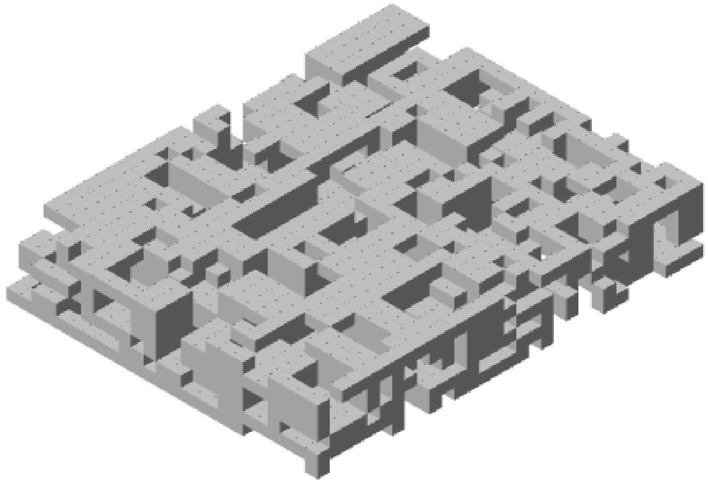


sDA

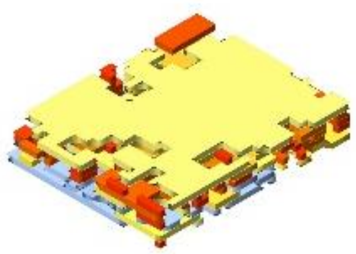


Geometry Simplification		
Block dim.:	31 x 25 cells	
Cell size:	3,5; 3,5; 3 m	
R. influence:	1 cell	
H. max.:	17 floors	
Context and Urban Restrictions		
Typology:	Point	
Nº buildings:	2 (x=2, y=1)	
Dim.:	8 x 16 cells	
Total bulk:	4352 cells	
Form Generation		
Generation:	17	
Rules:	min	max
Birth:	Y 1	5
Death:	Y 0	2
Max alive:	Y -	
Density Indicators		
Total Built:	2393 cells (87942,75m³)	
	New:	2393 cells
	Existent:	0
Total Empty:	10.782 cells	
	Private:	1959 cells
	Public:	8823 cells
FSI:	3,09	
GSI:	33%	
Height:	17 floors	
OSR:	0,22	
Dwelling Un.:	398,83 un.	
Simulation Parameters		
Occupancy:	8am – 6pm	
Location:	Porto Alegre	
Context:	N	
Daylight Simulation Results		
sDA:	0,47	
cDA:	0,63	

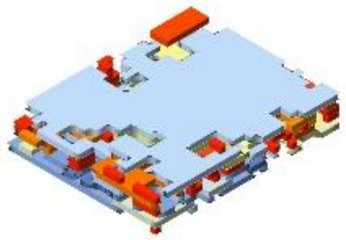
018 N85_2385_R3



cDA



sDA



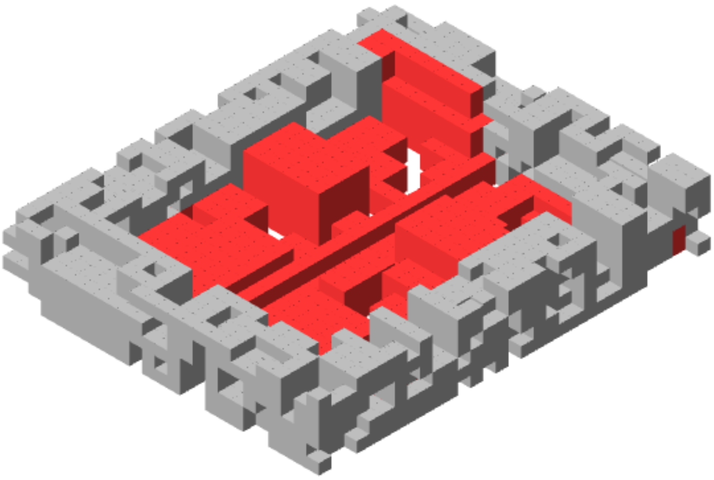
Geometry Simplification	
Block dim.:	31 x 25 cells
Cell size:	3,5; 3,5; 3 m
R. influence:	1 cell
H. max.:	6 floors
Context and Urban Restrictions	
Typology:	None
Nº buildings:	1 (x=1, y=1)
Dim.:	31 x 25 cells
Total bulk:	-

Form Generation			
Generation:	85		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	

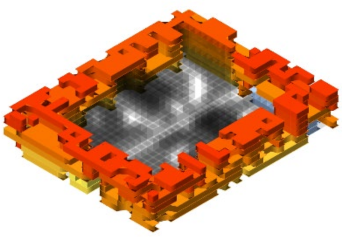
Density Indicators		
Total Built:	2385 cells (87648,75m³)	
	New:	2385 cells
	Existent:	0
Total Empty:	2265 cells	
	Private:	2265 cells
	Public:	0
FSI:	3,08	
GSI:	92%	
Height:	6 floors	
OSR:	0,025	
Dwelling Un.:	397,5 un.	

Simulation Parameters	
Occupancy:	8am – 6pm
Location:	Porto Alegre
Context:	N
Daylight Simulation Results	
sDA:	0,29
cDA:	0,43

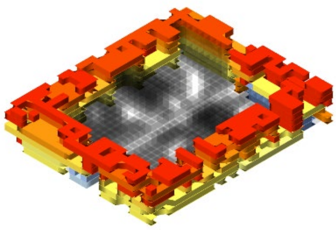
011 B89_2445e_R2



cDA

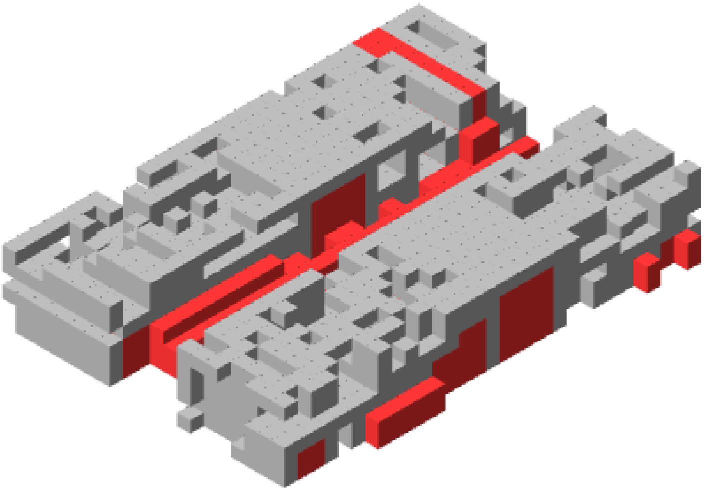


sDA

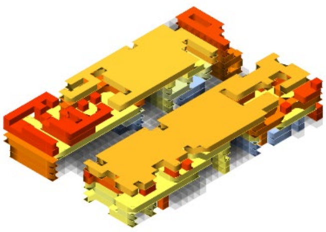


Geometry Simplification			
Block dim.:	31 x 25 cells		
Cell size:	3,5; 3,5; 3 m		
R. influence:	1 cell		
H. max.:	6 floors		
Context and Urban Restrictions			
Typology:	Block		
Nº buildings:	1 (x=1, y=1)		
Dim.:	4 cells (D)		
Total bulk:	2340		
Form Generation			
Generation:	89		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	2500	
Density Indicators			
Total Built:	2445 cells (89853,75m³)		
	New:	1260 cells	
	Existent:	1185 cells	
Total Empty:	2205 cells		
	Private:	671 cells	
	Public:	1534 cells	
FSI:	3,15		
GSI:	85%		
Height:	6 floors		
OSR:	0,048		
Dwelling Un.:	407,5 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	Y		
Daylight Simulation Results			
sDA:	0,68		
cDA:	0,76		

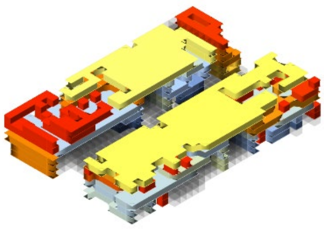
027 S29_2561e_R3



cDA

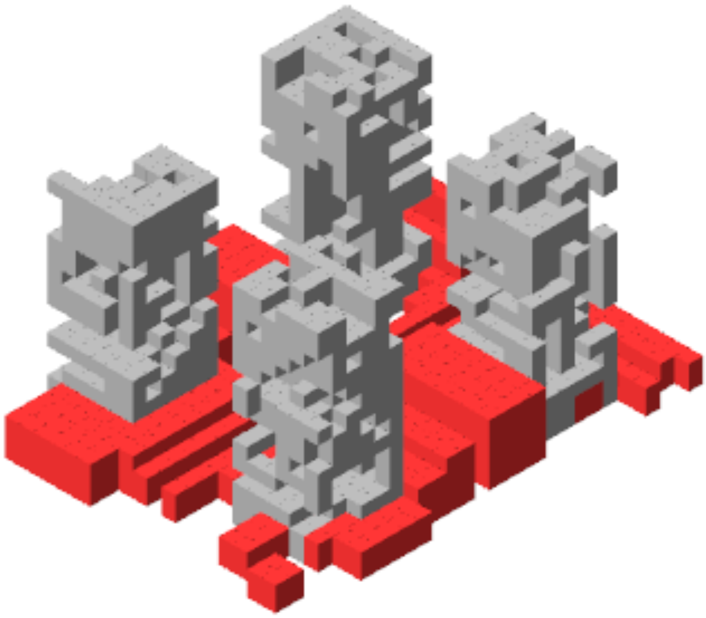


sDA

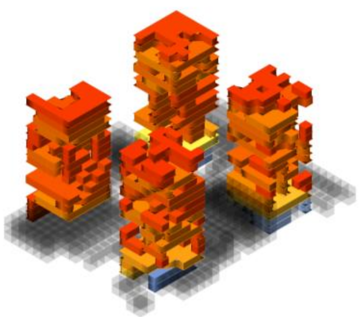


Geometry Simplification			
Block dim.:	31 x 25 cells		
Cell size:	3,5; 3,5; 3 m		
R. influence:	1 cell		
H. max.:	6 floors		
Context and Urban Restrictions			
Typology:	Stripe		
N⁰ buildings:	2 (x=1, y=2)		
Dim.:	31 x 8 cells		
Total bulk:	2976		
Form Generation			
Generation:	29		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	2561 cells (94116,75m³)		
	New:	1376 cells	
	Existent:	1185 cells	
Total Empty:	2089 cells		
	Private:	628 cells	
	Public:	1461 cells	
FSI:	3,30		
GSI:	76%		
Height:	6 floors		
OSR:	0,072		
Dwelling Un.:	426,83 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	Y		
Daylight Simulation Results			
sDA:	0,46		
cDA:	0,57		

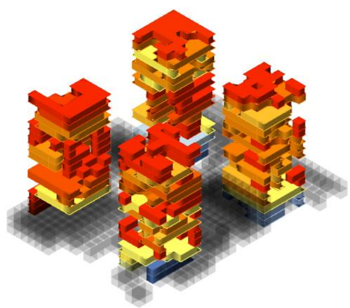
036 P19_2455e_R3



cDA



sDA



Geometry Simplification			
Block dim.:	31 x 25 cells		
Cell size:	3,5; 3,5; 3 m		
R. influence:	1 cell		
H. max.:	17 floors		
Context and Urban Restrictions			
Typology:	Point		
Nº buildings:	4 (x=2, y=2)		
Dim.:	6 x 6 cells		
Total bulk:	-		
Form Generation			
Generation:	19		
Rules:		min	max
Birth:	Y	1	5
Death:	Y	0	2
Max alive:	Y	-	
Density Indicators			
Total Built:	2455 cells (90221,25m³)		
	New:	1270 cells	
	Existent:	1185 cells	
Total Empty:	14075 cells		
	Private:	961 cells	
	Public:	13114 cells	
FSI:	3,17		
GSI:	59%		
Height:	17 floors		
OSR:	0,131		
Dwelling Un.:	409,16 un.		
Simulation Parameters			
Occupancy:	8am – 6pm		
Location:	Porto Alegre		
Context:	Y		
Daylight Simulation Results			
sDA:	0,72		
cDA:	0,79		