A Computational Design System
for Environmentally Responsive Urban Design

by

Saeran Vasanthakumar

A thesis

presented to the University of Waterloo

in fufillment of the

thesis requirement for the degree of

Master of Architecture

in

Engineering

Waterloo, Ontario, Canada, 2015

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis introduces a design tool that attempts to optimize urban energy needs through the mass-customization of urban typology. Developing low-energy, high-density urban typology is a critical goal for cities given current energy consumption and urban growth trajectories. This target is contradicted in part by the increase of building energy per square meter, required by dense urban typologies. Studies have shown that the energy impact of urban typology design is significant, due to city microclimates, and increased structural and mechanical inputs, and thus justifies coordinating building energy needs in urban neighborhoods.

Despite this, current urban energy modeling tools do not account for the consequences of different typology choices and urban modeling tools do not integrate state-of-the-art environmental and energy simulation methods. Recent advances in computational tools can be used to efficiently generate a solution space of potential typologies to fill this gap in current urban design and analysis software. As such the broader goal of this research is to develop a design system that derives high density urban fabric according to a nuanced simulation of urban energy demand.

Daylighting, out of the multiple energy reduction strategies available, offers significant opportunity for architectural optimization. Daylighting varies greatly, even at relatively high densities, due to the effects of ambient light, surface reflectance, and building geometry. In conjunction with the decreasing contribution of heating demand in the overall building energy budget this indicates that gains in urban energy efficiency today can be made by focusing on reducing lighting energy demand. Therefore the current goal of this research is to develop a proof-of-concept that generates and optimizes city fabric according to the conflicting objectives of building daylighting potential and urban densification.

The proof-of-concept will consist of a parametric set shape grammar that is extended with existing software or algorithmic models to achieve the current goal. The tool consists of four parts: algorithmic city simulation to derive density targets, a generative rule set to encode building typology, a performance simulator to derive solar zoning boundaries and interior illuminance metrics, and finally an optimization method to identify the typology solutions that best match the current thesis goal. Daylighting metrics and material simulation is achieved with the RADIANCE/DAYSIM modeler. Existing urban modeling algorithms will be translated within the shape grammar system to map the dynamics of non-uniform urban densities. Optimization is implemented through the Galapagos evolutionary computing plug-in for Grasshopper3D.

The thesis design system integrates research from two domains through computational methods: urban modeling and building performance simulation. The synthesis of this existing research and work thus puts forward a model of integrated city design via generative design systems. The contribution of the synthesis lies in the development of the urban energy-centric form generator, which extends procedural type generation of cities to simulated environmental and material data. The proof-of-concept is licensed under the open-source GNU General Public License, and packaged as a Python-based plug-in for Grasshopper3D, the visual scripting interface for the Rhinoceros3D CAD modeler.

Acknowledgements

This thesis would not have been possible without the fellowship and support from the following people.

My commitee members, in reverse order of their appearance.
My external reader José Duarte, for providing his expert insight and feedback. Kevin Stelzer, for his rigour and insight on the topic of building energy dynamics and post-defence drinks. Maya Przybylski, for her unerring pragmatism and our many discussions on the topic of computational design. Philip Beesley, for his tireless support, high standards and unrelenting criticality –it was always appreciated.

My sister, Vaithegi for her mentorship of my entrepreneurial ambitions.

My fondest memories at school will be my time spent with colleagues starting and growing F_RMlab the Computational Design Group at Waterloo Architecture: May Wu, Petra Bogias, Rakshya Gauchan, Sheida Shahi, Farzin Azad, Anam Khan, Fernie Lai, Henry Murdock, Miriam Ho, Connor O' Grady and my dear friend Kam-Ming Mark Tam.

Tim Wat, Andrea Hunniford, Sue Tang, Carlo Luigi, Jaliya Fonseka, Matthew Compeau, and Geoff Christou; for providing wisdom, critical feedback and most importantly, late night beers.

Dieter Toews, for wisely advising against writing my own optimization algorithm and introducing me to Galapagos.

Andrew Levitt for his counsel and support of my early energy simulation efforts and the experimental integration of my early prototypes in the 3B Design Studio.

The Ladybug community for integrating my solar geometry components in their plug-in. In particular I'd like to mention the creator Mostapha Roudsari, and contributers Chris Mackey and Abraham Yezioro for help with my

development process.

Terry Knight, for her expert feedback on the thesis shape grammar.

Finally, I’d like to mention author David Foster Wallace for his role in the awakening of my interest in annular systems.

Dedication

To my parents Jeyakumari and Thambirajah Vasanthakumar.

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1 Introduction

Developing low-energy, high-density urban typology is a critical goal for cities given the dual pressure to meet energy consumption[1] and housing demand[2] targets in the near future. Yet while net urban energy is reduced through densification[3] the resulting microclimatic conditions, geometric obstructions, and increased structural and mechanical inputs generally increase the per square meter energy-usage of individual building systems (Hegger and Fuchs 2008, 63) (Steemers 2003, 3). The impact of typology is not trivial. A study on the thermal energy consumption of different European typologies by the London School of Economics (LSE) found morphology alone varied thermal energy loads by a factor of six (Rode et al 2014, 2). As such, the net energy reduction of densification is contradicted by local building energy increase, in part due to the energy performance of different urban typologies.

This thesis develops a computational design tool that attempts to coordinate urban energy transfers and needs by optimizing the performance of different typology solutions. The design system is introduced here through an overview of: building energy dynamics; the broader research and thesis goals; the design system proof-of-concept; the research context and contribution of the work, and finally key research references.

Research in the 1970s assumed that energy efficient urban typology could be achieved through the reduction of heat energy transfer, which has had

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[1] The dominant housing stock in North America is low-rise detached residential, a typology that per capita energy consumption and GHG emissions is 2 to 2.5 times higher than high density equivalents (Niemasz et al 2011, 810).

[2] Dense housing typologies mitigate the current, unprecedented demand for urban housing, with Britain alone projecting the need for 2.5 million intra-urban housing units from 2000 to 2025 (Frampton 2007, 275).

[3] "On average, when comparing 10 major cities in the US with 12 European cities, European cities are five times as dense but the US cities consume 3.6 times as much transport energy per capita. The conclusion often drawn from such data is that dense cities are low energy cities" (Steemers 2003, 3).

considerable influence in promoting underglazed buildings with deep plans (Ratti et al 2005, 5). In recent times, there has been a shift away from the focus on heat energy transfer, partly due to the increase of internal heating gains, the advances in insulation and envelope assembly standards, and the increased proportion of glazing on building envelopes (Ratti et al, 6, 2005). Contemporary building energy models, such as the Lighting and Thermal (LT) Model (Baker and Steamers 2000) are based instead on the idea that energy efficiency is a function of exposure to the external environment as a means of promoting passive energy modulation for lighting, heating and ventilation (Ratti et al 2005, 5).

Recent advances in computational tools can thus be used to simulate and coordinate these passive and active energy transfers between buildings through typology design. Negotiating multiple, often conflicting energy efficiency strategies in the early design stage through the traversal of a typology solution space is not accommodated in current urban energy modeling and urban modeling software surveyed by this thesis. As is well known, such preliminary massing decisions have the largest impact on overall building performance and cost. Such a tool could therefore serve as a critical decision-making aid for stake-holders in the urban design process. The broader goal of this research area is thus to develop a design tool to address the energy-efficient typology gap in current urban design tools.

Of the multiple energy efficiency strategies available, daylighting offers significant opportunity for architectural optimization: daylighting varies greatly with different typologies due to the effects of ambient light, surface reflectance and surface geometry. Strømann-Andersen and Sattrup (67, 2013) established that type design in Northern Europe, with equivalent densities, can vary the average daylighting autonomy by 15%. Daylighting varies more than energy consumption due to the effect of typology design. In conjunction with the decreasing contribution of heat demand in the overall building energy budget, gains in urban energy efficiency today can thus be made by reducing lighting energy demand during the early urban design stages. Additionally this accommodates the well known mental and physical health benefits of adequate natural lighting.

If the proof-of-concept can control a fraction of the variation established by Strømann-Andersen and Sattrup (2013) it yields significant energy savings over the course of the 50 to 100 year lifetime of groups of buildings. The current goal is therefore to develop a tool that encodes user-defined formulas or protocols to optimize typology solutions according to daylighting and density considerations. Figure 1 illustrates the overall input and output data of the thesis proof-of-concept.

Figure 1 Black box diagram of proof-of-concept.

The tool consists of four parts. First a simulation of complex urban dynamics is used to derive density targets and drive typology decision-making. This model maps the development potential defined by user-specified zoning constraints and transit nodes, key criteria in decreasing urban transport energy. The decision-making component coordinates the density targets, daylighting considerations and produces a set of rules to drive the form generator. Secondly a generative rule set is used to encode building types and occupancy zones. It consists of a parametric set shape grammar[4] that defines a feasible solution space of architecturally-correct urban block typologies. The composition rules here control the street ratio, solar angles, building axis and surface coverage through shape relationships identified in §§2.3: plan depth, solar angles, courtyard shape and building height. The form generator executes the type rules from the decision-making component and selects typology designs specific to the broader urban dynamics. The grammar is then extended to generate building envelope assemblies to derive energy metrics.

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[4] Shape grammars are an algorithmic approach to design that generates complex structured designs by iterating geometric transformation rules to shape modules. The system guarantees formal design coherence by systematically controlling the correct application of composition rules. The form generation component of the proof-of-concept is not a strict shape grammar, but heavily references the production system to inform its methods.

Thirdly, a performance simulator is used to derive solar zoning envelopes and calculate the building performance metrics of the generated solution space. This component combines the type geometry data with material transmittance and reflectance values to derive illuminance metrics. Finally an optimization method is used to identify optimal typology solutions. The optimization algorithm systematically combines input variables for the grammar and computes the optimality of each solution, using natural selection heuristics to efficiently guide the search process.

The thesis goal, to find the urban typologies with the highest daylighting and density values, is thus fundamentally a design optimization problem resolved through the use of form-generation and multiple performance simulation methods.

Two domains are integrated through computational methods in this thesis: urban modeling and energy simulation. The synthesis of this existing research and work thus puts forward a model of integrated city design via generative design systems. The research contribution of the synthesis lies in the development of the urban energy-centric shape grammar program, which extends procedural type generation to simulated environmental and material data. The scope of the research is narrow; limited to density and daylighting considerations, specific to temperate climate zones, assuming fixed glazing ratios and wall assemblies for modeling and simulation purposes. However, the work here indirectly addresses issues of passive and active solar strategies, as well as material performance that lay the foundation in the broader scope for the need to coordinate the interaction of active and passive energy optimization strategies between buildings.

In developing the design system, this thesis will refer to a number of pioneering works in this domain. This includes Carlos Ratti's research in passive urban form from MIT's Senseable City Lab; Urban energy studies by Koen Steemers and Leslie March from the Cambridge Spatial Studies Center; José Beirão's development of urban grammars at Delft University of Technology; Michael Batty's studies in urban growth simulation; and finally Christoph Reinhart's development and research of solar illuminance modeling.

The design system proof-of-concept is written in Python and packaged as a series of components for Grasshopper3D, the visual scripting interface for the Rhinoceros3D CAD modeler. Two components developed for the thesis system, modeling minimum and maximum solar volume constraints, has been integrated with the open-source Ladybug environmental Grasshopper3D plug-in.

1.1 THESIS STRUCTURE

There are five sections in the thesis. First, the background and context of urban geometry and building energy relationships is examined and synthesized, identifying gaps or omissions that could be bridged by the thesis work. Secondly the relationship between urban geometry and building energy is studied, teasing out nuanced energy and form relationships within the context of the broader research goal and then identifying and formalizing key relationships to inform the proof-of-concept. Thirdly the design system is introduced consisting of the parametric set shape grammar extended with existing software and algorithmic models. Then the design system proof-of-concept will be tested, synthesizing the above concepts to achieve low-energy, high-density housing settlement in the context of southeast London, UK. Finally the conclusion will discuss the role of computational design tools in the context of creating high performing cities.

2 Background & Context

The thesis design system studies and integrates aspects from two domains through computational methods: urban design and urban building performance simulation. This chapter provides the background and context for the thesis design system by surveying the state-of-the-art in the specific application of each: computational urban design and computational urban energy modeling.

2.1 COMPUTATIONAL URBAN DESIGN

This section places the thesis design system within the broader context of urban participation, and surveys the state-of-the-art in computational urban modeling.

2.1.1 Urban Design Tools

Beirão (2012, 30) defines one of the key features of urban design as the "collaborative decision-making practice involving the transformation of territories from rural or rural to urban to upgraded urbanised forms, taking sustainability into account." This characteristic of urban design reflects the notion of city development as an innately democratic model, where urban design reflects broader decentralized processes through local participation. This participatory model leverages the local knowledge of citizens but is constrained by the non-specialist nature of users, and other problems of complete participation, such as allocating indivisible goods like clean air, or locating shared resources like the subway (Beinart 2013, para. 2). Embedding the different stakeholders of the city — including policymakers, politicians and local citizens — into the design process is thus an important characteristic of modern planning frameworks (Beirão 2012, 37).

This thesis takes the idea that the city requires a systematic quality and high degree of explicitness so that citizens can participate in constructing the city’s form (Beinart 2013, para. 2). How can we achieve this? Participation hinges on good decision-making by the participants to achieve good city form —it is dependent on the available information and on the technological advances that can portray outcomes. Thus tools can be used to illustrate probabilities and trade-offs as an aid to decision-making by providing information on urban processes. Within this context, urban design tools thus play a critical role in participatory urbanism. Specifically, Beirão defines two categories in which tools achieve this.

1. Tools to enhance information about the way cities grow and processes involved in growth, not directly involve in design process (Beirão 2012, 27)
    - models of urban topological structures such as space syntax, place syntax, route structure analysis
    - simulation tools for urban evolution and development using cellular automata or agent based models
    - “serious” games that reproduce complex multi-agent participation with players to model urban evolution
2. Tools used to directly improve the design practise, integrating analytical methods and tools with design methods and tools (Beirão 27, 2012)
    - density indicators, used to inform, analyse or establish goals in urban design
    - deterministic urban form generators such as CityEngine (2014) or CityMaker (2012)

Within this context, the thesis design tool sits within the latter category. Specifically, given the negative impact of dense urban geometry on building energy (Ratti et al 2003, 3) and its potential to increase passive energy transfer through typology decisions (Strømann-Andersen and Sattrup, 2011, 144), this thesis argues there is a need to make explicit the impact of urban development on building energy. This is achieved by integrating computational methods of generating urban design compositions and methods to derive corresponding energy consequences.

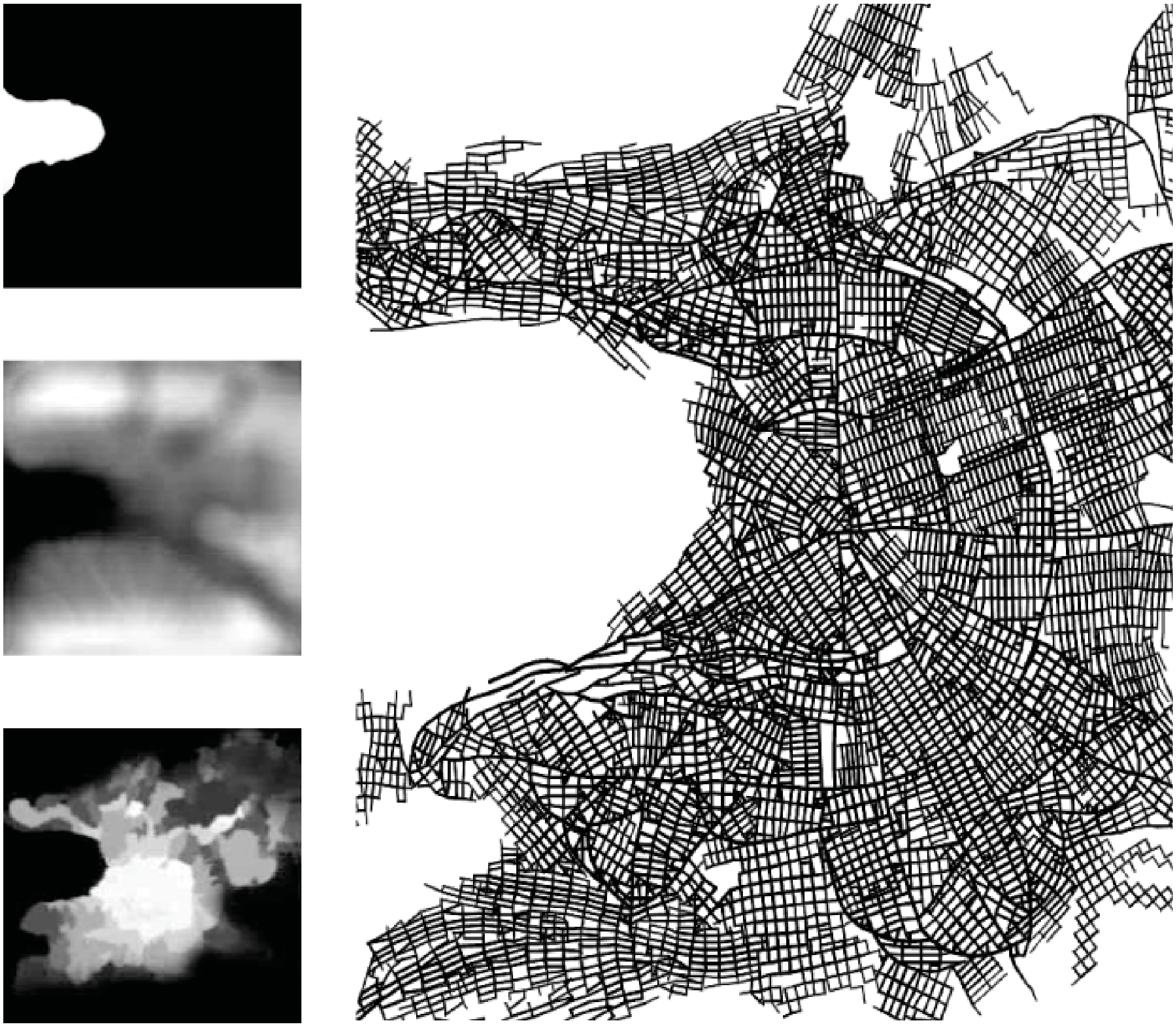

Figure 2 CityEngine inputs (land mass, topography, density) and output (streetgrid).

2.1.2 Survey of Computational Modelling of Built Environments

This section surveys the state-of-the-art design tools used to generate large-scale built form through computational methods.

Will Wright's SimCity games, currently on SimCity 4 (Maxos 2013) is a city-building simulation computer game that allows non-experts, acting as mayors, to make urban planning decisions and grow cities. Players can, for example, integrate public transit networks, specify vehicular traffic on streets and implement energy-efficient building codes (Reinhart, 477, 2013). The urban model is supported through 3D renderings and data visualization.

UrbanSim (Waddell 2002, 2011) is one example of a long-term research and practice effort to model larger scale urban performance measures. It combines land use, the environment, economy and transportation models, with the smallest unit analyzed being urban zones or parcels. UrbanSim has been under active development for approximately two decades. According to Reinhart, the target user group for these types of large-scale urban tools is the Metropolitan Organizations environmental organizations, real-estate developers and community shareholders (Reinhart 2013, 477).

CityZOOM is a Microsoft Windows tool developed at the SIMMLAB of the Universidade Federal de Rio Grande do Sul (UFRGS) in Brazil (Beirão et al 2010, 363). CiyZOOM is defined as a design support platform, complementing CAD and GIS systems for some urban design specific tasks, such as the simulation of urban design regulations. It is not available as a commercial package, but has been presented at various conferences and workshop. It has a partially implemented generative design model and integrated sustainability analysis (Beirão et al 2010, 364).

AutoCAD Civil 3D is a Microsoft Windows tool from Autodesk, extending its CAD package with urban specific features, such as road and urban site design, and GIS features. The focus is on more structural and larger scale design features, it does not include a generative design model or perform sustainability analyses (Beirão et al 2010, 364).

The next set of tools surveyed are dedicated urban modelling softwares that integrate a generative design system for the massing of built form. With the exception of CityCAD, all tools surveyed include a grammar-based method of generating urban compositions.

CityCAD (Holistic City Software, 2014) is a CAD environment for urban master planning. CityCAD's emphasis is on an interactive interface and data reporting. The software can compute direct shading studies, but offers limited environmental building performance simulation analysis beyond this.

Esri CityEngine created originally by Parish and Müller (2001) is a software application used to generate 3D urban models often in relation to GIS datasets. CityEngine is not shape grammar-based, but uses a related form generation method, L-systems. L-systems are described as a set of formation rules for branching fractal forms, most often used to model plant geometry. Using L-systems allows CityEngine to volumetrically model an entire city using a small set of statistical and geographic input data (Parish and Müller 2001, 301).

These datasets take the form of image maps of a given condition including land-water boundaries, population density or zoning. This input data is fed into an extended L-system that generates a two-dimensional traffic network. The areas between the roads are then recursively subdivided to define the allotments the buildings are placed on. Another L-system for the buildings uses a string representation of boolean operations on simple solid shapes. Image maps delineating zoning regulations allow the use of different L-systems for skyscrapers, commercial buildings and residential houses (Parish and Müller 2001, 306). CityEngine thus processes social, economic and legal data into image maps and generates urban form through the preset, recursive application of different L-systems. CityEngine offers a scripting environment available to designers, a JAVA-based shape grammar rule scripting environment, and a Python based input/output scripting environment to facilitate the development of new importers and exporters (Beirão et al 2010, 367).

City Induction (Beirão 2012) is a broad research initiative that aims to develop an urban design tool through the integration of CAD into a GIS environment. City Induction is composed of three models: 4CityPlan a model for forming urban programs based on Christopher Alexander's pattern language; CityMaker a model for generating urban plans that match program, based on shape and description grammars; and EvModule a model for evaluating urban plans used for analyzing, comparing and ranking alternative solutions based on Bill Hillier's space syntax.

CityMaker (Beirão 2012) the generation component of City Induction is a method and set of tools developed as a PhD thesis by Beirão. The urban morphology is created through urban grammars: a shape grammar for urban design. The designer develops a design solution at the site-planning scale from a set of programmatic premises and refines the resulting composition through parameters. It includes a set of measurements called urban indicators that quantify urban relationships, predominantly related to density.

2.2 COMPUTATIONAL URBAN ENERGY MODELING

Reinhart et al (2013, 476) notes that computer-based tools that can model building energy at neighborhood scale, or larger is not currently used in mainstream design practice, although there is a growing number of research teams working on such dedicated urban modeling tools. This in part, is because of the greater complexity of urban energy efficiency and the specalized issues that arise from considering building performance in the context of groups of buildings. Specifically, he observes:

> *...as one expands from individual to groups of buildings, weaknesses of existing simulation engines become more apparent such as difficulties to reliably model microclimatic effects including urban heat island and local wind conditions. Finally, as one's focus expands to the urban scale, operational energy use becomes but one concern with questions such as local transportation mode choices, access to daylight and outdoor comfort conditions equally competing for the designer's attention... Based on these observations, the authors determined a need for a new generation of urban performance simulation tools that are able to efficiently model multiple buildings, approximate microclimatic effects and consider multiple sustainable performance metrics.*
>
> Reinhart et al 2013, 476.

This section places design tools within the narrower context of urban energy modeling through two surveys of related computational tools and methods. Unlike the previous domain surveyed, computational form generation does not play a critical role in this domain. Firstly, the state of art in energy modeling tools for urban design contexts is examined. Secondly, state-of-the-art methods to increase simulated passive energy transfer, achieved through urban geometry is surveyed.

2.2.1 Energy Modeling Tools for Urban Contexts

There are three relevant categories defined for building energy modelling. First, screening tools, for use evaluating project viability in early programming states; next, architectural design tools, for use during programming, schematic and design development; and finally, load calculation and HVAC sizing tools, for use during the design development and construction documentation phases. The varying aims of each building model means that the energy consequences of building geometry or neighboring geometry are not necessarily accommodated in all categories.

Architectural design tools, such as the DAYSIM daylighitng analysis software, evaluate design decisions and therefore include more sophisticated methods for considering building form in terms of passive energy potential (Paradis 2010, para. 2). In contrast, screening tools tend to calculate periodic building performance by correlating building performance against predicted energy performance (Pardis 2010, para. 2). As such they are relatively simple and not able to evaluate the important trade-offs between certain interactive energy strategies such as daylighting and heating, or thermal mass and cooling (Pardis 2010, para. 3).

Load calculation and HVAC sizing tools, such as HAP, TRACE, DOE-2, BLAST, VisualDOE, EnergyPlus are designed to select and size mechanical equipment. Within this category, of relevance to the thesis, is the subset of such tools that is able to perform annual energy simulations. These models compute energy performance by subdividing the building into thermal zones[1] and loads[2] and calculating periodic loads for each thermal zone.

One common tool mentioned in the following survey is the EnergyPlus energy analysis and thermal load simulation program, developed by the US Department of Energy. EnergyPlus can accommodate urban geometry consequences through default values, or can be extended to include specific solar and daylighting conditions from neighboring buildings.

This thesis proof-of-concept will use DAYSIM through DIVA4Rhino for daylight analysis. The integration of DAYSIM in this proof-of-concept enables the software to account for the energy consequences of neighboring geometry. Most operational building energy softwares do not take this into account, focusing instead on building geometry and systems efficiency (Ratti et al 2005, 363). Furthermore, although not in the scope of the thesis, DAYSIM can be extended to generate electric lighting requirements to derive annual energy usage values for heating, lighting and cooling using EnergyPlus. Thus future energy analysis will also take into account the impact of neighboring geometry. This fufills the goals of the thesis, while also accomodating the intentions of the broader research area.

The Energy and Environmental Predication model (EEP), developed at the Welsh School of Architecture in Cardiff, is a computational tool for quantifying energy use and associated emissions for cities. The aim is primarily diagnostic and uses default values to simulate the effects of urban geometry (Ratti et al 2005, 4).

The Solar Energy Planning tool (SE) is a GIS based program to support urban planners and designers in evaluating the potential for solar heating (Ratti et al 2005, 4). Like the EEP, its aim is primarily diagnostic and does not take into account urban geometry and overshadowing of buildings.

SUNtool (Robinson et al 2007) is an urban modeling platform, not publically

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[1] A thermal zone is a discrete area of the building with similar thermal requirements serviced by the same mechanical equipment. The number and geometry of thermal zones is based on: building use, size, and shape.

[2] A load is the required rate of heat removal in summer and heat supply in winter.

released, that links XML input and output files, an integrated solver, and a JAVA-based GUI for data input and visualization of the results (Reinhart et al 2013, 447). The solver includes integrated custom models for modeling microclimatic effects (Reinhart et al 2013, 477).

Young Cities (Huber and NytschGeusen 2011) program simulates individual buildings in EnergyPlus (US-DOE-203) and couples the resulting loads with a Modelica-based (2011) plant model (Reinhart et al 2013, 478).

GSOL (Goretzki 2013) is a solar urban design tool. Integrated tools calculate heating demand of buildings in neighborhood using a simple heat balance algorithm and reports potential optimization strategies. It is thus far specific to Germany. In terms of the thesis focus, GSOL assumes all buildings are unshaded (Reinhart et al 2013, 478).

The Urban Modeling Interface (UMI) (Reinhart et al 2013, 477) integrates building performance simulation modeling with the Rhinoceros 3D CAD modeling platform (McNeel 2013). The developers wanted to introduce urban designers and architects to building performance simulations within a familiar modeling environment. Operational energy evaluations of complete neighborhoods are computed with EnergyPlus, daylighting simulations using DAYSIM, and walkability evaluations using custom Python scripts. UMI is focused particularly in simulating and negotiating energy trade-offs due to local urban microclimatic conditions such as self-shading and urban heat island effects (Reinhart et al 2013, 476).

The open-source Ladybug and Honeybee projects (Roudsari et al 2013) are described as a plug-ins for urban planning and city modeling, environmental design and architecture. Ladybug is similar to UMI as it is integrated with the Rhinoceros3D CAD modeling platform through the Grasshopper3D interface. Ladybug imports standard EnergyPlus weather files (.EPW) and derives solar irradiation metrics, sun-path, and wind-rose, radiation-rose and solar voluming tools. The Honeybee plug-in, focused more on building energy, connects Grasshopper3D to validated simulation engines such as EnergyPlus, Radiance, DAYSIM and OpenStudio for building energy and daylighting simulation.

Ladybug and Honeybee are fairly popular tools within the Grasshopper3D ecosystem. A rough idea of the user base can be assessed by downloads: 5037, 6278 and 3804 downloads for the first, second and third releases respectively. Two components developed for the thesis system, modeling minimum and maximum solar volume constraints, has been integrated with the open-source Ladybug environmental Grasshopper3D plug-in since the first release on April 8, 2014.

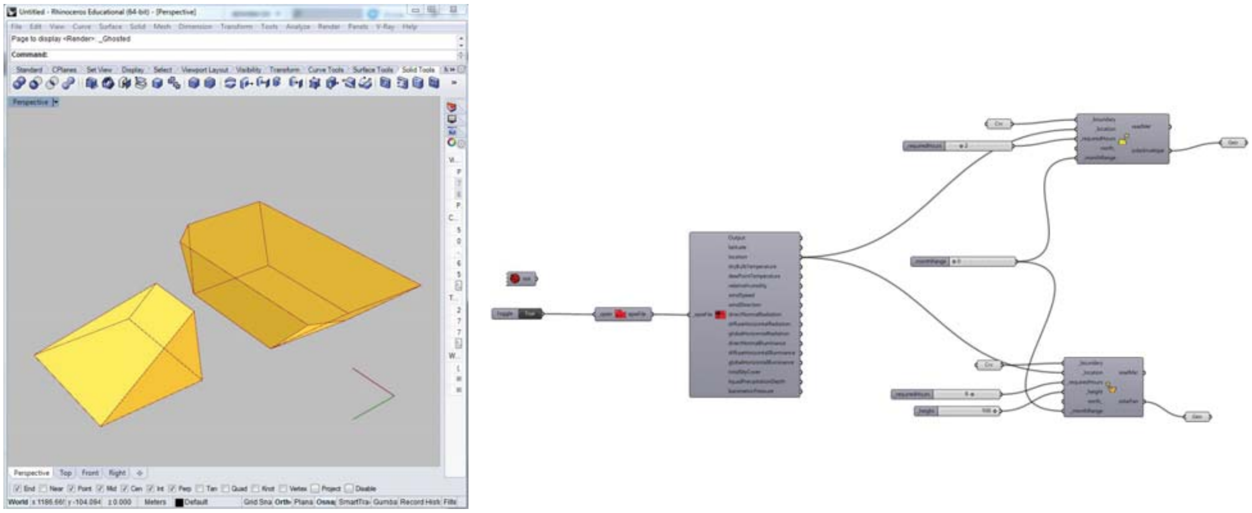


Figure 3 Author's Ladybug SolarFan and SolarEnvelope

2.3 BUILDING ENERGY OPTIMIZATION VIA URBAN GEOMETRY

Rode et al (2014, 23) notes that at building scale a number of studies have called into question the generally accepted view that more compact building types have reduced heat-energy demand. This surprising relationship can be explained by the complex trade-offs occurring between solar heat gains and the surface heat losses of urban form, as well as potential passive lighting and ventilation achieved through exposed envelope. Such trade-offs will be investigated in greater detail in subsequent sections. This section fleshes out the research context of low-energy, high-density urban tissue by reviewing the progress that has been made in optimizing urban geometries for passive solar gain and daylighting in urban tissue.

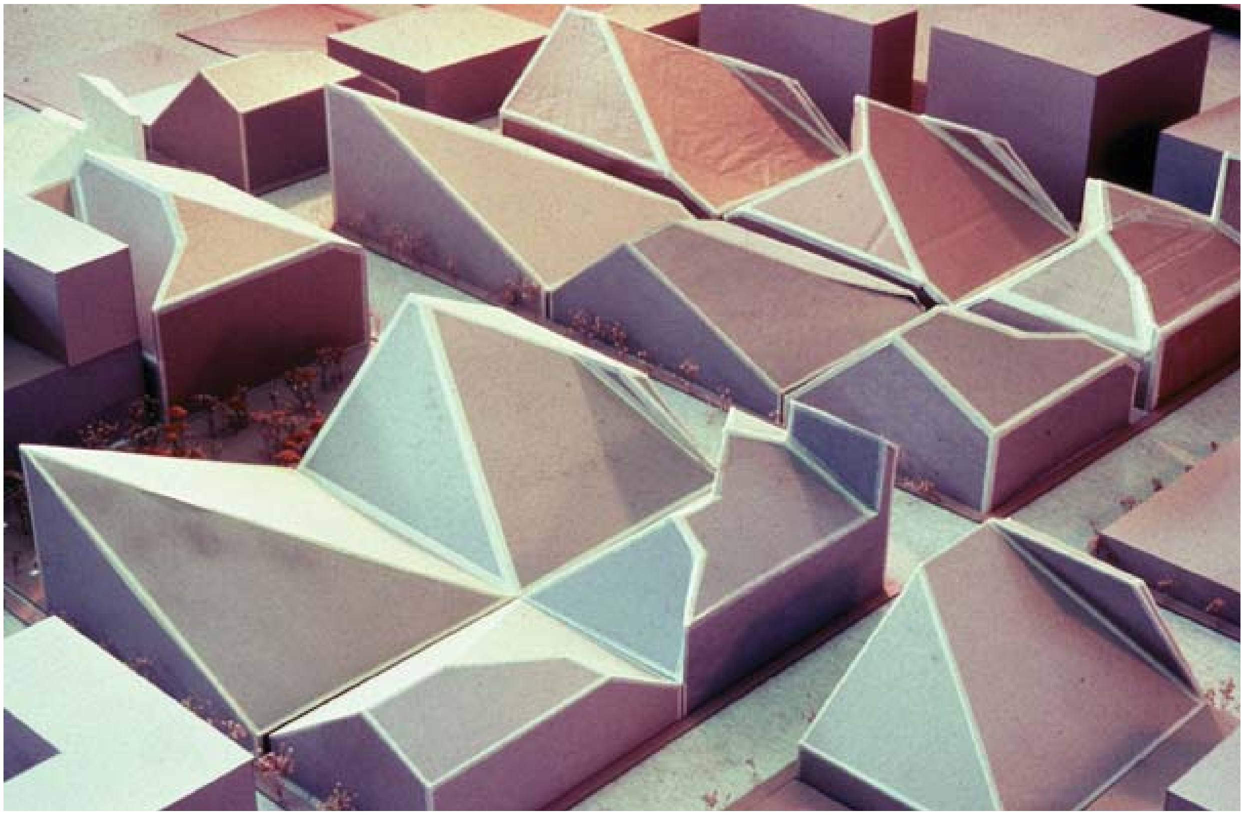
2.3.1 *Passive Building Energy Optimization and Urban Geometry*

Knowles (1974) introduced the concept of the ‘solar envelope’ by calculating the solar angles that define a plot to generate a solar volume. This solar volume is used to constrain the architectural form of buildings, guaranteeing a specified amount of solar access for buildings. Capeluto and Shaviv (1997, 148) extended this idea towards the calculation of ‘solar rights envelope’ and ‘solar collection envelopes’ which guaranteed a specified overshadowing and solar impact, respectively. Issues with solar modeling include: difficulty calculating over extensive urban areas, difficulty calculating complex irregular grids, and the inability to take into account illumination or radiation values (Morello and Ratti 2009, 27).

Figure 4 illustrates the use of solar rights envelope to generate urban housing typology. The envelopes are generated to provide four hours of sunshine in winter and eight hours in summer. State-of-the-art in solar volume modeling was achieved with Ratti and Morello’s (2009, 26) ‘isosolar surfaces’. The isosolar surface refined the solar volume concept by calculating all the areas that received the same amount of solar energy.

Strømann-Andersen and Sattrup (2011) examined the impact of the height and width of ‘urban canyons’ on building energy use and daylight performance, in a northern European setting. The urban canyon is defined as a place where the street is flanked by buildings on both sides creating a canyon-like environment. Variation in energy consumption due to differing height and width parameters, on residential buildings, was as high as 19%, albeit at different densities (Strømann-Andersen and Sattrup 2011, 134). The study also found that reflected light, from building facades contributed to the greatest fraction of daylight to housing on the lowest floors of high densities, and made an important contribution to the energy consumption of these buildings (Strømann-Andersen and Sattrup 2011, 134).

Cheng et al (2006) examined the impact of randomness in the plot layout and height of buildings at high urban densities, in the context of Sao Paolo, Brazil. Figure 5 illustrates the independent variance of both parameters. The study found that randomness in both parameters increased the overall



solar access to the buildings and surrounding space, with a difference factor of three, within the context of sky conditions and high solar altitudes of Sao Paulo (Cheng 2006, 1). This conclusion thus suggests it is possible, in specific climates, to increase urban density without decreasing solar access.

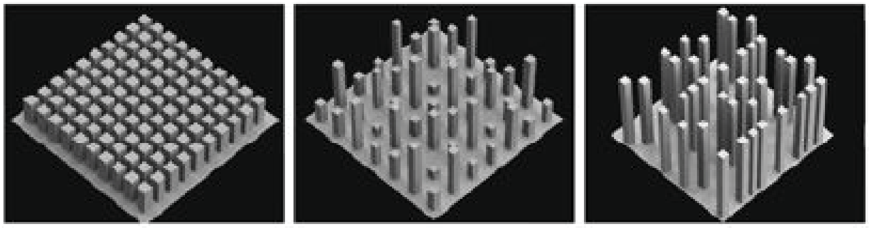


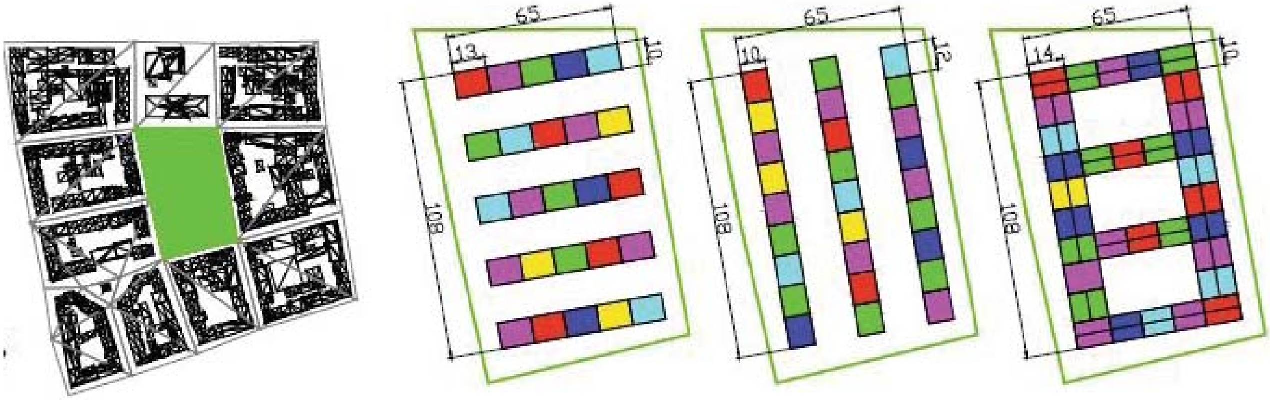
Figure 5 Testing the effect of randomness on solar access. From left to right the built form x and y directions were varied as: uniform-uniform; uniform-random; and random-uniform.

Ratti et al (2003) compared the daylighting performance between courtyard and pavilion building typologies, in the context of hot-arid climates. The study found that the courtyard's shallower plan depths and higher surface to volume ratios better exploited passive interaction with the climate through the relatively high exposed building envelope. The higher exposed 'skin' also increased the risk of excessive heat loss in the winter season, and heat gain during the summer season when coupled with shallow plan depths.

Arboit et al (2008) assessed the solar potential of low-density urban environments in the context of Mendoza, Argentina. The study parameterized the geometry of urban blocks, building glazing, trees and street width from the low-density residential areas, and examined the consequences for heat energy. The study confirming that the shape and orientation of urban blocks were critical factors for passive solar gain considerations, and that this solar energy could offset as much as 34 per cent of the existing heat energy demand (Arboit et al 2008, 1).

Kämpf et al (2010) calculated optimal building forms for maximum solar energy incident on the envelope, through the application of a multi-objective optimization algorithm, within the climatic context of Basel, Switzerland. The study optimized geometric parameters - facade height, roof orientation and height - on three typologies: terrace at roof, slab sloped roof and terrace court formations. The study reinforced the tradeoff between built volume and potential solar gains, and concluded that the terrace court typology performed best by maintaining a large collection surface to maximize solar gain and compact volume to minimize thermal loss (Kämpf et al, 2010, 602).

Figure 4 Ralph Knowles' solar envelopes (top), and derived built form (bottom); viewed from east.



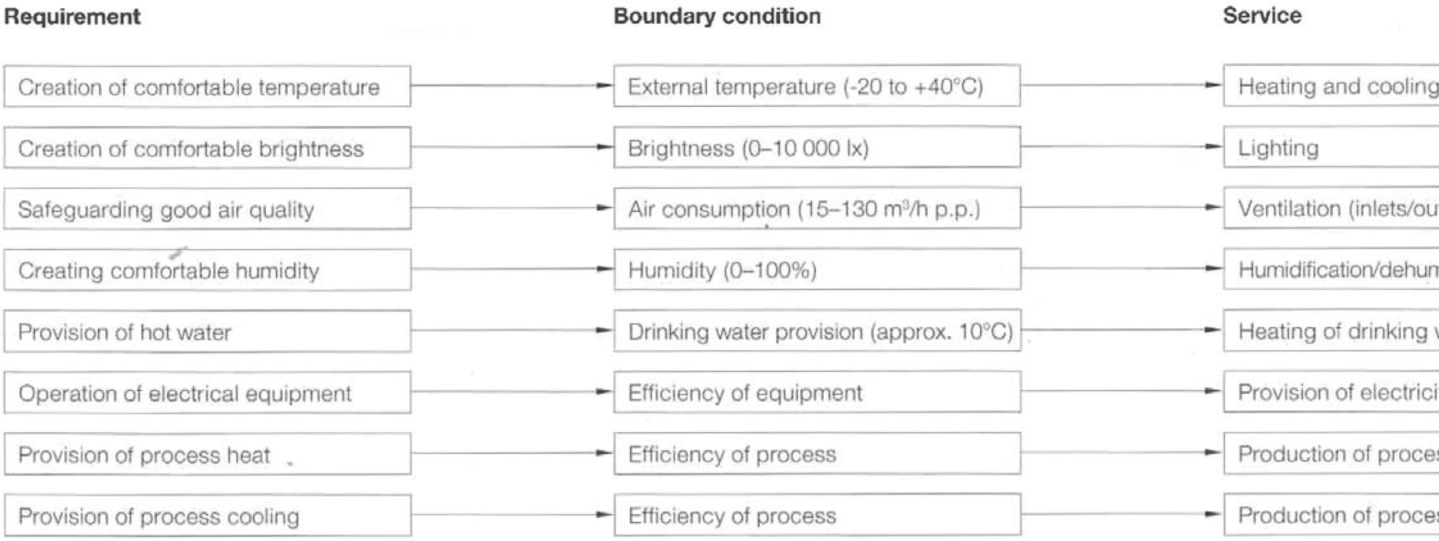
In general, optimizing urban geometry for low-energy through passive energy transfer is associated with reduced built densities. This survey of research has indicated, however, that the extent to which density is reduced can be mitigated through urban geometry. Furthermore Strømann-Andersen and Sattrup (2011, 139) note that very few studies have attempted to relate urban form to energy use, or solar access and daylight conditions. There is thus potential for further research in urban geometry to achieve greater building energy reduction.

Figure 6 Three typologies: terrace at roof, slab sloped roof and terrace court formations were tested to discover the optimal building form for maximum solar energy incident on the envelope.

3 Energy and Geometry

This chapter derives a model of building energy and urban geometry relationships for the design system. There are two aims. First this chapter will tease out nuanced net energy and urban form relationships within the context of the broader research goal. The second aim will be to identify key relationships to inform the proof-of-concept, as the former nuanced and detailed model lies outside the scope of the current goal. The focus will be on the broader scale of city geometry: neighborhoods of around 25 to 30 hectares traditionally known as the urban tissue, fabric or grain (Bosma et al, 2000, 258). According to the International Seminar on Urban Form (Moudon, 1997) there are three fundamental physical elements of morphological analysis: buildings and their related open spaces, building lots and streets. The geometric emphasis here will be on the former, specifically filtered through the lens of typology.

Research by Baker and Steemers (2000) estimated that building design, systems efficiency and occupant behavior vary building energy by factors of 2.5, 3, and 2 respectively. In total, building energy consumption varies by a factor of ten due to the cumulative effect of these variations, although in practise it varies by a factor of twenty (Ratti et al, 2005, 3). Some of this discrepancy can be attributed to the impact of neighboring geometry. In a study on the building energy consumption at tissue scale for Toulouse, London and Berlin, Ratti et al (2005, 1) found that the variation in energy consumption on urban geometry is 10% primarily due to overshadowing. In a similar investigation into the impact of urban geometry, a report by the London School of Economics (LSE) in 2014 focusing on theoretical heat-energy demand, excluding space cooling and air conditioning, found that: "urban morphology-induced heat energy efficiency is significant and can lead to differences in heat-energy demand by up to a factor of six," (Rode et al, 2014, 2). Optimizing these factors at tissue scale has been noted as having significant potential for energy conservation (Rode et al 2014, 2). These values thus suggest that urban geometry "could have a tremendous impact on the energy budget of cities and would justify careful thought in urban planning," (Ratti et al 2005, 30).



Requirement	Boundary condition	Service
Creation of comfortable temperature	External temperature (-20 to +40°C)	Heating and cooling
Creation of comfortable brightness	Brightness (0–10 000 lx)	Lighting
Safeguarding good air quality	Air consumption (15–130 m^3/h p.p.)	Ventilation (inlets/ou
Creating comfortable humidity	Humidity (0–100%)	Humidification/dehun
Provision of hot water	Drinking water provision (approx. 10°C)	Heating of drinking
Operation of electrical equipment	Efficiency of equipment	Provision of electrici
Provision of process heat	Efficiency of process	Production of proce
Provision of process cooling	Efficiency of process	Production of proce

However, at this scale the relationship between building energy and urban geometry is complex, depending on virtually infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives. The Birkhauser Energy Manual (Hegger and Fuchs 2008, 60) provides an abstraction of these factors, identifying five energy themes: heating, cooling, lighting, ventilation and electricity. The figure above illustrates these themes in relation to the building energy requirements, boundary conditions and the needs of the inhabitant. From this the Energy Manual defines ten energy optimization methods broadly divided in two categories: either minimizing energy requirements or optimizing the energy supply.

This is further divided according to either a high-tech or low-tech strategy, quoting at length:

> *One is centered around the respective technological means to guarantee optimum functioning, although numerous energy installations, flaps, valves, sensors, etc. enable an adaptive behavior… controlled by a complex computer program which guarantees the optimum regulation strategy depending on the climatic boundary conditions and the behavior of users….The other strategy aims to design the building in such a way that through urban planning*

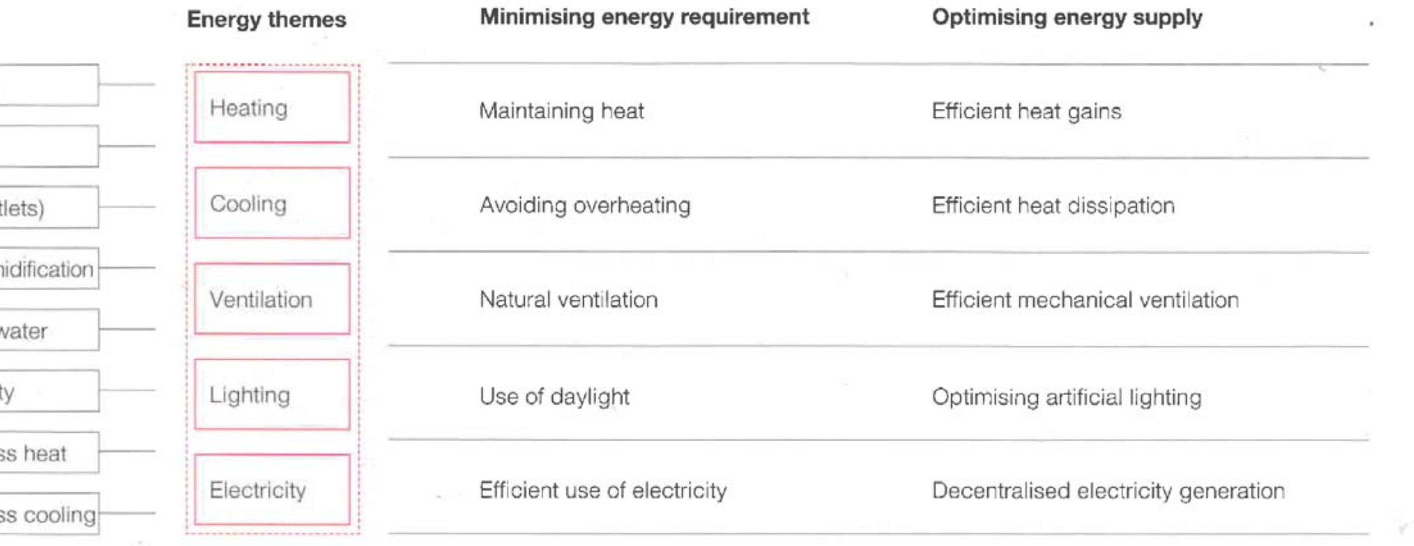


Figure 7 Deriving ten energy optimization methods, from the Birkhauser Energy Manual.

> *stipulations, a building form and envelope optimized for the energy needs, the layout and the choice of materials, the desired conditions – if necessary with minor compromises with respect to the optimum – can be achieved with a minimum of technology. Hegger and Fuchs 2008, 61*

A meaningful reduction of the energy budget of cities could thus be achieved through the coordinated interaction of high-tech and low-tech strategies - what Hegger and Fuchs identifies as cybernetic or self-regulating systems - in the broader domain of building optimization (Hegger and Fuchs 2008, 61). However, at what scale should this coordination occur? Buildings and their energy flows are enmeshed within a broader urban network, thus the coordination of energy systems *must* expand to groups of buildings and even whole city districts in the medium-term (Hegger and Fuchs 2008, 64). The thesis scope thus concerns the energy optimization methods of fabric geometry, belonging predominantly to the low-tech methods, by means of computational form generation and simulation. Within this limited scope, a nuanced model of building energy in urban contexts and useful interactions across energy strategies and requirements are sought out to inform the computational design system.

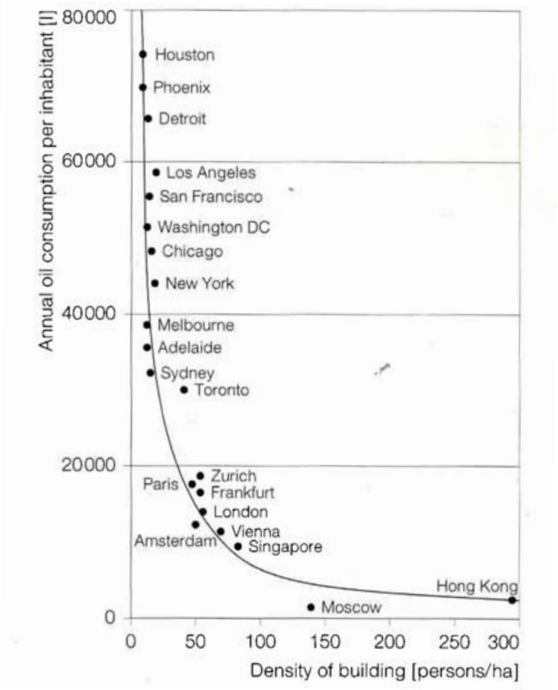
In this chapter I will systematically break down a model of low-energy urban design, taking care to illustrate the innate trade-offs, and possible opportunities that arise between different geometric strategies to reduce urban energy. This will be then be used to inform the proof-of-concept. This is achieved by examining key building energy and urban geometry relationships. First, the contribution of building energy within the context of net urban energy is examined. Second the building energy consequences of urban geometry are examined and a generic model of building energy and urban geometry is defined. Then the trade-offs in the context of different geometric configurations of common urban typologies is studied. The conclusion will summarize the key relationships discovered, and put forward a model of performance and form that can inform the thesis proof-of-concept.

3.1 NET URBAN ENERGY

In general, higher density positively correlates to lower energy consumption. Here we will more concretely break down the factors that contribute to this relationship, and identify the trade-offs inherent in this dynamic.

There is a clear relationship between density and energy efficiency, as illustrated by a comparison of the per head energy consumption of various cities in Figure 8. Densely populated cities exhibit an energy consumption reduced by a factor of eight. However, as density increases to more than 75 persons per hectare the energy efficiency begins to yield diminishing returns, with the 150+ persons per hectare mark yielding minor energy savings (Hegger and Fuchs 2008, 63). Broadly speaking however, the energy efficiency of high densities is a result of efficiencies gained through the concentration of activities and people in cities through the sharing of resources:

> *Most obviously, more intense use of land and sharing of infrastructure -- energy and water supply, drainage, roads, buildings and public transport--reduces the energy per capital associated with its construction (and possibly maintenance) and benefits from an economy of scale by comparison to a more dispersed urban configuration (Steemers 2003, 5).*



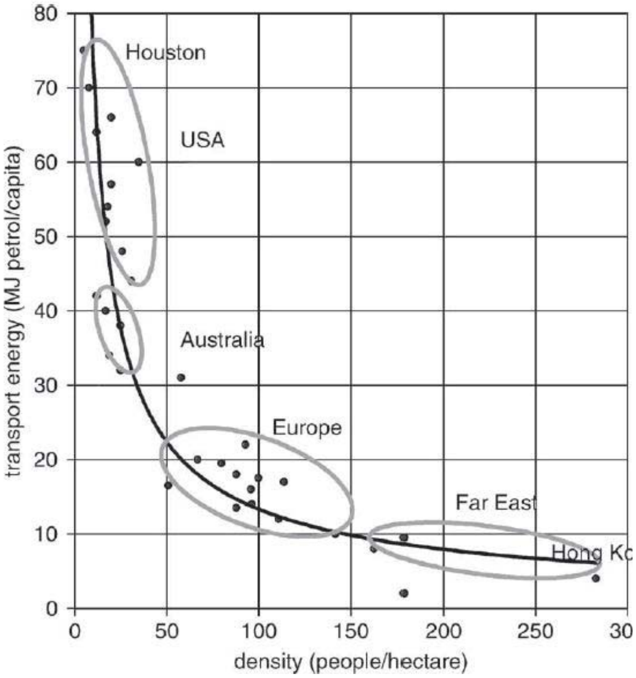


Figure 8 (top left) Density of buildng vs Annual oil consumption per inhabitant.

Figure 9 (top right) Density vs Transport energy.

A specific example of the energy efficiencies gained through use concentration would be district heating networks (DHN). Such networks are associated with high energy losses and therefore are implemented locally, with the maximum transport distance from the plant to consumer seldom more than 20km. Despite this, DHNs exhibit at times system-related losses of up to 40% (Hegger and Fuchs 2008, 72-73). Additionally in relation to other energy forms, there is low sales potential for heat energy because it cannot be universally employed, building insulation advances has increased thermal retention, and is seasonally specific. Therefore district heating network provider's benefit from the higher heat load demand provided by denser urban typologies (Hegger and Fuchs 2008, 73).

In terms of urban geometry, according to Steemers' landmark study (2003) of urban energy consumption, city form has a significant bearing on building and transport energy, two sectors directly impacted by urban planning (Steemers 2003, 3). Of the two, building energy comprises a much higher percentage of net urban energy: the national figure for the UK (not specific to urban areas), is a 2:1 ratio of building to transport energy, and approximately 2.2:1 for London (Steemers 2003, 3). Additionally, building and transportation energy have conflicting relationships with density, namely higher densities generally increases the former and reduces the latter (Steemers 2003, 3).

For building energy, while the per capita energy consumption and GHG emmissions of low-rise detached residential typologies is 2 to 2.5 times higher than high-density equivalents (Niemasz 2011, 1) - the per square meter energy requirements of a building increase with mid to high-rise typologies. Dense urban contexts deprive buildings of useful passive energy transfers; the increased structural requirements increase the amount of embedded building material energy; they require energy consuming means of access such as lifts; and finally, the greater space requirements for mechanical ventilation and lifts takes up more space and energy (Hegger 2008, 63). The relationship with high densities and lower per head energy consumption overall is thus achieved despite the relationship to greater per square meter building energy.

In terms of transit, Figure 9 illustrates that cities with higher densities are strongly correlated with lower transportation energy. However, it is reductive to generically equate higher density with lower transportation energy. For example, in the absence of an effectively integrated public transport network, increasing density will increase private vehicular usage and thus transportation energy (Steemers 2003, 5). Effective methods of reinforcing non-motorized-transport (NMT), such as the concentration of density at transit hubs, for example, through the promotion of non-uniform density[1], and integrating mixed-used development to reduce transit distance are key factors in fulfilling the sustainable and social benefits of higher density.

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[1] The principle of nonuniform density to promote walkability is simple: walking is distance sensitive; transit hubs are popular destinations; thus increasing density around transit hubs increases the per capita availability of public transport system via walking. Additionally transit stations are modal-transfer nodes that act as natural pedestrian catchement areas which symbiotically support the mixed-use development key to promoting walkability.

From Hegger and Fuchs:

> *The provision of services is crucial for the sustainable development of urban structures. Mixed usage always has a positive effect on energy consumption because traffic can be avoided. If a demand cannot be met locally (local traffic), people travel to another urban space in order to meet that demand (regional traffic)....Regional traffic in excess of 20% leads to energy, resources or economic strength being lost from a region[1] (2008, 63).*

These factors ultimately lie outside the scope of this thesis research, which is more narrowly concerned with building energy. In conclusion, despite its correlation with higher per square meter building energy, compact, high density city layouts that reinforce public transit networks contribute towards lower net urban energy budgets.

3.2 BUILDING ENERGY RELATIONSHIPS

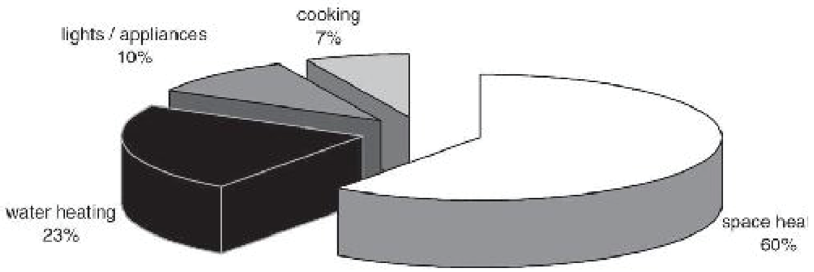


Figure 10 Energy use breakdown for UK housing.

This section investigates the energy consequences of urban geometry. First I will examine the relationship between heat energy and building geometry. From this initial study, I will then refine this relationship through a consideration of more complex trade-offs: between the passive heat gains or surface heat losses, and daylighting achieved through different urban geometry.

3.2.1 Heat Loss and Built Geometry

The question of energy reduction in urban form was addressed in a series of pioneering studies by Lionel March (1972). Specifically March attempted to resolve what shape a building should be to reduce heat losses (Ratti et al 2005, 5). To resolve this, March analyzed heat loss as a function of built geometry, taking into account just the necessary parameters for the study. Heat loss was targeted because as the energy breakdown in the figure below illustrates, it uses the bulk of energy in domestic buildings. March thus assumed: each surface was made of homogenous material with a given transmittance value, that heat loss is proportional to the thermal transmittance and the surface area of each face of the built form, that no heat transfer occurs from the building to the ground, and that urban forms consisted of rectilinear parallelepipeds (Ratti et al, 7, 2005).

From this he was able to prove that the urban shape that best conserves heat loss would be a perfect cube, as it would have lowest ratio of surface area to volume and thus reduce the exposure of the building skin to heating loss. This means if the constraints for rectilinear parrallepiped are removed the shape with the lowest surface area to volume ratio would be a sphere, and if ground heat loss were accounted would be a half-sphere (Ratti et al 2005, 7). The March cube thus indicated the focus for city design should be on compact urban forms best for reducing energy use. According to Ratti et al (2005, 5), March's studies can be credited with the historical trend for energy conservation for urban form focusing on retaining thermal load through compact building forms with deep plans and under glazed buildings. March's studies thus provide a framework for understanding the relationship between the dominant building energy factor and its physical form **-** as well as the historical trajectory of urban geometry.

3.2.2 Passive Energy and Built Geometry

Ratti et al further noted that the March cube: "while theoretically minimizing heat losses, is unlikely to minimize energy consumption as a whole. In fact, heat losses just tell part of the story of energy consumption in buildings," (2005, 5). Figure 10 portrays the energy breakdown, by building facade orientation for an office building in the UK as a function of the 'urban horizon angle' (UHA) - the mean angle of the skyline above the mid height of a window. The curves were derived with the LT Method (Ratti et al 2005, 6). The energy interaction is quite complex: in winter the south façade does not receive useful solar gains therefore increasing the heating load, while the heat energy along the north façade is unaffected since the solar gains are insignificant. Lighting energy increases the most significantly as a result of the increasing UHA. Energy consumption changes, in relation to urban geometry, therefore relates mainly to the availability of passive solar gain or surface heat loss, and daylight in building facades. Therefore buildings that are obstructed from daylight and solar radiation have correspondingly higher energy inputs (Ratti et al 2005, 4).

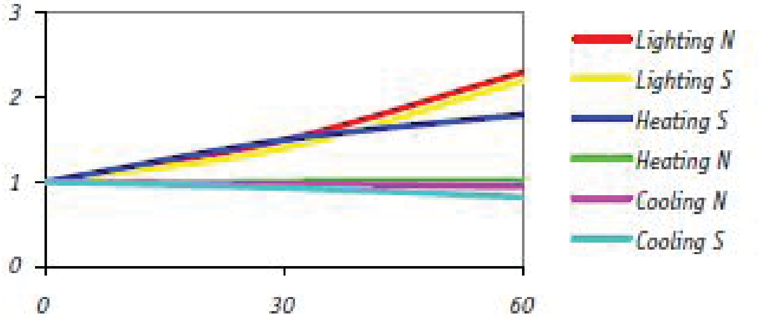


Figure 11 Energy breakdown, by building facade orientation for an office building in the UK. Note that the heating in the south facade (blue line) increases, as the UHA increases, reflecting the deprivation of passive solar gain. Lighting energy is highly sensitive to the increase of the UHA.

Comprehensive energy load analysis demonstrate that heating loads are not as highly impacted as much as lighting in dense urban contexts. Thus the increasing the compactness of the street grid reduce energy efficiency, primarily by reducing the building envelope exposed to solar gain and daylighting. This in part is because of recent energy trends; advances in insulation and envelope assemblies standards, and thus greater internal gains, have reduced energy transfer rates (Ratti et al 2005, 6).

These relationships highlight the role of neighboring geometry on building energy consumption, namely that urban geometry mainly relates to the availability of sunlight and daylight on building façades. Ratti et al observes that "...highly-obstructed urban areas are deprived of useful daylight and solar gains, thus necessitating generally higher energy inputs," (Ratti et al 2005, 6).

There are three caveats to this statement, first given the differing energy breakdowns; this is less true for residential buildings than office buildings. Secondly, as glazed areas exhibit higher thermal conductivity than opaque walls (Hegger and Fuchs 2008, 102), the resulting thermal demand can outweigh energy reduction benefits accrued through wasteful air-conditioning or heating (Ratti et al 2005, 13). Finally even assuming well-insulated wall assemblies effectively control the overall heat transfer of a building, the relative impact of lighting and heating depends on specific climatic zones, with colder zones requiring an increased thermal load.

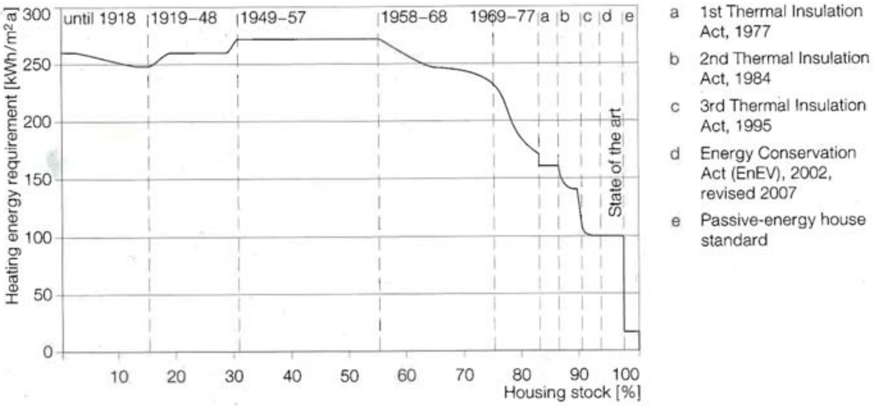


Figure 12 Heating energy requirements vs Housing stock. Heating energy demand has decreased drastically in the last 30 years with the improvements in thermal insulation standards.

However, in general the study by Ratti et al (2005) suggests that a building's surface to volume ratio in particular is too reductive to predict building energy performance because it does not account for the energy flows contributed through passive zones. Current integrated energy models, such as the Lighting and Thermal (LT) Model (Baker and Steemers 2000) is based on the idea that energy efficiency is achieved by shaping form to passive energy modulation for lighting, heating and ventilation. This is achieved by identifying the passive areas of the building and calculating energy consumption (through the LT Method), defined as the perimeter zones of the building within six meters of the facade or twice the ceiling height. In this way the LT Model "predicts the annual heating, lighting, ventilating and cooling energy use per m2, based on the simulation of a 9m by 6m by 3m module with one exposed glazed wall," (Ratti et al 2005, 12). It is thus able to simulate energy consumption, at urban scale, while accommodating more complex energy flows through the building envelope relative to March's model. For this reason Ratti et al used the LT Model to generate the energy calculation for their study.

Because the study was limited to the energy consumption consequences of urban geometry the study assumed that the various factors affecting energy consumption were independent. It assumed there was no influence between urban context, building design, efficiency of building systems and occupant behavior.

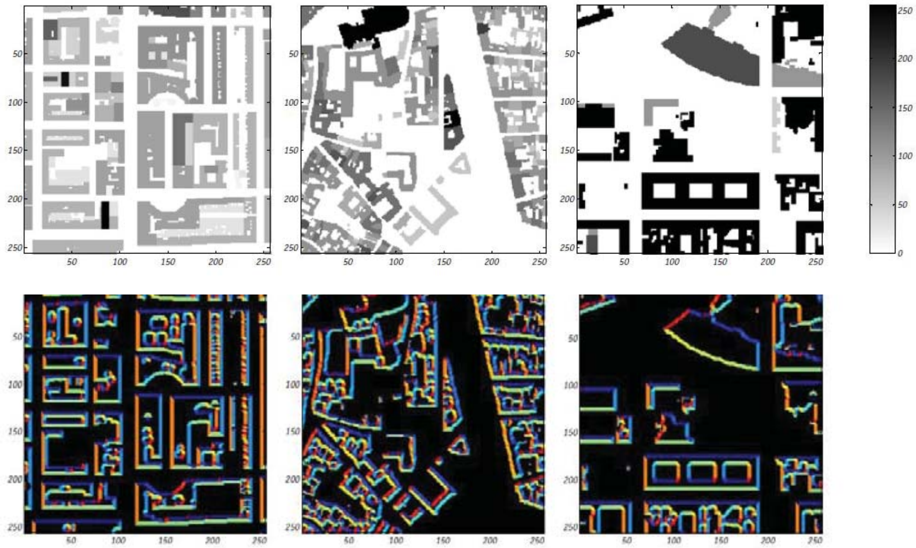


Figure 13 (top) Digital Elevation Models (DEM) of London, Toulouse and Berlin. Height is color-coded according to a grayscale gradient and (bottom) passive zones, 2nd floor (6m), color-coded according to orientation.

The study found almost a 10% difference in annual per-metre energy consumption in Toulouse and Berlin, due to urban morphology impacts. Further, it found that passive zones present a significant reduction in energy consumption (almost 50%) compared with non-passive ones. Surprisingly, even when passive zones faced small and obstructed courtyards, they lose energy through the glazed façade, but still benefit from natural light and ventilation. This suggests that heat losses through the building envelope are not the most prominent component of building energy, within the climatic context of southern UK, for the studied urban fabric samples.

Reducing building energy through urban geometry involves negotiating complex trade-offs between passive heat gain or surface heat loss, and daylighting. There are predominately two conflicting strategies for urban geometry, reducing and increasing the building envelope respectively. Measurement against three case study cities by Ratti et al (2005) has indicated that the latter strategy is more successful in achieving overall building energy reduction, within the constraints of the study.

Figure 14 Paris typologies, left to right: detached housing, high rise apartment, slab housing, regular urban block, and compact urban block.

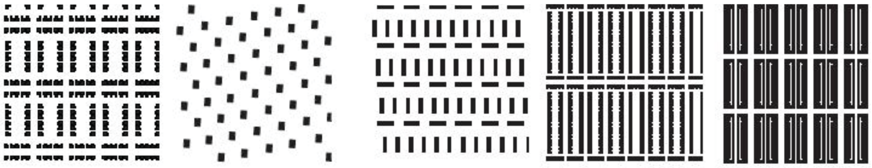


Figure 15 London typologies, left to right: detached housing, high rise apartment, slab housing, terraced housing, and compact urban block.

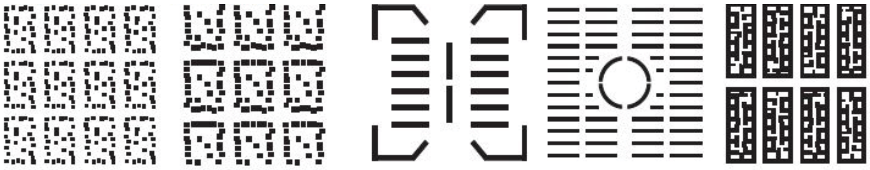
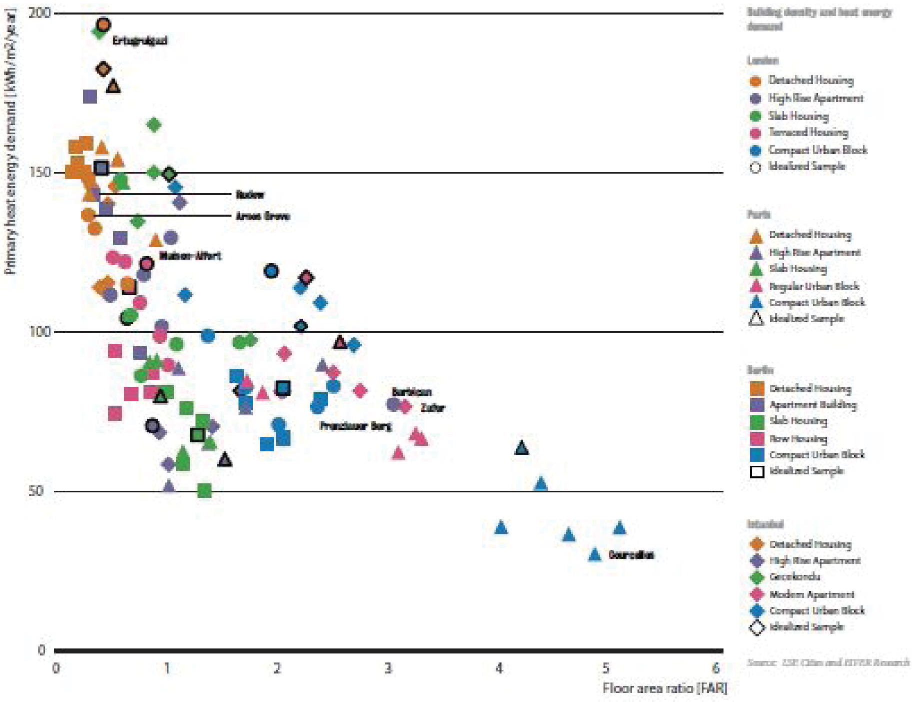


Figure 16 Berlin typologies, left to right: detached housing, apartment building, slab housing, row housing, and compact urban block.

Figure 17 Istanbul typologies, left to right: detached housing, high rise apartment, gecekondu, modern apartment, and compact urban block.



Source: LSE Cities and EIFER Research

Figure 18 Primary heat energy demand vs Floor area ratio, of the different typologies in the four cities.

3.3 ENERGY CONSUMPTION OF URBAN TYPOLOGIES

In the previous section I established the complex tradeoffs between heat demand, passive solar gain or surface heat losses, and daylighting in dense urban geometries. This section investigates these trade-offs in the context of different geometric configurations of common urban block typologies.

3.3.1 Building Typologies in Paris, London, Berlin and Istanbul

Figures 13-16 illustrates the four most prominent building typologies in Paris, London, Berlin and Istanbul. These urban typologies were modeled to computationally simulate the heat energy demand of common European urban morphologies by city, in a report by the London School of Economics (2014). The image illustrates idealized building types, derived from aerial satellite fabric samples. This was done to decontextualize the samples from their environment and thereby isolating the key shape and volume characteristics of the typology samples for the heat energy simulation (Rode et al 2014, 30). While the LSE report only examined simulated heat energy demand, it is worthwhile to summarize key points here regarding typology, heat energy demand and density. In general the study found that there was a strong negative correlation between density and heat energy demand: greater density lead to lower heat energy demand. In particular the uniqueness of the compact urban block in Paris, cleverly balances conflicting relationships between density, energy and geometry.

Relative to the other typologies the compact urban block in Paris achieves:

- High densities: FAR 4.88, the second highest of samples studied (Rode et al 2014, 11)
- Moderate heights: 6 or more floors, the greatest average building height of samples studied (Rode et al 2014, 13)
- Low heat energy demand: 29.8 kWh/m2/year, the lowest simulated heat energy demand of samples studied (Rode et al 2014, 73)

In contrast the majority of compact urban blocks in all cities displayed a heat energy demand of around 100kwh/m2/year or lower. The Parisian

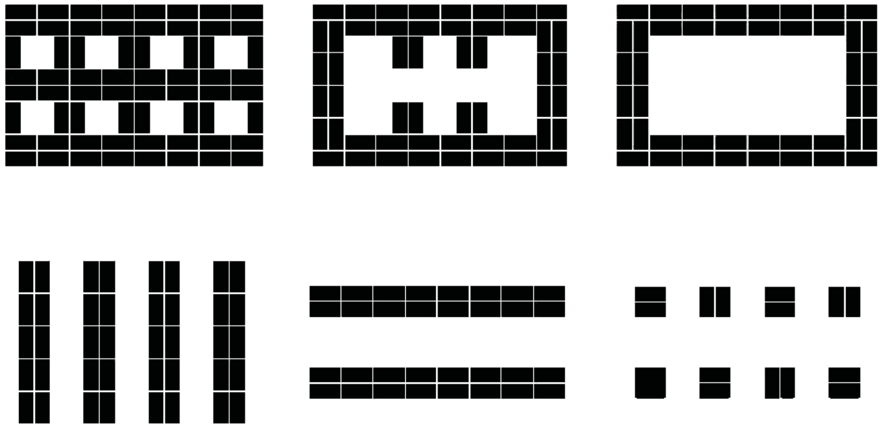


Figure 19 The six typologies studied: A, B, C, D, E and F.

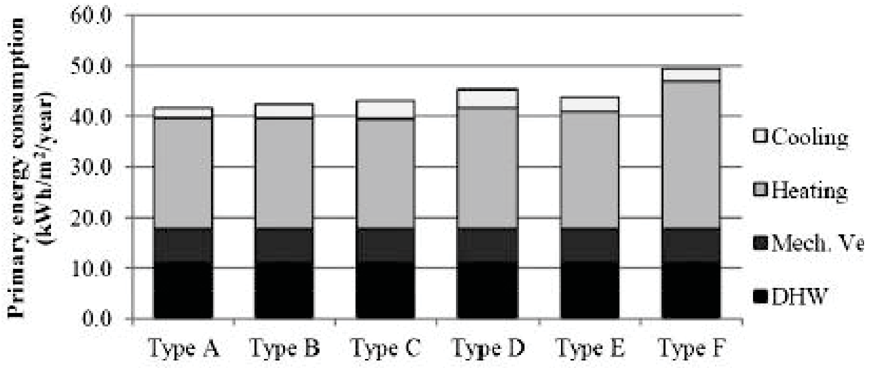


Figure 20 Primary energy consumption breakdown of the six typologies.

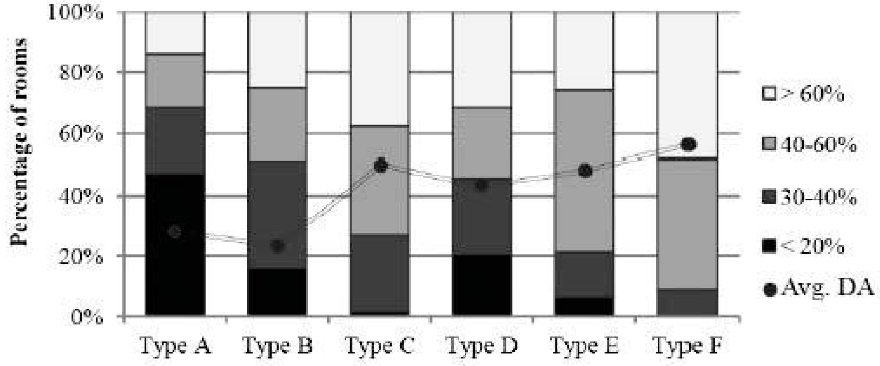


Figure 21 Daylighting Autonomy (DA) percentage of the six typologies. Poor daylighting is defined as rooms with equal to or less than 20% DA. The optimal average DA is 50%, which is achieved by Types C and E.

compact block sits on the lower-bound of surface to volume ratio, and upper-bounds of building height, and surface coverage. It is therefore in general more compact, taller and less porous than the other urban typologies. In this way, the typology can achieve high densities even while constraining its building height.

Such shape characteristics however are likely to negatively impact other energy transfers. Comparing the surface to volume ratio against FAR of the typology, the Parisian block is the only typology that increases density and reduces this ratio after the FAR of 1. In other cities, the ratio stops when the point of diminishing returns of density is reached at a FAR of 1, where the surface-to-volume becomes relatively constant. Rode et al suggests that this may because of daylighting requirements which require buildings to be more elongated as density increases to ensure a maximum building depth of 8 to 10 m in residential buildings (2014, 46). This suggests that the 'compactness' of the Paris compact urban block typology performs poorly in terms of daylighting, despite its superior conservation of heat energy.

This typology breakdown illustrates in part how Paris strikes a balance between moderate energy use, moderate density and high-livability. While the study did not perform a comprehensive energy simulation, the authors have indicated that such shape strategies have a negative effect on passive zoning, which likely mitigates the energy performance of this block.

3.3.2 Building Typologies in Northern European Cities

This section summarizes a study by Strømann-Andersen and Sattrup (2013) where building energy consumption was simulated according to urban typology within the climatic context of Copenhagen Denmark. The six typologies, typically found in Northern European cities are illustrated as ideal geometries in the adjacent figure, listed in decreasing density. Note the approximate similarity to the typologies derived in the LSE study. Overall the study found that for the different typologies with fixed densities (plot ratio of 200%), there was no great variation in yearly energy consumption (not including electrical lighting) and a quite high 15% variation in average daylight autonomy (Strømann-Andersen and Sattrup 2013, 67).

The resulting energy consumption values are illustrated in Figure 18. Note that these values do not include electrical lighting loads. Daylighting is measured separately in Figure 19. The study found that Types C and E performed the best, relativly, yielding savings of -2.3% and -3.6% respectively in relation to Type A (Strømann-Andersen and Sattrup 2013, 67). Type F performed the worst, with extremely high heating loads. The higher heating load of Type D, in contrast with Type E, despite having the same shape, highlights the importance of building orientation in absorbing useful passive solar gains.

Type A had the lowest cooling energy load and an approximately average heating energy load. This seems to correspond with Type A's "compactness", as it had the lowest exposed building envelope per unit floor area (Strømann-Andersen and Sattrup 2013, 67). Within the climatic context of Copenhagen, it seems that Type A's superior performance can be attributed to its compact geometry reducing the level of solar gains during the summer season. The increased passive areas in other typologies seeming to increase the cooling load.

However this compact geometry, as one would expect, reduced the potential for daylighting space. Interestingly, the study concluded that daylight and passive solar gain does not fall proportionally with density, and instead the exposure to sunlight depends on the design of the individual typology. For Type A, the typology with the worst average DA of approximatly 35%, slightly more than half of all rooms in Type A had a daylight autonomy (DA) metric of less than 40%. That is, over 50% of all rooms required artificial lighting over 60% of the time. This would have had the effect of increasing electrical lighting loads relative to other typologies (such as Type C) reinforcing the role of passive zones in reducing total energy consumption. Strømann-Andersen and Sattrup defined the optimal average DA as 50%, which is achieved by only two typologies: C and E. Type A and C thus varies by approximatly 15%.

3.4 PROOF-OF-CONCEPT ENERGY MODEL

Having explored the relationship between building energy and urban geometry, this section will summarize these findings in order to derive key relationships that can be used to structure the thesis proof-of-concept.

Ultimately, as Oke (1988, 133) states, there are "almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives… there is no single solution, i.e. no universally optimum geometry." This chapter attempted to break down this innate complexity by examining the research goal through three key considerations. First, net urban energy was broken down and the per capita energy efficiency achieved through public transit-oriented, mixed-development high urban densities was stressed as an overarching goal. Secondly, the role of passive energy transfers in terms of the overall building energy loads and urban geometry was explored. From this two conflicting geometric strategies have been identified for building energy efficiency: reducing or increasing the building envelope. Broadly, the former is beneficial to reducing heat and cooling energy and the latter to the availability of daylight, solar gain and natural ventilation. Passive solar gain and increased daylighting seems to yield the superior energy reduction strategy, for the studied WWR and insulation range, temperate climatic zones, and residential or office occupancies. This chapter noted that outside these caveats, such passive gains could potentially increase the energy loss associated with the building envelope, and thus increase the overall energy consumption. Thirdly, specific typologies were studied in this chapter including the compact urban block, regular urban block, and slab and detached housing. Reinforcing the findings of the previous section, the typologies with greater passive ratios corresponded with greater solar and daylighting potential and overall, less energy usage. Specifically there is a noticable difference in the performance of different typologies, at equivalent densities: a relative variation of 3.6% in yearly energy consumption (minus lighting energy) and a quite high 15% variation in average daylight autonomy (Strømann-Andersen and Sattrup 2013, 67).

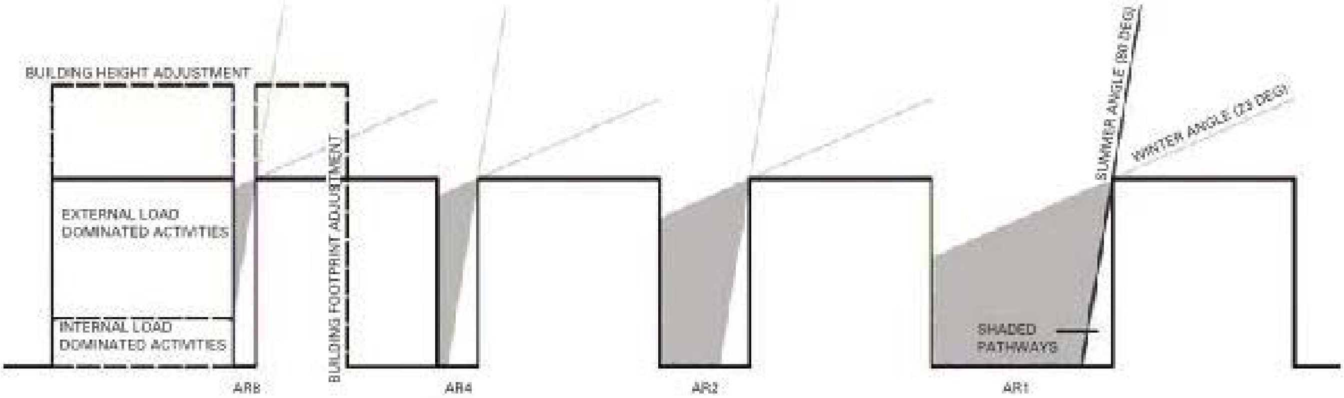


Figure 22 Solar obstruction and relationship to occupancy loads and street canyon ratio.

The nuances of the energy performance point towards the need for treating the urban fabric as an integrated energy concern: beginning with density and transit considerations, and extending to heating, lighting, ventilation and cooling. The broader goal of this research area is to develop a design system that derives urban typology according to a nuanced model of building energy consequences. There is a more general body of work in building energy dedicated to negotiating these trade-offs through building design[2] that lie outside the scope of the thesis. For the purposes of the thesis proof-of-concept however, optimizing daylighting performance, circumscribed within overarching density targets, will be used to inform the urban geometry relationships. Daylighting here is intended to behave as a rough proxy for the overall building operational energy of urban fabric, the ultimate aim stated in the broader research goal.

Daylighting is chosen as a suitable proxy here because, as Ratti et al (2005) indicated, thermal energy loads do not vary as much as lighting energy, in relation to type design - assuming the stated caveats in §§3.2.2. This suggests energy efficiency gains today can be made by targeting lighting energy demand.. In contrast to the thermal energy load, reducing the lighting load by means of daylighting presents several opportunities for architectural optimization that lower energy-usage as well as yield other

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[2] Two strategies that were investigated to inform the proof-of-concept, although ultimately discarded, included the positioning of thermal masses to buffer external and internal loads, and the optimization of the envelope boundary through an optimized window to wall ratio (WWR).

benefits.

To summarize key daylighting characteristics:

- Daylighting performance has a nonlinear relationship to increasing urban density.
- A varied lighting can be achieved even as density increases. For example courtyards enable the interior space of buildings to be lit from two sides, which helps to provide a consistent level of illumination. (Hegger and Fuchs 2008, 107). The intensity of this light will be noticeably less at the lower floors, but the percentage of the diffuse radiation - the solar radiation reaching the Earth's surface after having been scattered by atmospheric particles - increases, therefore these lower floors enjoy a more even luminance distribution (Hegger and Fuchs 2008, 107).
- Different typologies at equal density yield a relatively high variation (35% in the Strømann-Andersen and Sattrup study) of daylighting autonomy, indicating innovation in building geometry could allow for greater daylighting even while promoting density.
- Daylight reduces the electrical requirement for artificial lighting and reduces the internal heat loads caused by artificial lighting, for the same level of illumination (Hegger and Fuchs 2008, 58).
- Access to daylight and environmental variety affect human comfort and health in multiple ways: light is much more difficult, relative to heat, to reproduce in qualities and quantities that are anywhere near that of daylight (Strømann-Andersen and Sattrup 2013, 73); and natural daylight provides more comfortable lighting for human perception because it includes all the colours of the spectrum (Hegger and Fuchs 2008, 108).

These characteristics, along with the established density charactersitics, will inform how to shape the fabric typology. Specfically the proof-of-concept will drive type shape and function decisions at three scales: fabric grain, block zoning envelope, and typology.

First, the fabric grain is differentiated, geometrically and by function, in order to promote non-uniform density, and the integration of mixed-used development. This will be fufilled by increasing density around transit hubs, and demarcating mixed-use developement to take advantage of modal-transfer nodes that act as natural pedestrian catchement areas.

Secondly the zoning envelopes for the blocks are determined to reduce the overshadowing effects of density. The local zoning strategy according to solar zoning here can be integrated with the solar access needs of the mixed-use occupancy load profiles. As such the respective load profiles can exploit differing energy requirements and spatial adjacencies in order to share energy or buffer peak loads.

Lastly, the typology shape is then refined in order to increase daylight. This chapter has established how building performance is a function of the fabric grain, building ‘compactness’, passive-zone ratio, the urban canyon, terracing and urban height angles. The proof-of-concept will control these geometries by defining the following shape parameters: block dimension, terracing angle, building height, street depth, courtyard shape and plan depth.

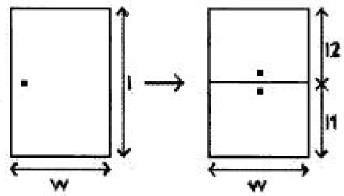
In this way the daylighting and density targets can be coordinated to satisfy the current goal, while laying the foundation for the broader research goal. Of course without an integrated energy simulation it is impossible to quantify the overall energy impact of increased daylighting. This is outside the scope of the thesis and will be left for further study. However, Strømann-Andersen and Sattrup (2013, 67) established that type design with equivalent densities can vary interior DA by 15%. If the proof-of-concept can control even half of this variation, it yields significant energy savings over the course of the 50 to 100 year lifetime of groups of buildings.

4 Design System

The thesis goal is to develop a proof-of-concept that generates and optimizes city fabric according to the conflicting objectives of building daylighting potential and urban densification. The previous chapter has established the nonlinear correlation between typology shape, passive solar gains and daylighting, and identified specific morphology strategies that will be used to inform the design system proof-of-concept. The research contribution of the thesis thus lies in the design system introduced here. Specifically the synthesis of existing procedural form generation, simulation and optimization methods as a Grasshopper3D plug-in, geared towards low-energy, high-density urban design solutions.

Radford and Gero (1980) define three computational design methods: generation, simulation and optimization. These three methods are not discrete entities: optimization subsumes form generation and simulation; simulation repeated systematically can provide a weighted solution space similar to optimization; and optimization emulates simulation if the feasible solution space is constrained to a single solution. Digital design efforts traditionally involve some combination of these three computational models. Key combinations include the Generative Performative Design (GPD) paradigm, which simulates performance criteria to drive form generation; or the Integrated Design paradigm which takes the GPD and further integrates multiple building systems.

The thesis design system integrates the three computational design methods into four sections. First, the form generator consisting of a shape grammar to produce residential morphology. Secondly the environmental and material simulation methods used to derive solar illuminance data. Thirdly a simulated network of city relationships used to derive density targets. The last section consists of an optimization platform to identify the typology solutions that best achieve the thesis objectives. This chapter will introduce the design system proof-of-concept through these four sections, each of which consists of multiple Python scripts packaged as Grasshopper3D components.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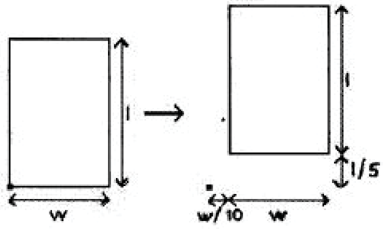
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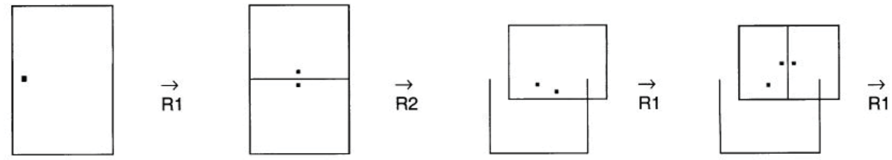
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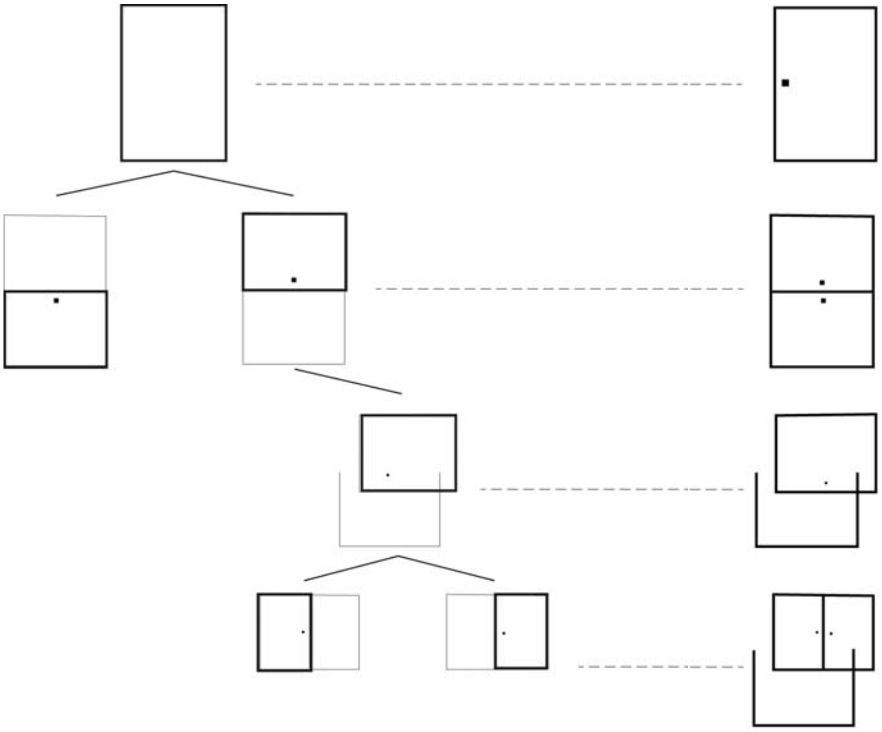


4.1 FORM GENERATION

Of the dedicated city modeling software surveyed in §2.1.2 CityMaker (Beirão, 2012) and CityEngine (Parish and Müller, 2001) are based on grammar-based generative systems. This, in part, is because grammars are ideal methods to concisely encode typology definitions (Mitchell 1990, 138). Typology is defined here as building designs that are historically derived over time through sustained human contact. Types therefore act as efficient and already tested design solutions, offering an underlying social agreement on ways of living, building and behaving in society (Beirão 2012, 36). In architectural theory some authors, such as Aldo Rossi in 'L'architettura della citta' (1966) emphasize the role of urban form developed through the local application of spatial and social relations of built typology. Mitchell (1990) in 'The Logic of Architecture: Design, Computation and Cognition' details the application of grammars to derive classic building typologies. As such this thesis will develope a grammar-based form generator to derive typologies.

The use of typology grammars allows the designer to structure protocols or formulas that can negotiate fluctuating city conditions while still producing coherent, architecturally-correct design compositions. The systematic application of possible form combinations defines the 'solution space' of the design:

> *If a designer designs the rules of a system, for instance, a housing system or an urban system, rather than defining a single design they are, in fact, proposing a system of solutions corresponding to the solution space defined by the grammar.*
>
> Beirão 2012, 47

Therefore, in the context of the thesis, given the set of all possible urban typologies, the shape grammar method specifies the subset of shape transformations that satisfy its grammar rules. These grammars consisting of dimensional constraints, equalities and inequalities in turn define architecturally-correct building types. This rule-based application thus allows the design system to model a broad solution space using a relatively small set of statistical and geographic inputs.

Figure 23 (top) Shape grammar example from José Duarte's PhD thesis.

Figure 24 (bottom) Hypothetical derivation tree after three levels of recursion, by author.

This section introduces the form generation engine based on a set parametric shape grammar. It is important to note that the form generator script is not a strict shape grammar, for one thing it also has attributes of L-systems, but is based on the shape grammar production system. First set parametric shape grammars will be defined, secondly the basic structure of the written code is outlined, and finally this section will demonstrate why shape grammars are an ideal method to generate urban geometry.

4.1.1 Set Parametric Shape Grammar

Shape grammar is an algorithmic approach to design pioneered by George Stiny and James Gips (1972). Shape grammars specify the incremental development of designs by recursively applying shape rules to defined geometries. As these grammars take the form of geometric 'rules', the use of shape grammars as a form generator allows the architect to encode coherent compositions while generating diverse design solutions. This property of structuring the composition of designs in terms of the spatial relations defined between self-similar sub-shapes or sub-designs is suited to modeling the fractal-like forms of cities, as well as building typologies.

The grammar refers to the set of rules that define the conditions to identify and apply corresponding transformations to a shape module. The grammar - a set of production rules for geometry - therefore defines the syntax of the formal design language. By describing how to form grammatically correct combinations from the language's body of text, shape grammars can generate 2- and 3-dimensional languages. It is important to note that a grammar does not describe the meaning of the combinations or what can be done with them in various contexts. This needs to be handled by another method or system.

Figure 23 represents a set of simple shape rules, from Duarte (2001, 61) for a rectangle shape. Since Stiny and Gip's seminal paper, shape grammar studies have expanded to include other variations on the basic shape grammar approach (Duarte, 61, 2001). The grammar presented in this work is a set, parametric shape grammar. Set grammars are grammars that lack emergence —the ability for the shape grammar rules to recognize and apply rules to shapes that were not predefined, but ‘emerge’ in computation (Duarte 2001, 61). In parametric shape grammars such rules are parameterized so that each rule represents a set of rules (Duarte 2001, 61).

Parametric shape grammars can be represented as an ordered sequence of five elements (S, L, T, G, I), where:

> S = set of shape rules, i.e. A⟶B (when you find A, replace by shape B)
> L = set of labels used to control computations
> T = set of unary or binary transformations (scaling, split, rotation, push) under which rules apply
> G = set of functions that assign values to parameters in rules, deriving specific rules
> I = initial shape to which the first rule applies to start a computation

The elements of the 5-tuple correspond to the computational structure of the thesis shape grammar script. The primary purpose of the script is to derive shapes by applying S shape rules consisting of T, transformations to an initial shape I. Through recursive application to the resulting shapes, a design is incrementally derived according to the grammar, until a set of terminal shapes are produced and the script is halted.

Secondarily, applying G functions to T determine the conditions under which the left-hand side of the rule can be matched to a shape in the design during the rule application. Additionally the set of labels, L supply contextual information not provided by the shapes themselves such as how where and when a shape rule may be applied to the design. Figure 24 represents the derived rule after three levels of recursion.

4.1.2 Data Structure

In the python script written for the thesis, there are three main classes for the shape grammar: Tree, Grammar and Shape. The Shape class contains an instance of the geometry, and multiple methods for transformations, based on the (G) parameters from input that are applied to the transformations.

The Grammar method contains a method for labeling the shape, and then generates a rule based on that rule. The Shape method is nested within the Grammar method, so that the Grammar method calls the geometry to determine the labeling, then generates rules, then applies the rules to the geometry and returns the child geometries.

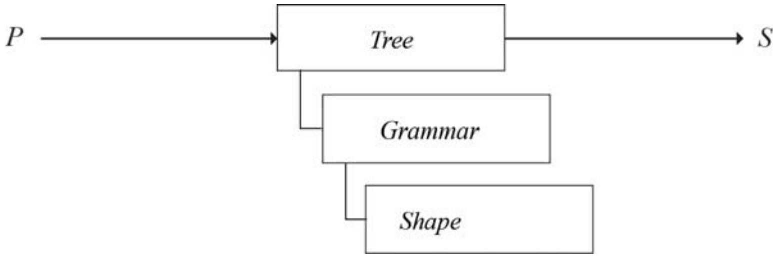


Figure 25 Nested Tree, Grammar and Shape Classes.

The Tree class is responsible for the shape grammar derivation process: the sequential replacement process of A⟶B. I have chosen a binary data tree to generate the shape grammar data. In this context it is called a derivation-tree, whose internal nodes are non-terminal shapes and the leaf nodes are terminal shapes. The tree class contains an instance of the Grammar class (which contains an instance of the Shape class), as represented in Figure 24. The tree structure calls the Grammar methods, which generate labels, rules that are in turn applied to the Shape geometry, using Shape transformation methods. The resulting shapes are stored as child nodes in the binary data tree, thus arranging the derived shapes in a hierarchical order. The process is then repeated on each child.

4.1.3 Object Hierarchy

These Shape and Grammar classes are structured as parent child objects. Two child classes are introduced. First a Shape3D child class, extending generic geometric methods from the parent Shape class. Secondly a Shape2D child class is also extended from the parent Shape class. Both child classes will contain methods specific to 2D or 3D unary and binary transformations, respectively. Additionally the Shape3D object is composed of Shape2D objects, that is, every face in a Shape3D object is built from Shape2D objects.

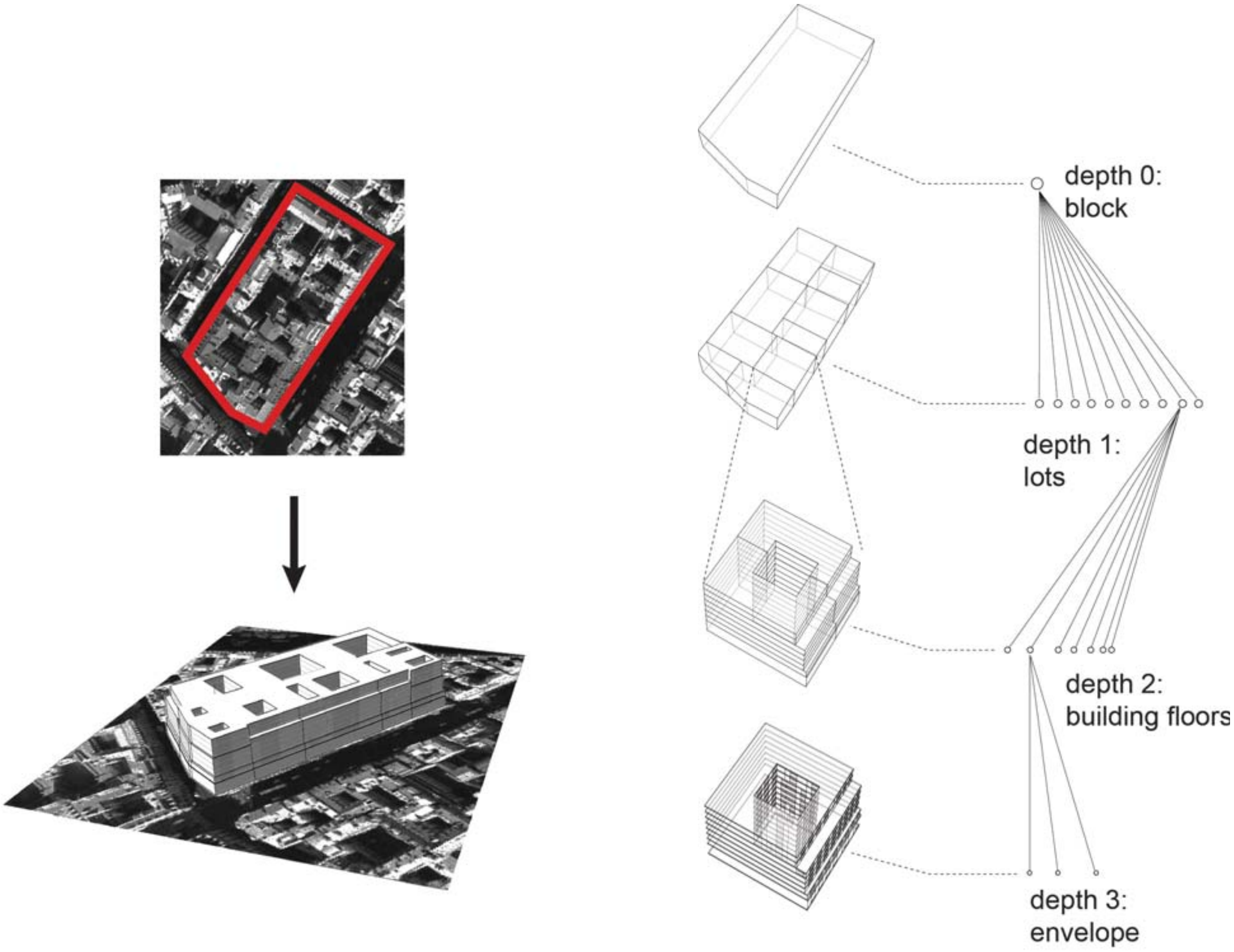


Figure 26 Paris compact urban block using the thesis shape grammar.

A similar parent child relationship is created for the Grammar class, with two child grammar objects: Building_Grammar and Facade_Grammar. The derivation process is handled by the same Tree class. In order to generate, for example, a compact urban block from Paris, the building mass would be generated by recursively splitting the initial block to define building lots, building floors and the envelope. Figure 26 illustrates these nested geometries, as well as indicates their depth within the derivation tree. This process is guided by labels, which terminate when the dimensions of the geometry element corresponds to specified user data. §4.2 will detail the process by which the Facade shape grammar script generates a labeled envelope assembly, and integrated with environmental simulation methods to derive illumination data. §4.3 will illustrate how the labels create the design system's "universe of discourse" which will be used to inform the system's decision-making.

4.1.4 Typologies through Shape Grammars

The shape grammar introduced here generates urban geometry by parsing and applying the grammar rules to geometric transformations in a hierarchical manner to generate architecturally-correct geometries. This corresponds with the application of grammars to specify a way of decomposing shapes into parts of recognizable typologies — via the assignment of syntactic structure to instances — such as 'lot' or 'floor' in Figure 26. These parts thus comprise a 'kit of parts', the combination of which (defined by the grammar) defines the 'solution space' of the design. The adjacent figure illustrates a hypothetical solution space for urban typologies, derived through different combinations of type rules. Each rule is parameterized to accommodate varying constraints defined by the user or environment. In this case there are 7 solar access rules, 4 courtyard subdivision rules and 2 lot massing rules which gives us 56 (7 × 4 × 2) possible combinations of the rules. This gives us a solution space of 56 massing typologies.

As an aside, it is important to note that the derivation tree hierarchy roughly coincides to the order of permanence and scale of urban planning, from the street grid, block, plot, building, and finally to the apartment. This is important for two reasons. First this is closely associated with the legal framework of planning and ownership in liberal economies (Strømann-Andersen and Sattrup 2013, 60). Thus, in terms of the participatory design process, the proof-of-concept accommodates the different urban stakeholders by clearly partitioning the user-inputs and corresponding spatial and performance outputs. Secondly, in terms of net urban energy, the slowest changing spatial geometries, such as the fabric which encompasses the street grid and block), affects the performance of individual buildings throughout their lifetime (Strømann-Andersen and Sattrup 2013, 60). For this reason coordinating the fabric typology should be considerable over

the lifetime of the building. In fact this cascading spatial and performance impact is a key justification for the priority Habraken, in his urban design regulations and zoning work (via SAR73), places on the form of urban tissue, over the traditional emphasis on function (Bosma et al 2000, 254).

The thesis shape grammar thus encodes and expresses typologies through parametric, grammar rules. The system is thus capable of producing architecturally-correct building typologies, corresponding to key legal and performance hierarchies, while maintaining the flexibility to accommodate complex environmental conditions. Integration with simulated building energy subsystems, and the application of these types at broader scale to produce structured design solutions for low-energy, high-density urban fabric is detailed in the following two sections.

Figure 27 Hypothetical urban type solution space.

4.2 SIMULATION

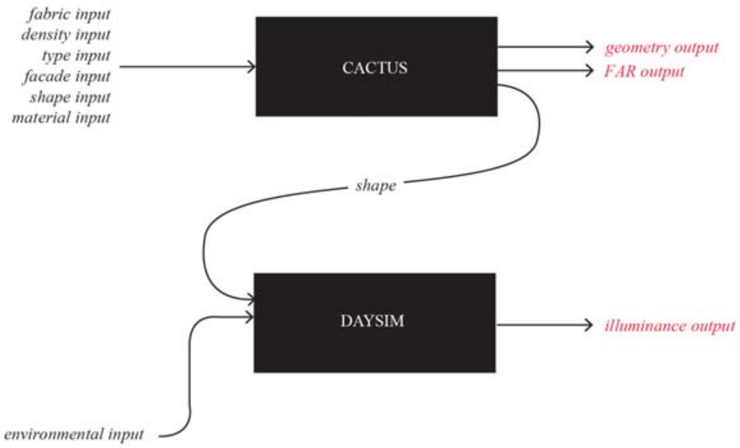


Figure 28 Thesis form generator and the DAYSIM simulation engine.

This section will investigate the simulation of daylit spaces, solar angles and identify the necessary information for its procedural generation. The goal here will be to define the minimal data required to derive reasonably accurate solar and daylighting metrics, useful in an urban context at neighborhood scales. First the DAYSIM software (via the DIVA plug-in) for daylighting simulation will be introduced relative to other state-of-the-art performance simulation computer programs. Then the daylighting metrics are defined and an appropriate one for the stated research goal is selected. Thirdly a process for modeling daylight performance is outlined and the inputs and settings to be used for the shape-grammar engine is illustrated. Finally the solar zoning envelope and its integration in the proof-of-concept will be briefly summarized.

4.2.1 Tools and Methods

Simulation is defined as a technique for representing the behavior of a system by mathematically modeling the basic components of a system (Fasoulaki 2008, 22). By describing the system's physical behavior, including all variables and constraints that describe the system, designers are able to observe the performance impact of the design. Traditionally designers have relied on 'rules of thumbs' to account for thermal, lighting or energy performance. Deriving metrics from computational simulation is meant to combat such imprecise or incorrectly applied heuristics.

In this thesis, daylighting performance will be simulated and rendered through the DAYSIM program. DAYSIM is a daylighting simulation and analysis software that models the annual amount of daylight in and around buildings (Reinhart and Weinold 2011, 2202). DAYSIM is based on Radiance a powerful ray tracing program. Ray tracing is a calculation technique where the individual light rays are tracked as they are reflected from the building surfaces. In this way the lighting data for the interior space is produced (Hausladen et al 2005, 187). Compared to the state-of-art tools that simulate daylighting, such as EnergyPlus and Ecotect, DAYSIM is slower but more accurately represents the behavior of light (Reinhart and Weinold 2011, 2202). DAYSIM's solar calculations take into account the impact of neighboring geometry, a key factor for the broader research goal. The design system will run DAYSIM by means of the Design Iterate Validate Adapt (DIVA) environmental analysis plug-in for Rhinoceros3D and Grasshopper3D. DAYSIM, via DIVA, thus offers a good compromise between realism and speed available for the Grasshopper3D environment.

4.2.2 Performance Metrics

Figure 29 Daylight Autonomy visualization of a simple, side-lit space with an unshaded, south-facing facade.

Reinhart and Wienold (2011) defines daylighting as:

> *[A] space that is primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling.*
>
> Reinhart and Wienold 2011, 411.

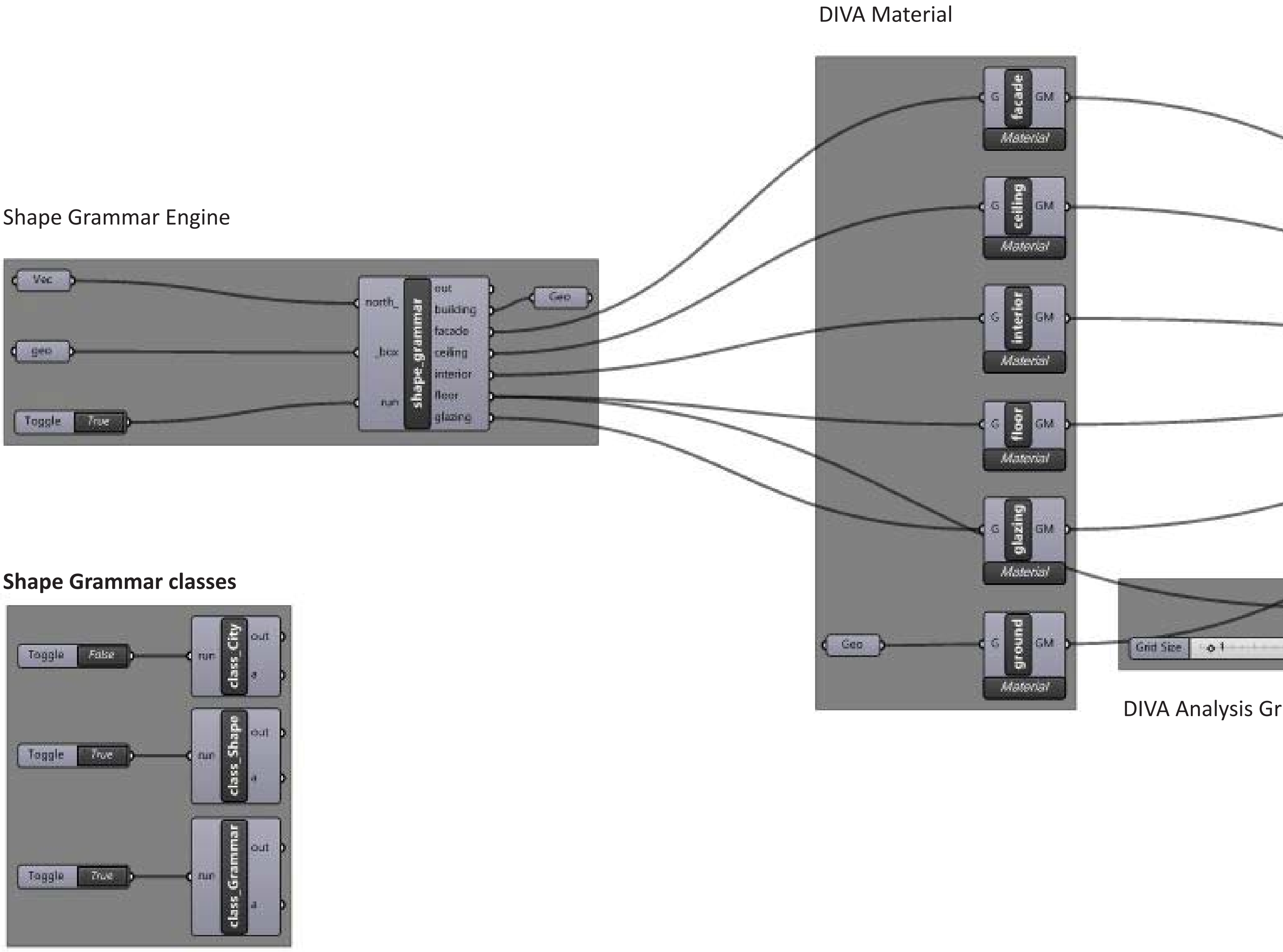
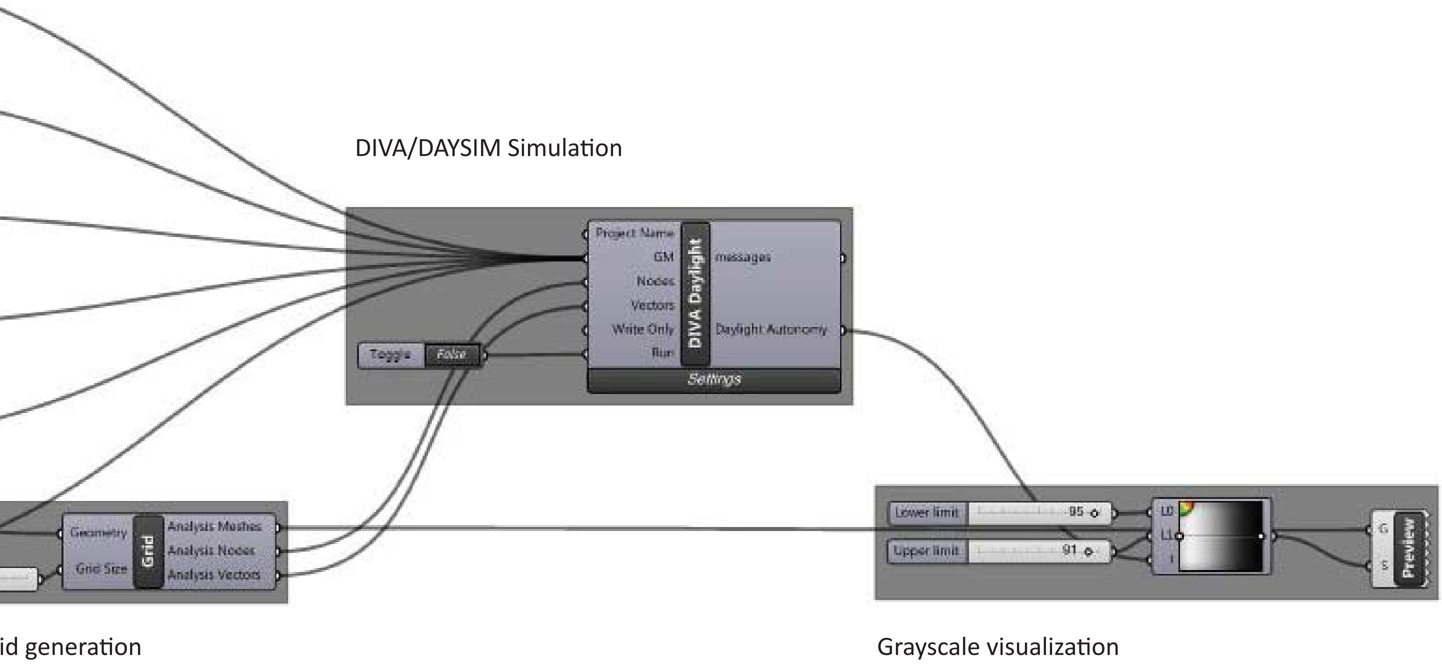


Figure 30 Annotated GH script of envelope generation and daylighting simulation.

This definition suggests three performance categories for daylight: availability, visual comfort and thermal loads. This subsection will test daylight availability, which is quantified through a measure of a space's illuminance value. Illuminance is defined as the per unit area total luminous flux that strikes a certain surface. Luminous flux describes the entire light output of a light source, and is a measure of the human-perceived power of light quantified by lumens (lm). A space's illuminance value is thus the light power per square meter, as perceived by a human being, and is measured by the unit lux (lx) (Hegger and Fuchs 2008, 58). An illuminance profile is used to quantify the annual amount of daylight in a space. This is calculated by simulating sub-daily interior illuminance or luminances due to daylight, generated from a local climate file (Reinhart and Jakubiec 2010, 412).



The brightness of daylight varies from 0 lx in the night to approximatly 100, 000 lx on a sunny day (Hegger and Fuchs 2008, 60). Target illuminance levels are derived from the most difficult visual task that is to be expected - for example 300 to 500 lx is defined as appropriate for office work. There are no defined benchmarks for illuminance values in residential buildings. (Hegger and Fuchs 2008, 58).

However, there are various metrics to intuitively represent the annual illuminance data for design purposes. This subsection will focus on daylight autonomy (DA), as it is the metric used by the Strømann-Andersen and Sattrup (2013) in their daylighting study of urban typology. To reiterate: DA is defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by interior daylight alone. A unit area is thus considered 'daylit' based on the amount of time it meets or exceeds the minimum illuminance threshold.

This is represented as a grayscale gradient dividing the space into a 'daylit' and a 'partially daylit' areas. The grayscale is set to saturate to white for DA values above 48%. These represent points in space that meet or exceed the minimum illuminance threshold, 48% of the total occupied hours in a year. Figure 27 represents the plan view of a simple, side-lit space with an unshaded, south-facing facade. The DA values for this space show that approximately three quarters of the room adjacent to the window are daylit.

4.2.3 Process Breakdown

Here I will briefly define the inputs for the DA metric, with the intention of deriving them from the shape grammar engine. The daylight autonomy calculation requires four inputs: context, analysis points, space-usage simulation and a sky model. These four inputs are accommodated by the DIVA 'Daylighting' component.

The context geometry consists of all geometry that will effect the lighting condition of the interior space. Technically this means a daylighting simulation, at minimum, requires the interior geometries and glazing. However including the outside facade and ground surfaces will allow

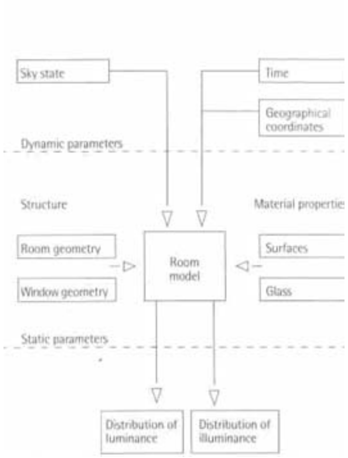
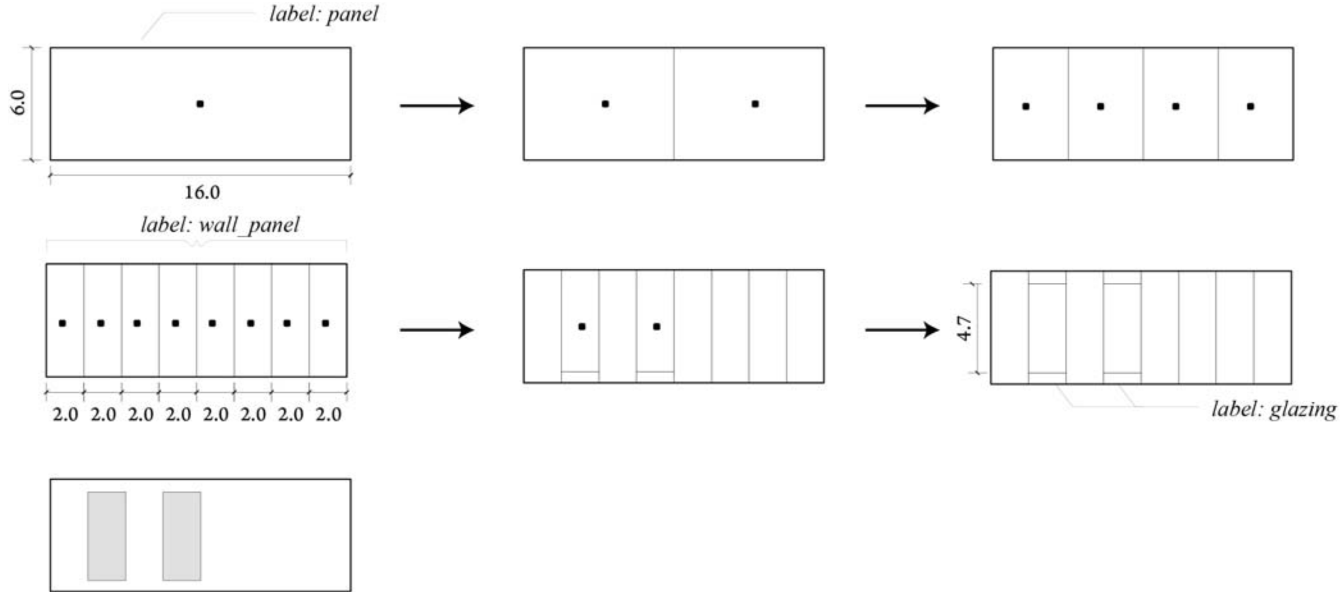
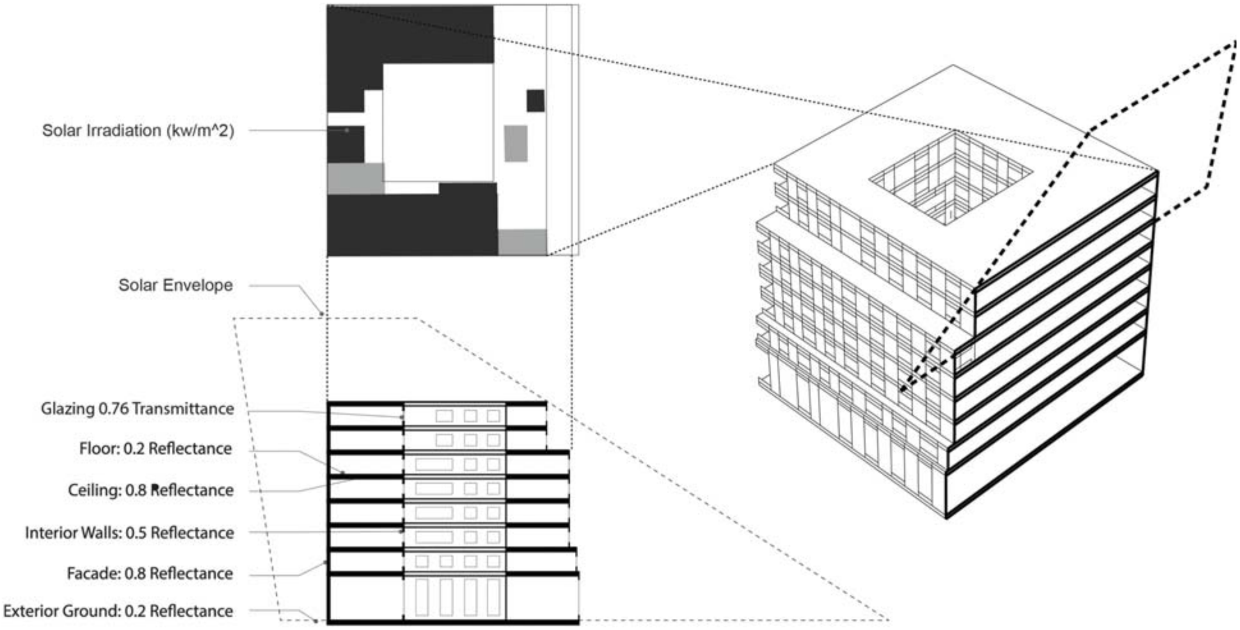


Figure 31 Flow chart diagram of inputs and outputs for DAYSIM simulation.

Figure 32 (right top) Recursive generation of building facade. Note the sequential labeling.

Figure 33 (right bottom) Building envelope geometry and material data for daylighting simulation.





the simulation to account for the reflected light and shading from these geometries, an important criteria identified in §3.3.2. For simulation, the context data needs to incorporate material data, such as reflectance or transmittance values (see Figure 31), through DIVA's 'Material' component. The analysis points are derived from the 'Grid' component, which subdivides and offsets the analysis surface into a grid of points. Fig 31 illustrates the data flow for simulation. The space usage input (a simulation of user occupancys schedules) and sky model (from weather and location data) are derived from respective data files, and can be selected from the 'Daylighting' component itself.

It is important to note that DAYSIM through DIVA4Rhino allows other daylighting metrics to be created. In particular, modifying the inputs generates hourly schedules that determine the status of shading devices such as venetian blinds and electric lighting requirements for a space. This electrical lighting schedule, defines the periods of the day when electric lighting is used. It serves as an additional input parameter used to make accurate lighting load calculations and in turn deriving annual energy usage values for heating, lighting and cooling using the EnergyPlus load calculation tool (surveyed in §2.2.1). Using DAYSIM to generate the lighting schedule allows for a more accurate lighting load calculation than using the native EnergyPlus lighting load simulation. Daylighting metrics however offer a reasonable proxy for artificial light requriments.

4.2.4 Facade Shape Grammar

According to Granadeiro et al (2012), the design variables of the shape grammar must correspond to the simulation model. Thus for their energy simulation of single-family residential houses, they modified their shape grammar program to calculate the perimeter of each floor, define each floor as a single thermal zone, and identify geometries as walls, windows, floors and roofs. This information was then compiled to a data structure of an EnergyPlus file and used to run the energy simulation.

This roughly corresponds to the thesis simulation methodology. For the DIVA daylighting program, the simulation will require a set of geometries corresponding to a simplified building envelope: walls, glazing, floors and roofs. Each of these geometries must in turn correspond to material data. The thesis shape grammar script therefore generates a building mass, and can easily generate corresponding ceiling and roof geometries.

It is worthwhile to go into further detail about the generation of the facade system, consisting of wall panels, glazing and interior walls. A notable precedent for generating facade compositions with grammar-like engines is Müller and Parish's CityEngine (2001). In CityEngine, the 3D modeling of architectural buildings turn 3D meshes into a set of 2D faces and allows designers to efficiently go from mass modeling to facade modeling (Parish and Müller 2001, 3). Shape grammars are suited for facades design as they show several layers of partitions (floors, windows, balconies) (Teboul 2011, 31) that must be positioned locally relative to one another.

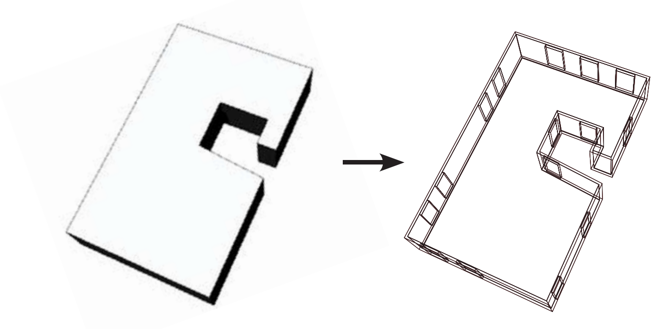


Figure 34 : Initial built and mass and resulting facade geometries.

The facade system is therefore generated in a similar fashion, that is by recursively splitting the inital mass faces to define window elements and wall panels. This process is guided by the labels, which terminate when the dimensions of the envelope geometries correspond to standard construction data provided by manufacturers. The resulting labeled geometries are then transferred from the shape grammar engine to the DIVA 'Material' components to append further material data.

4.2.5 Test

Briefly, this subsection will conclude by testing the shape grammar and DA metric tested on a single prototype building. A single-story building mass, with a small, U-shaped lightwell was modeled in Rhino3D. The south and north facades are unobstructed. The prototype building is kept small in order to reduce simulation time, but geometrically complex (nonorthogonal and concave) in order to test the Facade Shape Grammar method. The intention here will be to test the appropriateness of the daylighting simulation method for an urban context. The criteria for appropriateness being speed, accuracy and the usefulness for urban analysis.

The annotated grasshopper script for the overall process is shown in Figure 30. The overall process consists of setting the massing geometry as an input for the shape grammar component. The shape grammar program defined the building as a mass, labeled as a low-rise building, then used the derivation tree to recursively subdivide the wall faces of the building, according to a preset glazing-wall ratio. Figure 34 shows the initial massing geometry and resulting facade division. The resulting building envelope elements are set as inputs for DIVA Material and Grid components, which in turn are set as inputs for the DIVA Daylighting component. The resulting DA metrics are rendered by the grayscale visualization in Figure 35.

They represent the percentage of hours in a year, that match or exceed the minimum illuminance threshold. The grayscale lower-bound is set to black for DA values below 50%. Given that DA value of 50 is considered 'daylit', the portion of the space in black is thus 'partially daylit'. Figure 32 thus shows that almost all the space is daylit more than 50% of the time, with exceptions along the perimeter between windows. This is a function of the small size of the test massing.

4.2.6 Evaluation

The metric's 'appropriateness' for urban analysis is based on four criteria: speed, accuracy and usefulness for urban analysis. The prototype building here was modeled and it's simulation rendered according to standard best practices as recommened by DAYSIM. The purpose of this section will be to understand which practices are best to be used or modified in an urban context and scale.

The test model used a 1m x 1m grid, which was found to provide a reasonable grayscale 'grain' for analysis scale. However the render time was high taking approximately one hour. Assuming daylighting simulation scales linearly, a small neighborhood block could take upwards of 10 hours[1]. It is

---

[1] The area of the building is approximately 250 m2, so there are roughly 250 analysis points. A regular lot is 12m x 40m, with 80% coverage gives approximately 380 m2.. If we define a neighborhood block as six buildings that gives us a total of around 2300 m2. or roughly a magnitude greater in time, than a single building.

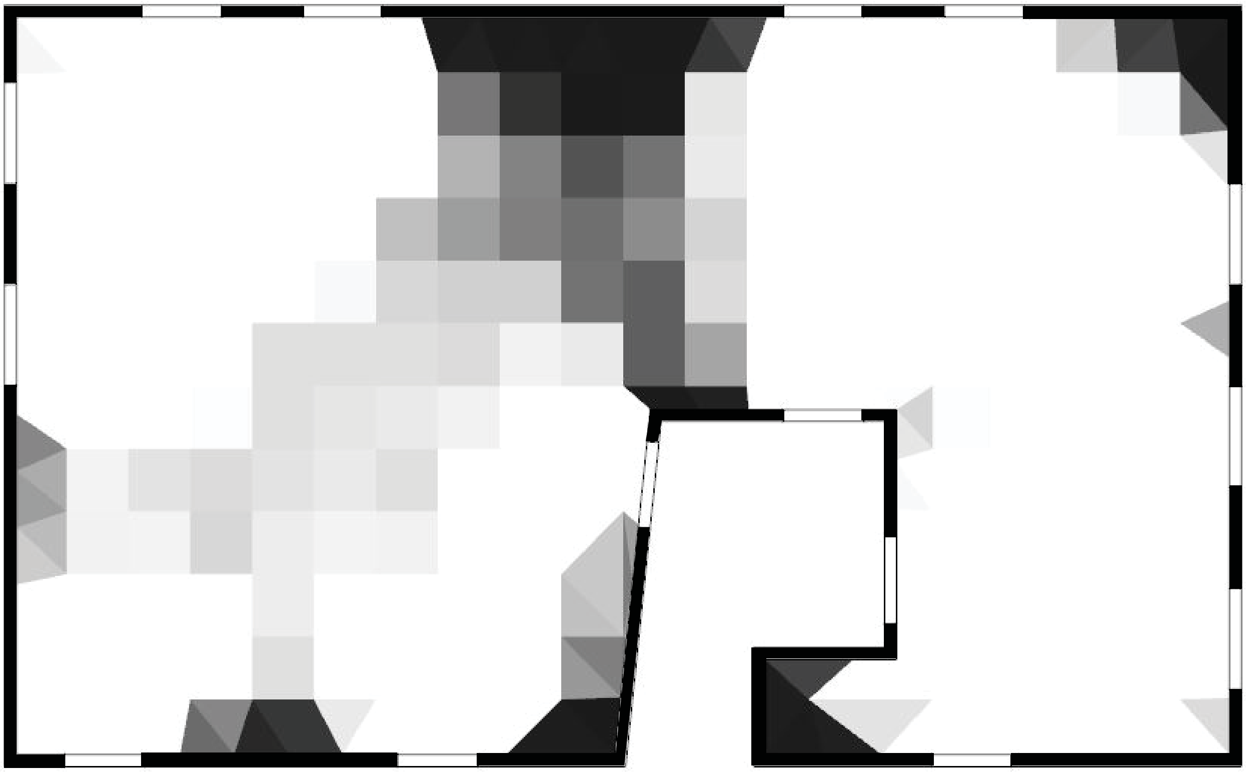


Figure 35 Resulting Daylight Autonomy render. The greyscale is set to saturate to black (the lower-bound) for values below 50%.

thus not suitable for the proof-of-concept. Therefore I will use illuminace “point-in-time” calculations, which is significantly faster. Such calculations measure the light levels at a specific date and time. The proof-of-concept will set the simulation period to occur during the location’s summer extreme week.

4.2.7 Solar Zoning Envelope

The building zoning envelope in the proof-of-concept is achieved according to solar access theory pioneered by Knowles (1981). Knowles’ solar envelope is used to ensure that its adjacent neighbors (defined as anything outside of a chosen boundary curve) will receive a specified minimum hours of direct solar access for each day in a specified month range of the year. Any geometry built within the solar envelope boundaries will therefore not cast any shadow on adjacent property for the given hour and month range. As surveyed in §2.2.2, I developed two solar zoning tools, based on Knowles

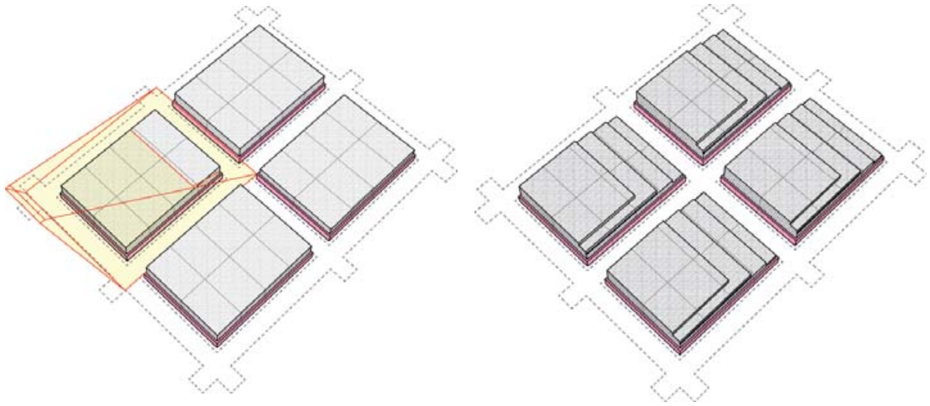


Figure 36 Terracing residential occupancies, while maintaining density, according to solar obstruction angles. The solar envelope here guarentees one hour of solar access during the summer season to the residential massing. The commercial units (in pink) with higher internal loads are shaded.

work, that is currently included in the open-source Ladybug plug-in for Grasshopper3D.

§3.4 put forward a model of vertically differentiated mixed-use development where solar terracing is used to guarantee occupancy-specific periods of solar access (Knowles 1981, 60). This is illustrated in the above figure, where using the Ladybug solar envelope the calculation of the solar envelope is used to demarcate the occupancy types at which neighboring geometry casts shadows, for a specified time-range. Thus the residential and commercial occupancies are mapped with differing solar access potential in relation to their corresponding load demands. In this way the daylighting availability of the overall fabric massing can be controlled, specific to the local solar angles and typology function.

4.3 DECISION-MAKING

The shape grammar provides the set of rules to parse and generate building typologies. It is thus an ideal vehicle to generate architecturally correct building geometry. However, as Beirão (2012, 72-73) points out, urban transformation is not only provided by shape transformations but also by political, social and territorial contexts which are informed by factors beyond simple relationships between shapes. This means the shape grammar alone cannot ascribe “meaning” to the typologies in order to apply them within a broader urban context. To achieve this the thesis design system requires a way of expressing and encoding the relations amongst urban conditions. This is handled by the decision-making component of the thesis design system, based on work by Batty (2005): the algorithmic simulation of urban dynamics developed through agent-based and cellular automata models.

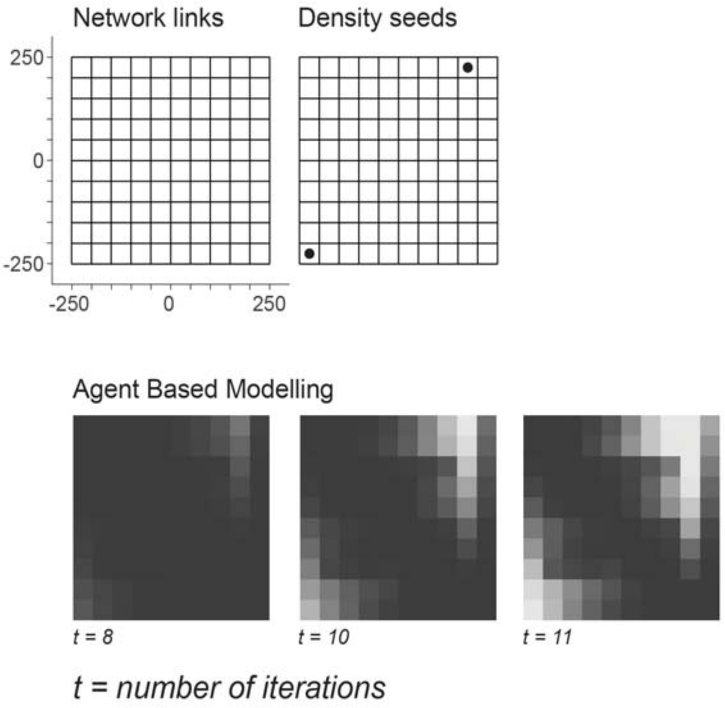
4.3.1 Urban Simulation

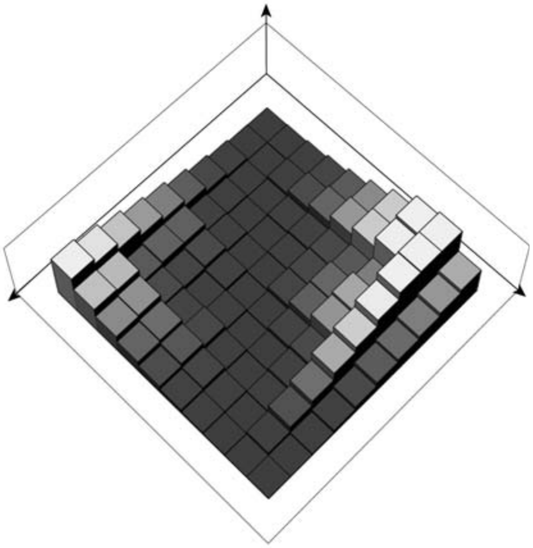
Within the context of tools to support urban design, in lieu of user participation computational simulation provide a simple method of modeling complex urban behaviour:

> *The use of simulation processes can enhance awareness of phenomena that may influence the evolution of certain urban contexts and provide insights into how alternative solutions may evolve over time or according to specific changing conditions*
>
> Beirão 2012, 27.

Within this domain, Batty and Portugali have pioneered various methods of simulating the evolution of urban contexts. According to Beirão (2012, 27) Portugali cites the non-linear behaviour of cities to explain why certain urban phenomena cannot be modelled correctly. This points to the built-in epistemological gap regarding such tools: can a system ever be developed that systematizes all the pieces in an optimal relationship? While acknowledging the futility of modelling accurate urban behaviour, here it is used to map typology application within a rudimentary idea of actual urban constraints and goals.

The thesis semantic network is based on Batty's computational models that abstract urban development as a function of positive feedback loops that disproportionally amplifies the initial conditions of the site (Batty 2005, 26). Specifically, the shape grammar engine will allocate built form according to land development values, converted to FAR values simulated by Batty's algorithm for landscape watershed dynamics. This work is based on my prior simulation work in Processing. In this program, sediment erosion over time is simulated via the gradual erosion of terrain as water 'agents' interacts over time in complex ways with eachother and the landscape 'cells'.





```
def distribute_flow(self,dpt):
    #distribute_flow: index -> eroded ht
    #purpose: new ht = uplift - erodibility * sqrt(flow area) * slope
    nei_dpt = dpt.low_N
    dpt.slope = abs(dpt.factor - nei_dpt.factor) # z values
    if dpt.index != nei_dpt.index:
        dpt.slope = dpt.slope/1.4142 # diagonal distance bc square
    # giving flow
    if dpt.factor <= nei_dpt.factor: # make sure not local max
        nei_dpt.prep += dpt.prep #transfer localcell prep to it's highest neighbor

def erosion(self,dpt,nei_dpt,minh,maxh):
    uplift = 0.06
    erodibility = 0.12
    inc = uplift - erodibility * math.pow(dpt.prep,0.7) * math.pow(dpt.slope,0.8)
    dpt.factor += inc
    if dpt.factor < 0:
        dpt.factor = 0
```

In ‘Cities and Complexity’ Batty (2005, 212) introduces urban dynamic modelling through such watershed dynamics and then extends these ideas to distributed settlement systems and full scale models of urban evolution in later chapters (2005, 213). This algorithm is thus used because it is a simple method of capturing the positive feedback between active agents operating in a tesselated landscape, that can then be adapted to model actual settlement dynamics.

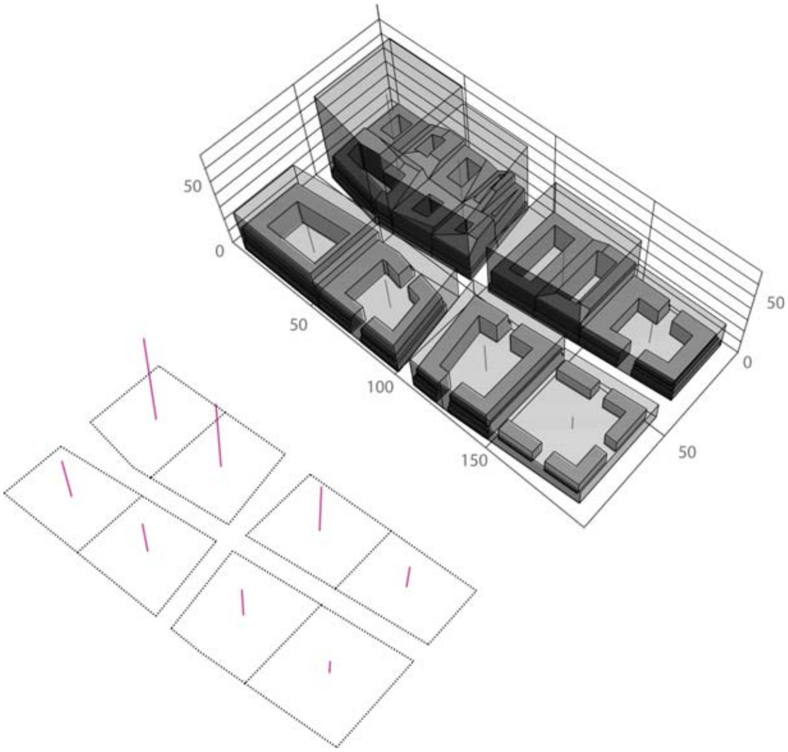


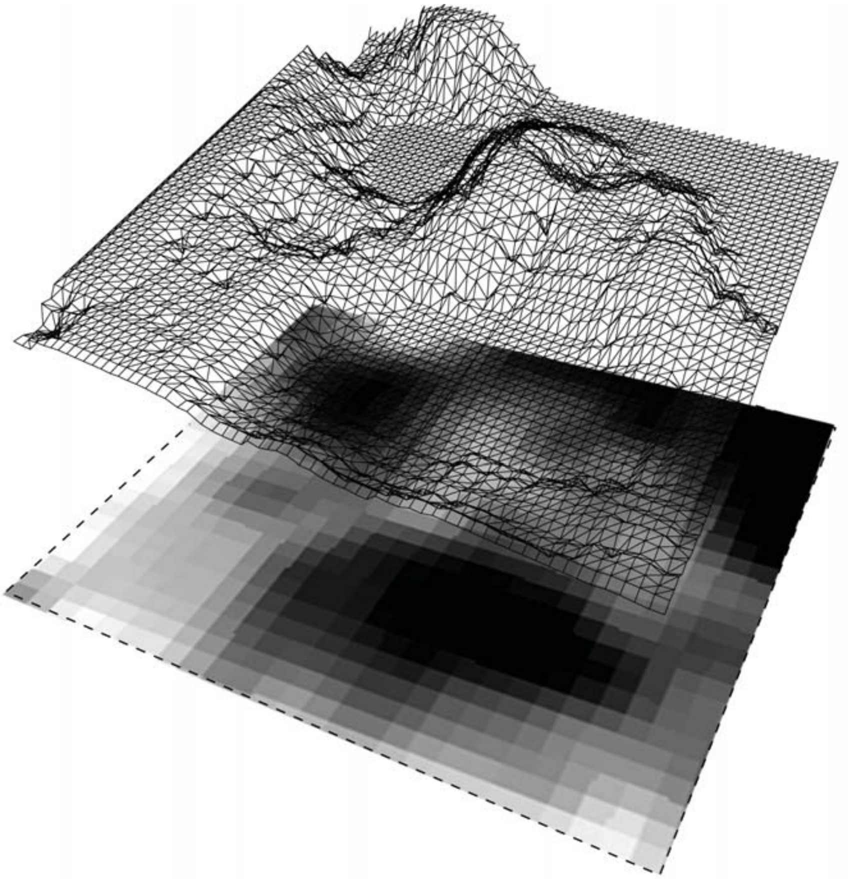
Figure 37 (top left) Cellular Automata and Agent Based Modelling density modeling.

Figure 38 (bottom let) Sediment erosion script modified for density simulation.

Figure 39 (top right) Density targets combined with the shape grammar for urban typology.

The model consists of two simple rule-based systems: Agent Based Models (ABM) and Cellular Automatas (CA). ABMs are a class of computational models that simulate the actions and interaction of autonomous agents with fixed rules. A CA is a cellular space based on regular tessellation of grid squares that exists in one of a finite number of discrete states.

In the thesis semantic network, a CA provides the underlying spatial structure or landscape for the ABM interaction, based on the local networking of the defined building lots. The simulation begins with user-inputted data, in this case, point geometries representing places of high



value, into the cells of the CA, and a single unit of property value in each building lot. For every time step the building lots transfer their property values to the closest cell with the greatest amount of property value. The agent rules thus interprets the user-generated, discretized datasets as resources and allow form to generate around them.

In figure 37, after enough generations there is noticeable spatial developement. The basic dynamic here is marked by exponential growth: empty city zone growth near a high property value initially begins exponentially, but as a threshold of development is reached (defined by zoning constraints) this growth begins to dampen (Batty 2005, 26). The agents and the space they exist in is characterized by interdependent

Figure 40 Higher resolution CA structure and corresponding ABM feedback, done on Processing by author.

factors: the value agents transform the urban landscape, and the urban landscape in turn transforms the property agents. This sensitivity to initial conditions is a common dynamic associated with complex models: their state at any given time is a function of multiple interdependent variables (Batty 2005, 28).

The urban growth values are converted to FAR values that can then be achieved through one of the building typologies encoded into the shape grammar. This serves as an abstraction of the dynamics of urban growth. The figure to the left illustrates how this dynamic would emerge at a much larger scale. The positive feedback here results in a more organic mapping of FAR values, a function of a greater complexity afforded by more interaction amongst agents and cells. Thus while the thesis goal is limited to neighborhoods of 25 to 30 ha, it also limits the actual complexity of the ABM and CA systems. While not in the scope of the thesis, this indicates modelling broader urban swatches, with a greater diversity of typologies could point towards an potential path forward for this work.

4.4 OPTIMIZATION

The simulation methods explained in the previous section therefore produce a great deal of performance information, albeit for one predefined solution at a time. What is lacking in simulation is thus an automated method to produce and compare multiple solutions, unless one repeats the analysis with different solution combinations multiple times (Radford and Gero, 1980, 75). Essentially the generation and simulation methods produce a subset of the broader solution space, but tell the designer nothing about the relative performance of the solution other than the satisfaction of the design criteria. This is especially burdensome for non-specialist users, who lack the knowledge to navigate the generated solution space. As Piller (2013, 18) writes in the context of mass-customization, “when a customer is exposed to too many choices, the cognitive cost of evaluation can easily outweigh the increased utility from having more choices.”

A potential solution for design guidance is optimization (Mueller and Ochsendorf, 2015, 70). In the design optimization phase, the designer defines a performance objective, problem, and then selects the 'best' solution. Specifically, optimization models search the whole field of feasible solutions to identify those that best suited to stated goals. The search is guided by weighted objectives that narrow down the solution set to optimal or near-optimal solutions. As Radford and Gero (1980, 75) note, unlike the previous two design methods optimization provides prescriptive information, "that expresses the design options and that addresses the problems of the sensitivity and stability of solutions given changes in the assumptions on which they are selected."

Fasoulaki (2008, 17) defines four elements in a design optimization problem:

- Variables: quantities or mathematical expressions that form the design space.
- Objectives: the functions that designers try to maximize or optimize. This is goal is expressed in terms of design variables. Fasoulaki (2008, 17) notes that while often the objective is simplified — as in this thesis — to a scalar function, in real systems there are multiple, often conflicting objectives.
- Constraints: the boundaries of the design space. Constraints are either inequality constraints or equality constraints.
- Parameters: fixed quantities that affect the design objectives, and thus cannot be changed by the designers. If turned into variables, they increase the design space and vice versa.

The thesis goal is thus fundamentally a design optimization problem: to find the urban typologies with the highest daylighting and density values. The role of the optimization algorithm is to search through a generated feasible solution space and identify solutions that best match the thesis goal. In the context of the thesis design system, the feasible solution space refers to the set of architecturally correct typologies specified by the shape grammar. Specifically, given the set of all possible urban typologies, the shape grammar method specifies the subset of shape transformations that satisfy its grammar rules, consisting of dimensional constraints, equalities and inequalities that define the architecturally-correct building types. The optimization algorithm systematically selects the input variables for the grammar and calculates the resulting performance simulation values. The performance values are evaluated through a defined fitness function that computes the 'fitness' or optimality of each solution. In order to avoid brute forcing a search through the extremely large and complex solution space, heuristics (in this case, natural selection) are used to exploit partial knowledge of the feasible solution space and guide the selection and evaluation process.

4.4.1 Genetic Algorithm

Optimization methods require a search algorithm to find the optimal or sub-optimal solution for the design problem, amongst the design solution space. Designers traditionally use heuristic algorithms, a particular class of optimization algorithms that, "...follow a simple set of rules to return within a minimal computing time an acceptable and approximated solution of a design problem," (Fasoulaki, 19, 2008).

Examples include Simulated Annealing (SA), Tabu Search (TA), and Genetic Algorithms (GA). Heuristic algorithms are efficient and can be used for large scale optimization problems which cannot be solved optimality by standard optimization algorithms, however they usually only guarantee a near-optimal solution.

The thesis design system will use the GA optimization method. GAs are defined as adaptive heuristic search methods they solve optimization problems by modeling the processes of biological evolution (Fasoulaki, 20, 2008). Specifically, GAs takes an initial population design solution variables (called the genotypes or chromosomes) and transform them, overall, into a fitter population using the Darwinian principle of reproduction and survival of the fittest (Fasoulaki, 20, 2008). Specifically the variables in this function behave as the genotypes in the GA. The GA optimization will generate an initial population of fitness values from random genotypes and then select the best performing genotypes. The GA will then perform the genetic operation of crossover, by combining the high-performing genotypes or variables, and generate a new population. The highest-performing combinations of

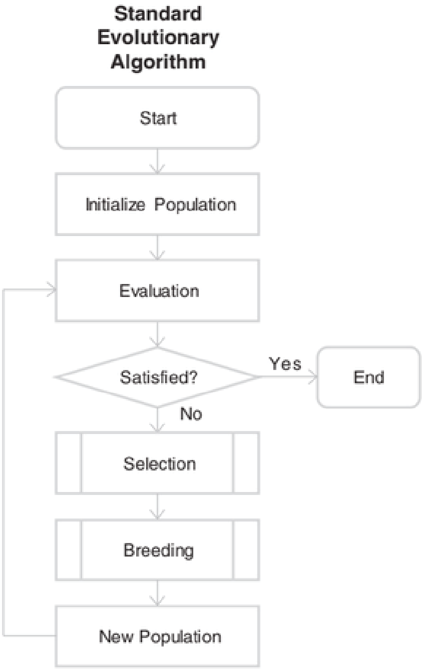


Figure 41 Flowchart of Standard Evolutionary Algorithm.

genotypes will prevail after multiple iterations, and lead to near-optimal or optimal design solutions.

The thesis optimization method uses a GA because they can robustly and efficiently search through large and complex solution spaces. For this reason, precedents for architectural optimization related to energy consumption and structural analysis tend to favor GAs (Fasoulaki, 20, 2008).

GAs in this thesis will implemented via Galapagos (Rutten, 2010), an evolutionary computing platform for Grasshopper3D. Galapagos is a generic platform for the application of evolutionary algorithms chosen for its minimal interface and capabilities. This allows flexible, complementary integration with the thesis design system compared to other evolutionary computing platforms. First, because it is limited to single-objective optimization, the thesis multi-objective problem must convert the design problem into a scalar function. This allows the thesis design system to control how the multi-objective thesis problem is guided to optimal solutions in a very straightforward manner. Secondly Galapagos has no built-in method of storing key data, such as the generated genotypes and phenotypes. This allows greater flexibility in integrating the thesis design system components and extending it to store and archive geometry and data for statistical mapping and visualization purposes.

The thesis optimization component thus extends the Galapagos platform to accommodate its limitations, first by defining a scalar function that encompasses the multi-objective thesis problem, and secondly by integrating storage and visualization methods so the user can evaluate the populations being generated, access and interpret statistical trends and qualitative issues such as the subjective aesthetic criteria. Figure 42 illustrates an initial test of Galapagos integration with the thesis form generation and simulation components. It illustrates one population of 50 typology solutions testing street ratio, surface coverage, solar angle, and building orientation variables or genotypes.

Figure 42 One population of 50 phenotypes of typology optimization test.

5 Proof-of-concept

The previous section broke down the primary components of the design system and their respective application through a series of simple, generic tests. This chapter will demonstrate how these components are synthesized in order to generate locally-customized energy-efficient typology solutions through two applications. First the test site is introduced, and important characteristics impacting the density conditions are defined. Secondly, in the first application test five design compositions are derived, and corresponding density and illuminance metrics are manually compared. Finally the second application chapter incorporates computational optimization into the thesis design system.

5.1 SITE INTRODUCTION & ANALYSIS

Lewisham is an inner city district in southeast London, two kilometers south of the River Thames, identified in the London Plan[1] as one of the 35 major centres in Greater London[2]. The neighborhood around the Lewisham Rail Station is one of the major regeneration projects in southeast London targetted to add cultural, commercial and residential built fabric, and strengthen the existing transit interchange. This site was chosen to apply the proof-of-concept because it shares the residential typology and environmental conditions of the research in §§3.3-4, is undergoing rapid development changes reflected in the gradual shift of the fabric density, contains multiple transit nodes that, in part, are driving the increasing densification.

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[1] The London Plan is the statutory spatial development strategy for the Greater London area in the United Kingdom. The plan is written by the Mayor of London and published by the Greater London Authority, in compliance with the National Planning Policy Framework.

[2] Greater London is an administrative and ceremonial area covering the United Kingdom capital of London. It consists of the city of London and 32 London boroughs. Twelve of the boroughs are categorized as Inner London and the other twenty are Outer London boroughs.

The figure to the left illustrates key points around the Lewisham Rail Station that will be used to inform the proof-of-concept typology and density modeling. The area serves as an important multi-modal transit node in London's robust transit network, serving as an interchange for Southeastern rail services, the Docklands Light Railway (DLR) and Transport for London bus services. The Ladywell rail station lies approximatly 1 km southwest of the Lewisham station.

In terms of existing building typology and density there is currently a single skyscraper adjacent to the shopping center, however the redevelopment plan includes includes the addition of compact mid and highrise multi-residential buildings (6-30 storeys) directly south of the Lewisham rail station (Arup 2014, 53). Older low-rise terraced and detached housing sits further west of the Lewisham station, and comes in contact at it's southern edge with Ladywell station. The nonuniform site density reflects, in a large part, the major transit nodes. The yellow border indicates the residential fabric (39.5 ha) that will be used to test the proof-of-concept.

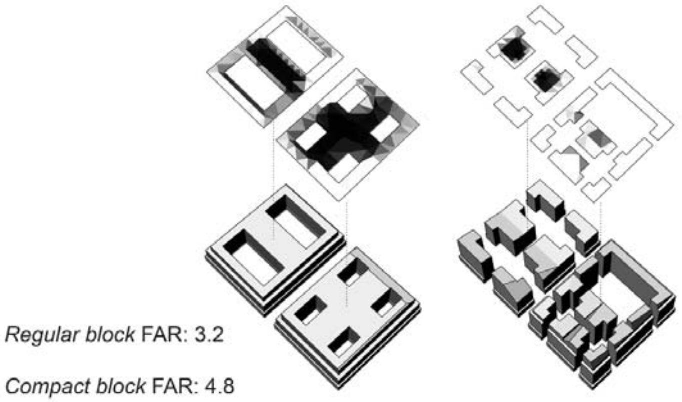
Figure 43 (top) Lewisham within the Greater London and (left) Lewisham site analysis.


Elverson Road
St Johns
Lewisham
LEGEND
Residential
Commercial
Park
Rail lands
Rail station
Railway
Roads
Pathway
River
100 m
Ladywell

5.2 APPLICATION I

In order to coordinate the energy transfers and needs between buildings through mass-customised type design, the design system must enable the user to iteratively prototype and evaluate different typology solutions. This section will break down how the form-generation, simulation and decision-making components are synthesized in order to traverses the solution space of fabric compositions. First the design method is broken down, with reference to the design system, and secondly the resulting solutions are illustrated and evaluated relative to the thesis objective.

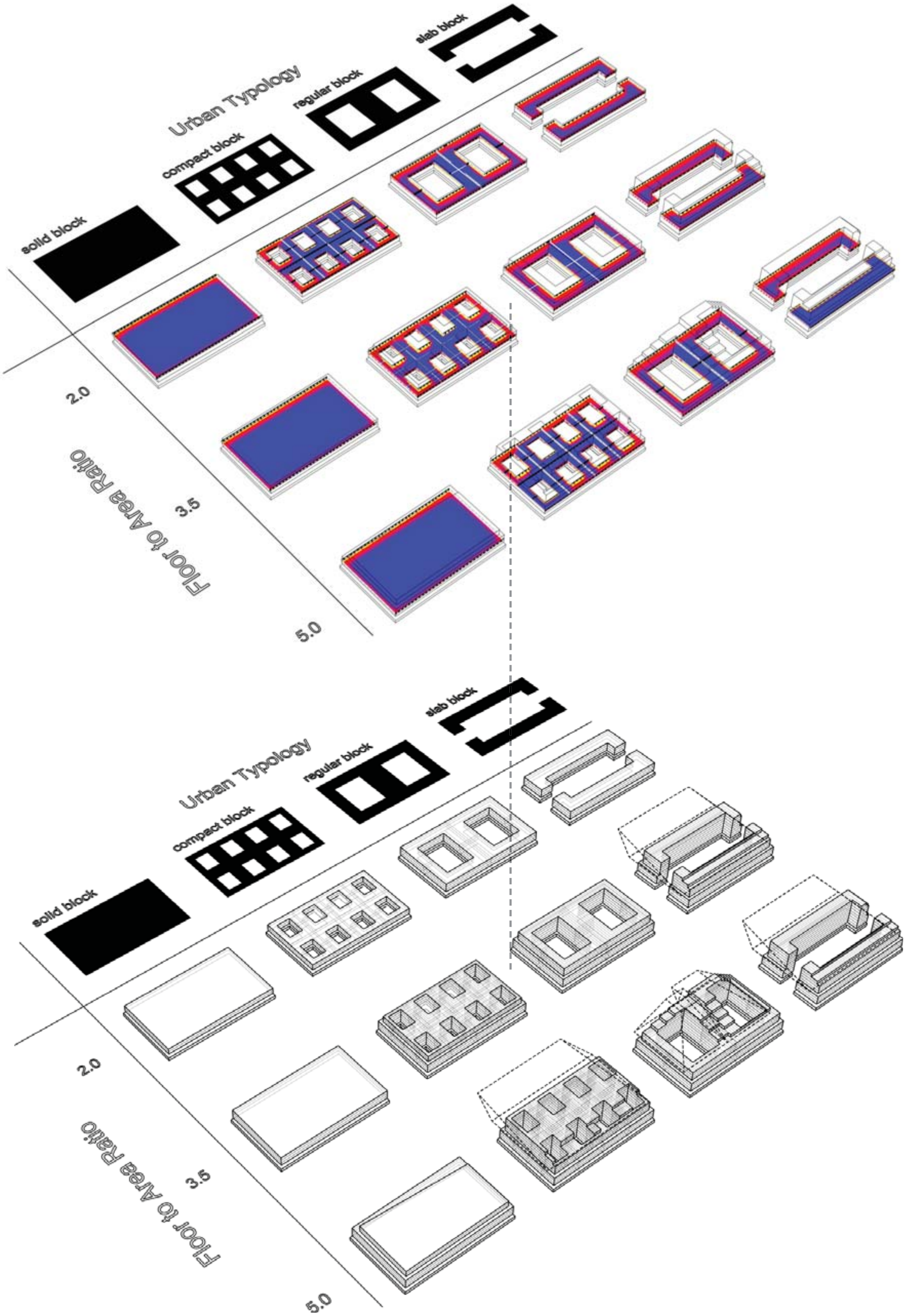
5.2.1 Design Method



The design method occurs at three scales: fabric grain, block zoning and typology. In §3.4 it was established that interior daylighting can be optimized, via morphology, by controlling the geometry of the fabric grain, building 'compactness', passive-zone ratio, the urban canyon, terracing and urban height angles. The proof-of-concept will control these geometric relationships by defining the following shape parameters: block dimension, terracing angle, building height, street depth, courtyard shape and plan depth. The figure above how these spatial parameters can be modified in order to increase daylighting potential, while retaining density values. The figure to the right illustrates the initial urban block typologies that will

Figure 44 (top) Refining type rules to derive better performance while retaining density.

Figure 45 (left) Four urban block typologies at 3 different FARs, and corresponding illuminance performance.


Urban Typology
solid block
compact block
regular block
slab block
Floor to Area Ratio
2.0
3.5
5.0
Urban Typology
solid block
compact block
regular block
slab block
Floor to Area Ratio
2.0
3.5
5.0

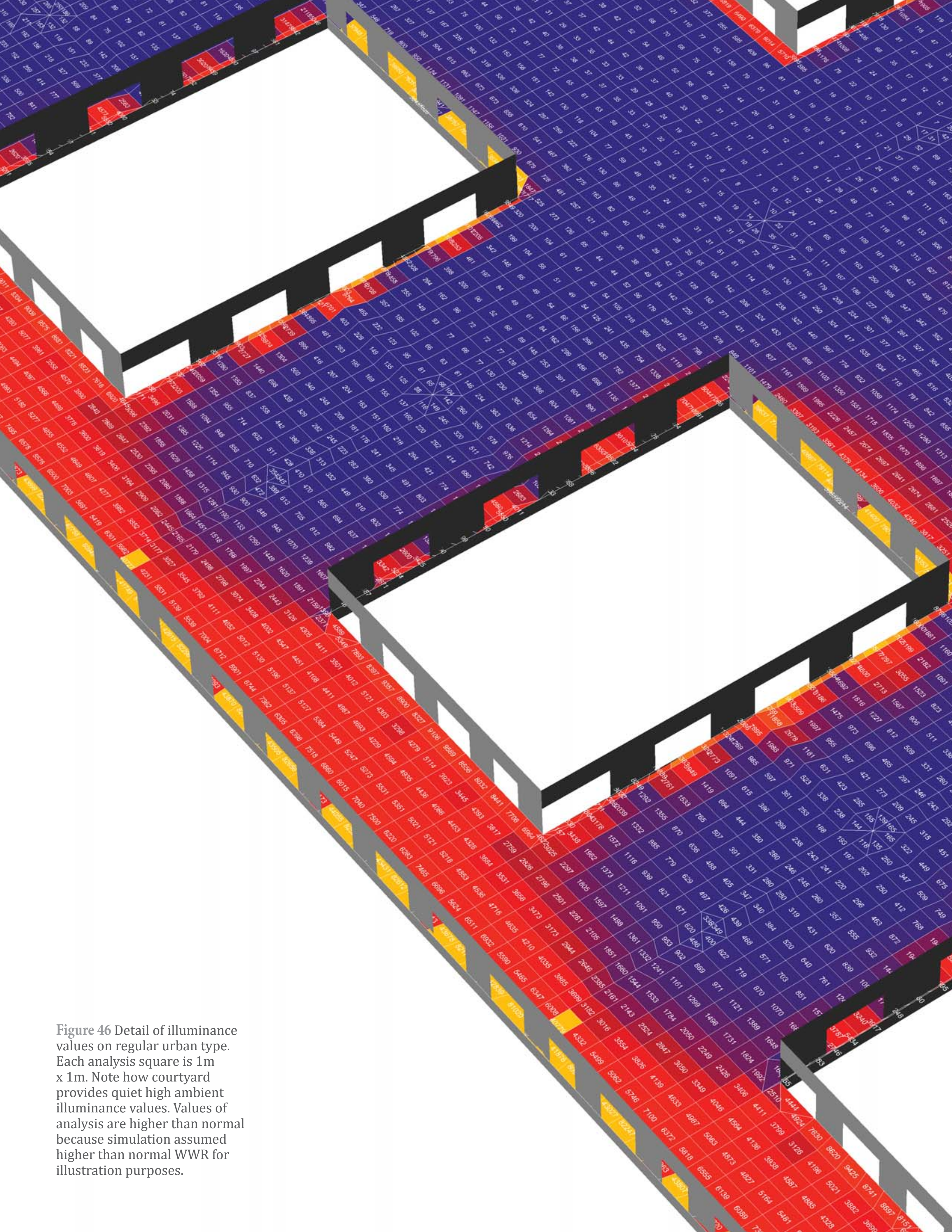
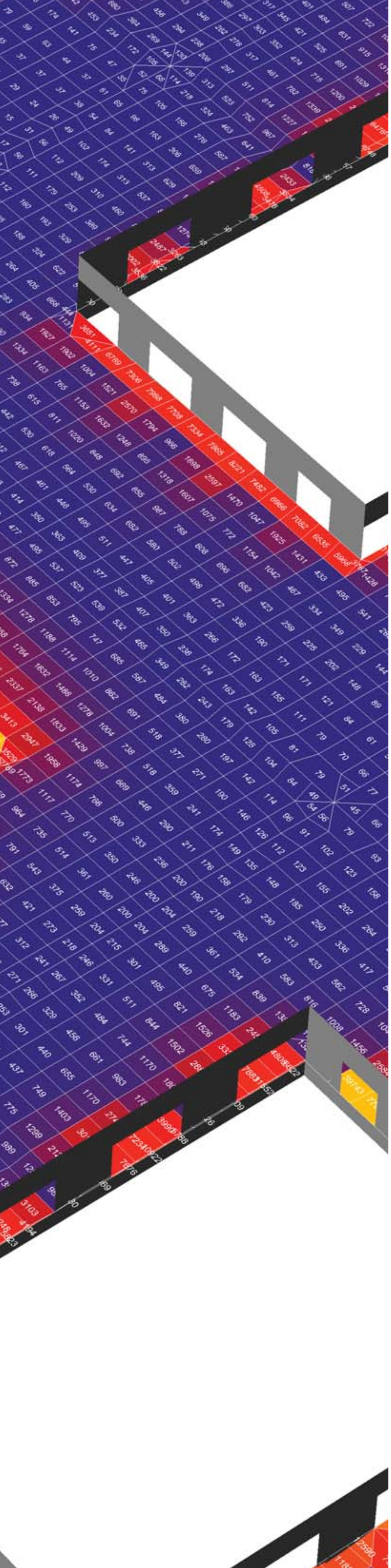


Figure 46 Detail of illuminance values on regular urban type. Each analysis square is 1m x 1m. Note how courtyard provides quiet high ambient illuminance values. Values of analysis are higher than normal because simulation assumed higher than normal WWR for illustration purposes.

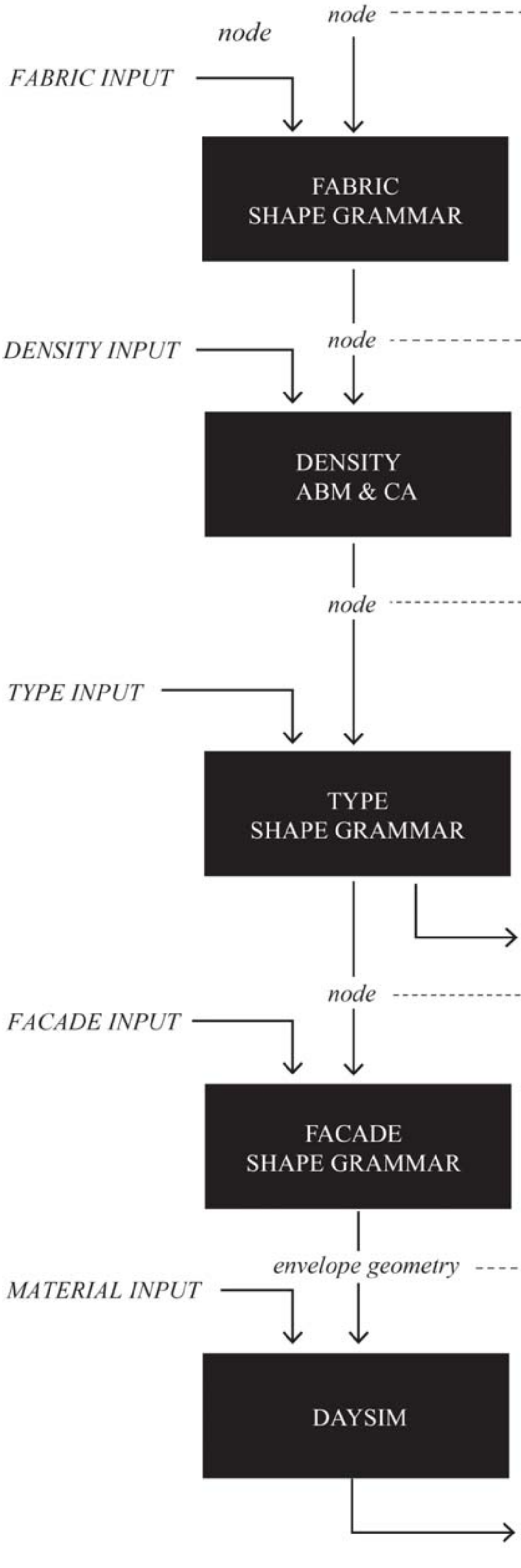


be used to derive the final composition, in relation to FAR and corresponding illuminance metrics. Specifically it references four common urban typologies studied in §§3.3.1-2, that are derived through different combinations of type rules. Each rule is parametericized to accomodate varying constraints defined by the user or environment. In this case, the building height is modified to portray three different FAR values, and solar zoning. This allows the designer to decide how to allocate block typologies according to the unique density and daylighting trade-offs of each type. This indicates that more compact typologies (compact block) have lower passive zone ratios in relation to less compact typologies (slab block). However, this is achieved by increasing the building height of the slab block, which increases the overshadowing impact on neighboring buildings. The actual impact can only be gauged in the context of the an actual urban layout. Additionally, the solar zoning places a lower ceiling on the density of the slab housing, in relation to more compact built types such as the solid block. The more compact block types thus should be placed where reduction of transit energy through higher densities is vital, for example beside key transit nodes.

Figure 47 illustrates the design method to achieve this in relation to the three design system components. The design method enables the user to traverse the solution space and in doing so derive five design solutions. Essentially the refining of the shape grammar parameters defines different design paths within a larger solution space. The derivation tree can be traversed simultaneously in order to explore multiple design scenarios. In this case, the street grid and density targets was kept consistent, and five different typology grammars was explored.

First, the initial site outline is fed into the FABRIC SHAPE GRAMMAR component, which defines the boundary geometry as the root of the grammar derivation tree, and then recursively subdivides it into a street grid according the user-inputted values. The street grid is then fed into the DENSITY ABM & CA component, which is used to simulate local FAR values. This component implements decision-making through the use of an algorithmic model of urban dynamics. The model maps the development potential defined by user-specified zoning constraints and transit nodes, key criteria in increasing NMT, as established in §2.1. The component chooses different type rule sets according to the simulated density target. In this case, two different density methods were chosen, uniform and non-uniform. These density values are in turn channeled to one of five possible TYPE SHAPE GRAMMAR components.

This component defines a solution space of potential urban block typologies, according to the shape relationships identified in §2.3: plan depth, solar angle, courtyard shape and building height. The form generator executes the type rules from the decision-making component to generate architecturally-correct, highly localized, differentiated typology designs. Finally, in order to evaluate the daylighting potential of each solution, the massing geometries are fed into the FACADE SHAPE GRAMMAR component. This component combines the type geometry data with material transmittance and reflectance values to simulate the building material properties for daylight simulation. The DAYSIM component, from DIVA consumes the material and geometric data in order to derive the illuminance values for the interior of the building. In this way the design system illustrates the daylighting consequences of different urban forms, for a specified target density.



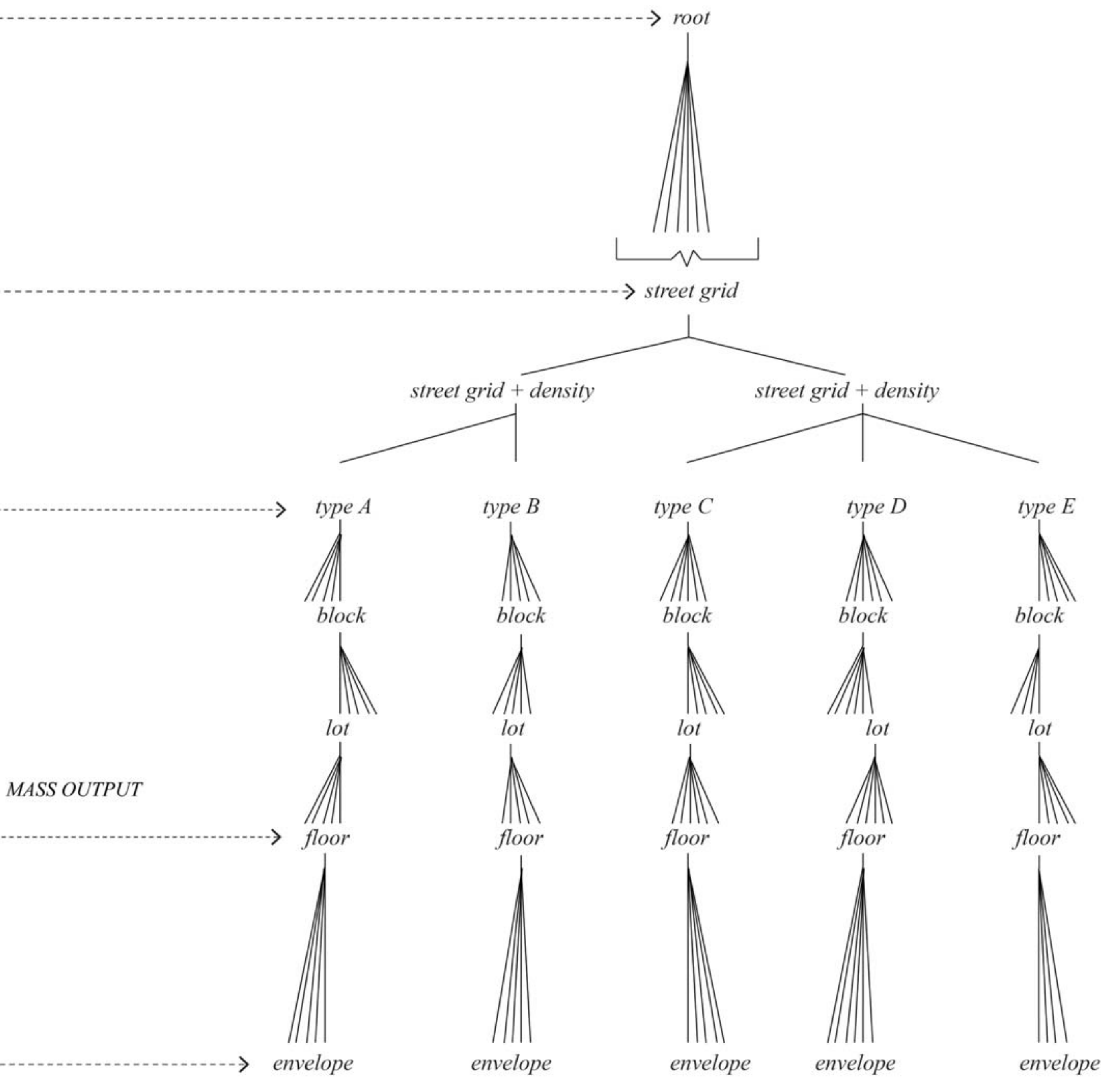
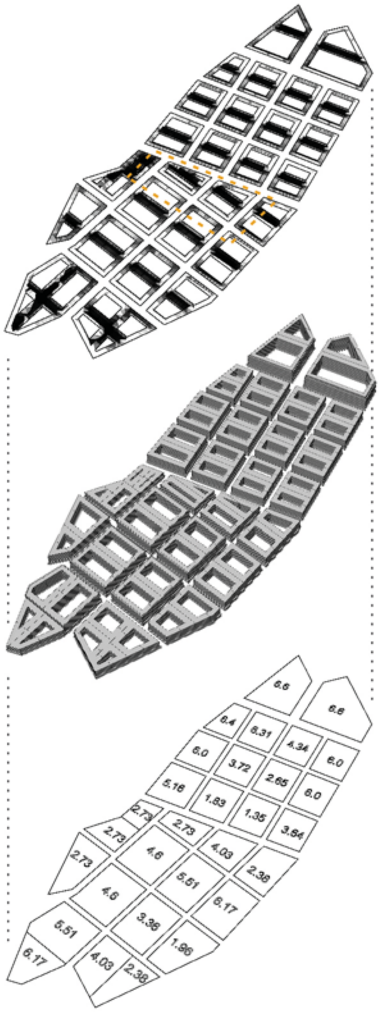
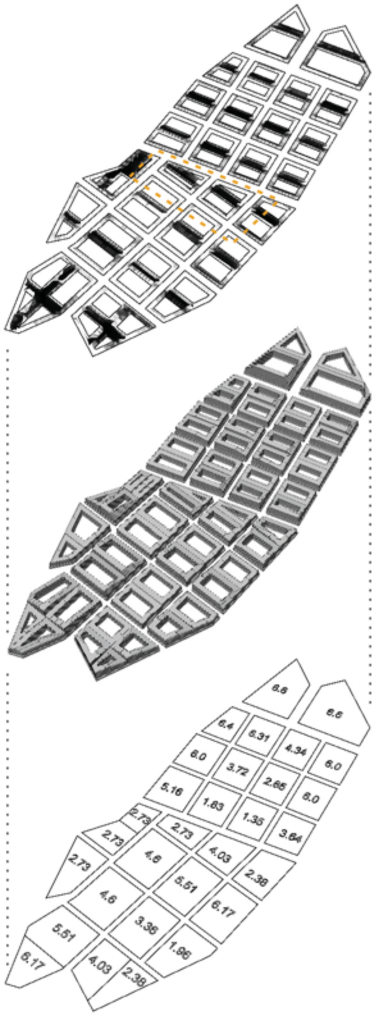
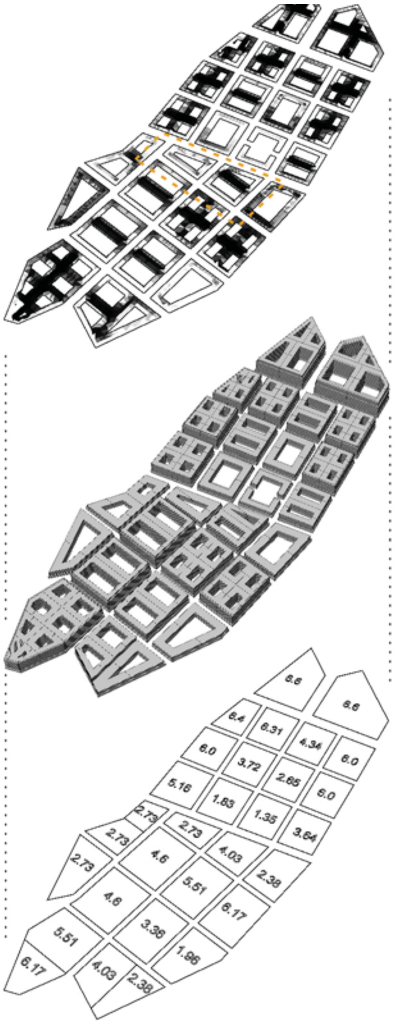


Figure 47 Design method: the shape grammar derivation tree in relation to the design system components.

Rule	A	B	C	D	E
Floor area	759515.51	673219.27	812472.82	703171.01	702670.9341
FAR	4.528641057	4.014096337	4.844401098	4.192684763	4.189703041







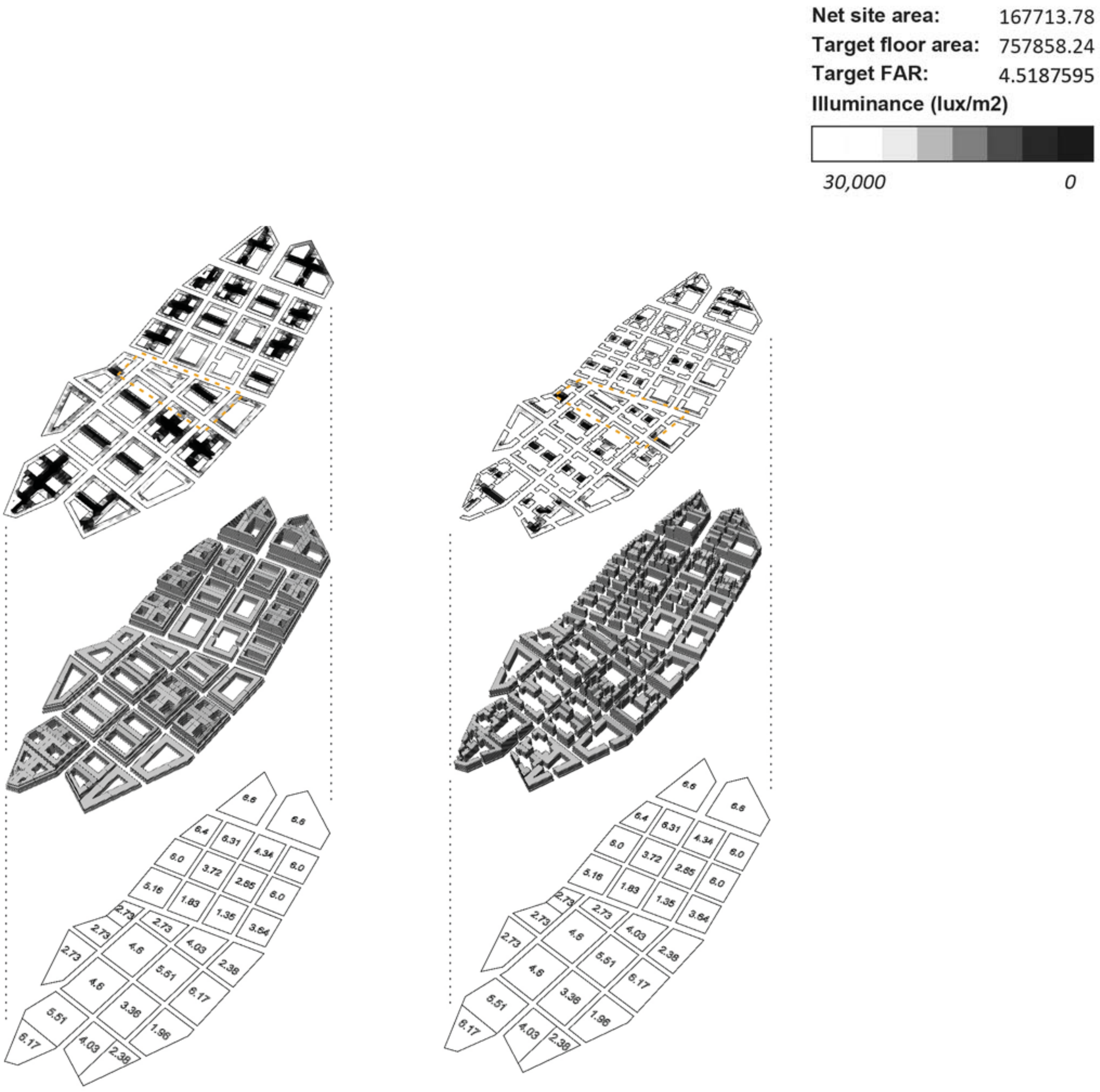
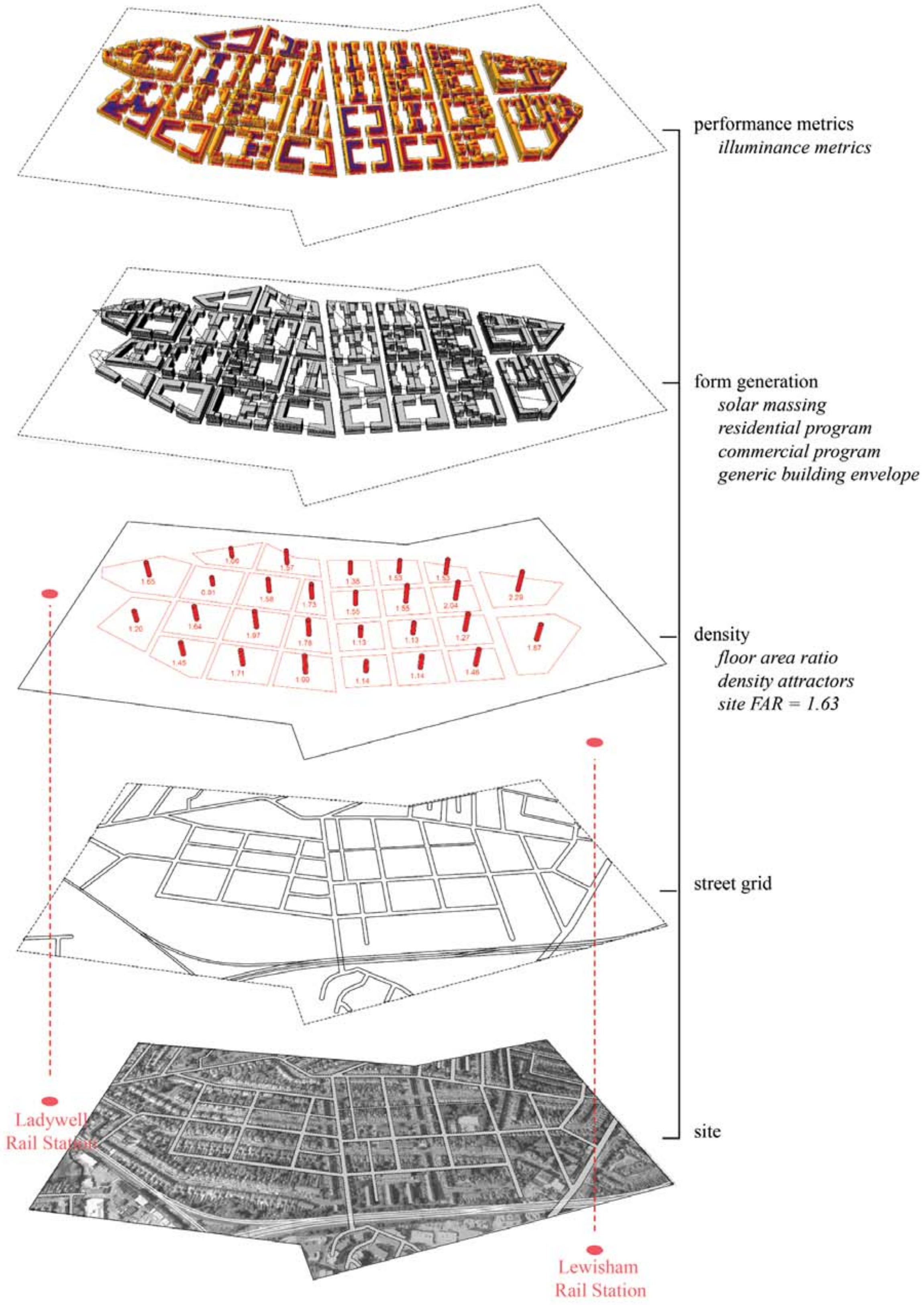


Figure 48 Comparison of five different type rule combinations.


performance metrics
illuminance metrics
form generation
solar massing
residential program
commercial program
generic building envelope
density
floor area ratio
density attractors
site FAR = 1.63
street grid
site
1.06
1.57
1.65
0.91
1.58
1.73
1.38
1.53
1.53
2.29
1.55
1.55
2.04
1.20
1.64
1.97
1.78
1.13
1.13
1.27
1.87
1.45
1.71
1.90
1.14
1.14
1.48
Ladywell Rail Station
Lewisham Rail Station

5.2.2 Evaluation

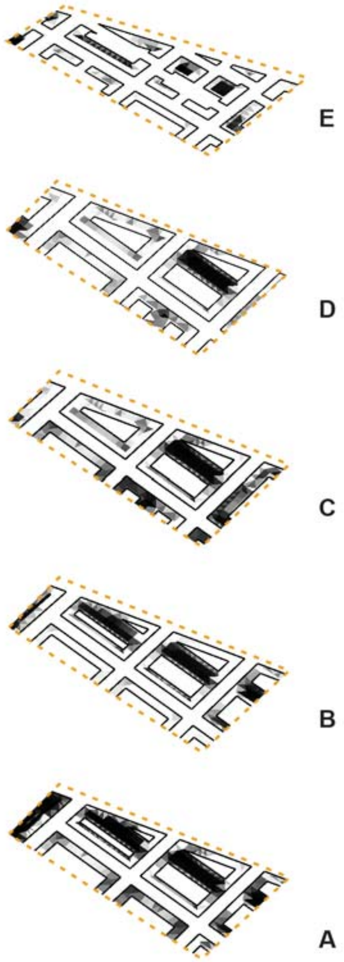
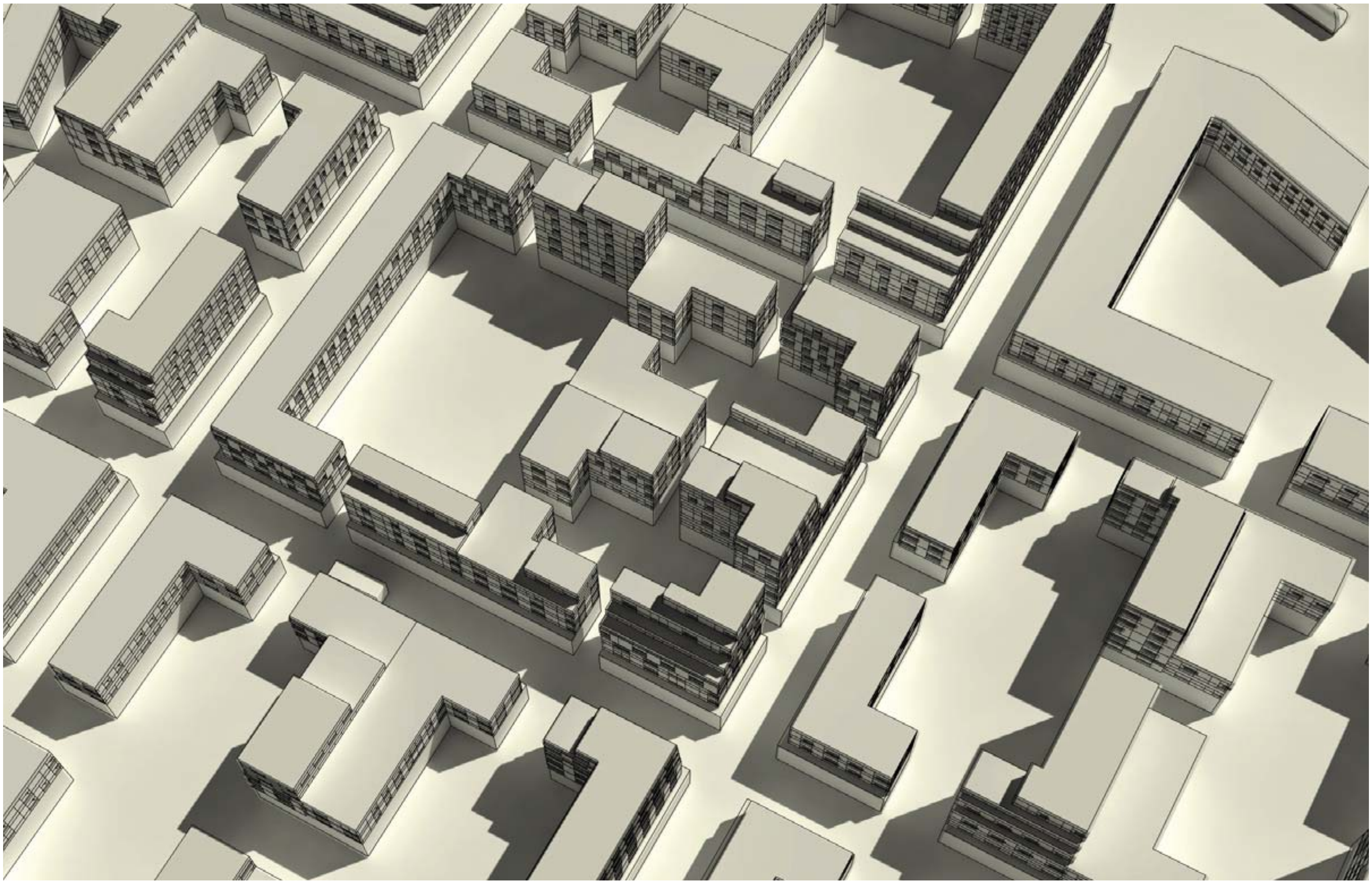


Figure 49 Comparison of daylighting obstruction due to different type rule combinations.

Figure 50 Type E separated according to the threee main shape grammar stages.

Type A consisted of the simplest possible urban layout, where because of its compromise between passive-zoning and density the regular block was used throughout the site without solar obstruction massing. This grammar was quite effective in terms of density, exceeding the FAR target by 0.32 FAR. Type B was the same as Type A, with solar zoning. As can be seen in the adjacent figure, this noticably reduced the overshading effects on neighboring geometry - however the solar zoning in this case appeared to have prevented the design from achieving the density target, by 0.2 FAR. Type C and D therefore used a strategy of concentrating more compact typologies around the transit nodes, with solar obstruction angles applied, again, only for the latter. In both cases the target density was reached (with Type C achieving the highest density of 4.84 overall FAR), and Type D achieving greater daylighting potential. Having established Type D as the best overall strategy for coordinating solar obstruction and building height, it was further refined for other grammar parameters to produce Type E, which greatly increased the daylighting potential while still approximatly reaching the FAR target. Type E thus achieved the greatest daylighting potential for the target density of 4.2 for the site.

Figure 49 portrays how the various energy strategies are coordinated by means of the fabric, block and typology characteristics in Type E. Specifically, the final design composition is divided amongst: site, street grid, density targets, form generation and the performance data. While the target 4.2 site FAR was achieved, it came at the cost of the scale of the human-scale grain with an average building height of eight levels or higher. A lower FAR target of 1.5 was found to result in a finer, less-imposing building fabric. Achieving a the high FARs required by the thesis objective will thus require experimentation with high-rise typologies, demonstrated in the next section. Generally, the script allocated compact urban typologies close to the transit nodes and calculated plan depth, solar obstruction, courtyard shape to mitigate the resulting lower passive-zoning ratio. The opposite strategy was used for the less compact typologies. The solar zones were set to provide solar access to the residential occupancies, with the range of hours randomized to vary the daylighting conditions for different spaces.



5.3 APPLICATION II

The previous subsection demonstrated the application of the type shape grammars, daylighting simulation, and urban modeling components for five predefined solutions. While the resulting solution fufilled the thesis objective, it is clear that manually producing and comparing type solutions is quite burdensome for even a specialist user. In this section a genetic algorithim (GA) is used to guide the selection of an optimized design solution.

Before implementing the optimization algorithm, two modifications are made to the thesis context defined in the previous section. This is done in order to reduce the complexity of the computation and to increase the fabric density while maintaining nonuniform densification. First, in order to limit the computational intensity of the search algorithm the development area will be reduced to the south edge of the site. Secondly, the mid-rise and low-rise housing types in the previous application were found to yield only medium to low site density. Thus an additional high-rise typology was added in order to achieve greater site FAR.

With these changes, this section incorporates computational optimization into the thesis design system. First the design method is introduced by deriving the design problem, its corresponding variable inputs, and the fitness function. Secondly the optimization script is run and the resulting sample populations are illustrated and evaluated relative to the thesis objective.

5.3.1 Design Method

The optimization algorithm searches through the feasible solution space defined by the shape grammar and identifies solutions that best match the thesis objective. This subsection will define the thesis design optimization problem. As defined in §4.4, the design optimization problem will break down the thesis objective into mathematical values and relationships that are used to define the optimization search process. The thesis-specific design problem is broken down in the following figure.

Figure 51 (top) Aerial and (bottom) pedestrian view of Type E.

Nomenclature

TD	theta density [-] (difference between actual and target density)	*bh*	building height [m]
ND	net density [-]	*sw*	street width [m]
IR	solar irradiation [kWh/m^2/day]	*pd*	plan depth [m]
ph	podium height [m]	*ls*	lot setback [m]
fpa	footprint area [m^2]	*ts*	terrace setback [m]
la	lot area [m^2]	*sr*	street ratio [-]
ld	lot depth [m]	*pra*	primary road angle [radians]

Design Parameters

- Fabric
  - Fabric subdivision depth [m]
  - Street dimension [m]
- Density
  - Density trigger [coordinates]
  - Maximum height [m]
  - Iteration [-]
  - Erodability [%]
  - Uplift [%]
- Type SG
  - Type data [-]
- Facade
  - Glazing width/height [m]
  - Panel width/height [m]
- Environmental Input
  - Geographic location [coordinates]
  - Time [dd:hh:mm]
  - Sky state [-]
- Material Input
  - Context geometry [-]
  - Ground geometry [-]
  - Facade reflectance [%]
  - Glazing transmittance [τ-value]
  - Ceiling reflectance [%]
  - Floor reflectance [%]

Design Variables

- Street ratio [-] = sw / bh
- Surface coverage [%] = $(fpa / la) \times 100$
- Solar angle [π] = $\arctan(((3+sr) + (1.2+sr) \times 3) / ph)$
- Building orientation [π] = pra

Design Constraints

- Fabric Input
  - $0 \leq pra \leq \pi$
- Density
  - $0 \leq bh \leq 150$
- Type
  - $8 \leq pd \leq (ld/2)$
  - $0 \leq ts \leq 3$
  - $0 \leq ls \leq 3$

Design Objective

- $f(ND,IR,TD) = \mathrm{sqrt}(\alpha \times ND) + \mathrm{sqrt}(\beta \times IR) - (\gamma \times TD)^2$

The design objective in the context of optimization is defined here as a scalar function. The thesis objective, like most architecture design problems, has multiple objectives: to increase the daylighting potential of built typology while achieving target density goals. In order to simplify the optimization method, this thesis will simplify the multi-objective problem into a single objective problem that can be solved in a more straightforward manner. In formulating the scalar function, the goal is ensure the variables, or genomes can be guided to reach optimal or near-optimal solutions.

The thesis design objective is to increase ND and IR[1] while reducing the difference between the target density and actual density, the TD. The simplest possible scalar function, or fitness function is thus:

$$f(ND,IR,TD) = ND + IR - TD$$

In order to produce a useful fitness value $f(ND,IR,TD)$, this function must be modified in two ways. First the variables must be normalized between two numbers to allow comparison of different metrics. This is done by deriving highest, lowest ND, IR and using following formula:

$$\mathrm{n}v = ((hi - lo) \times (v - min)) / (max - min) + lo$$

where:
n = normalized value
hi = upper bound
lo = lower bound
max = maximum range
min = minimum range

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[1] The performance metric was switched to solar irradiation in this application because simulating illuminance was found to be prohibitively time-consuming during the optimization process.

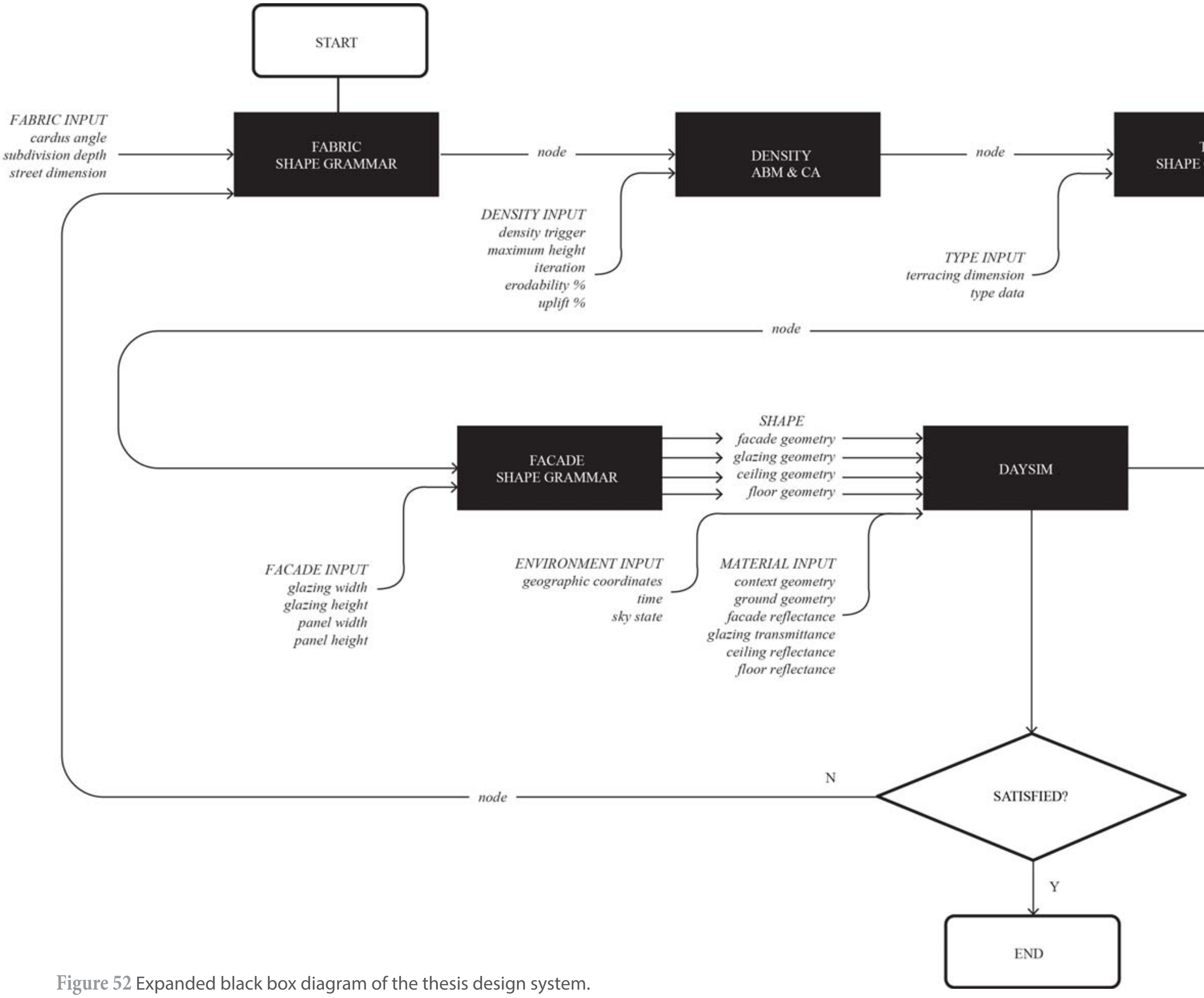
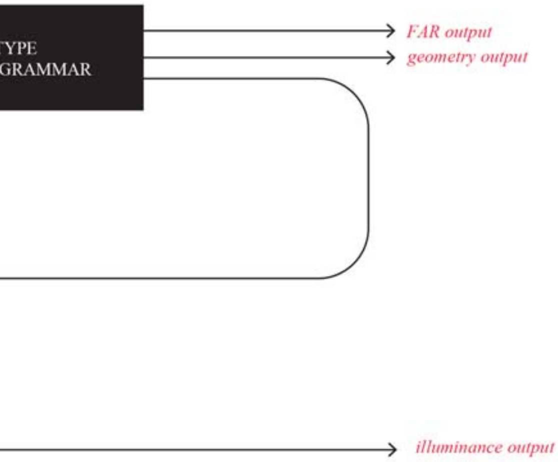


Figure 52 Expanded black box diagram of the thesis design system.

Thus, including the normalization formula and substituting the appropriate values the fitness formula is:

$$f(ND,IR,TD) = ((11.5-1) \times (ND-0))/(10-0)+1) + (2700-425) \times (IR-0))/(10-0)+425) - TD$$



Secondly the current function is linear, so the increment of each variable does not vary its contribution to the overall fitness function. By converting each variable into a nonlinear function we can control the variable contribution to the fitness. For example, while we want to maximize solar irradiation, it is preferable to penalize passive lighting and heating when there is already plenty of it overall. If we convert the performance variable into a nonlinear function, $IR = \mathrm{sqrt}(IR)$, then the IR is lower at higher values and higher at lower values. Thus a specific increase of heat and light results in a lower fitness value when there's already a large amount of these properties. The resulting function is therefore as follows:

$$f(ND,IR,TD) = \mathrm{sqrt}((11.5-1) \times (ND-0))/(10-0)+1)) + \mathrm{sqrt}((2700-425) \times (IR-0))/(10-0)+425)) - (TD)^2$$

To summarize the optimization process, the evolutionary algorithm will generate multiple populations of fitness values from random variables, which are defined as genotypes. The algorithm then selects the best performing individuals and performs the genetic operation of crossover, by combining the high-performing genotypes and generating a new population. The role of the fitness function here is designed to exert selection pressure during the optimization process by guiding variable selection towards the optimal fitness value.

The fitness function thus determines how effective the optimization algorithm is at reaching optimal or near-optimal solutions. After multipe iterations the fitness function should lead the evolutionary solver to the highest-performing combinations of genes, which produce near-optimal or optimal design solutions. Figure 53 illustrates a sample of the resulting types from each population.


5.4


5.3


5.2


5.1


5.3

1st

Street ratio: 1,2,3,4
Surface coverage: 40-47
Solar angle: 4,8,20,30
Building axis: 0,30,60,90,120


5.2


4.9


4.9


5.1


5.1

2nd

Street ratio: 1,2,3,4
Surface coverage: 40-47
Solar angle: 4,8,20,30
Building axis: 0,30,60,90,120


5.3


5.1


4.9


4.9


5.3

3rd

Street ratio: 1,2,3,4
Surface coverage: 40-47
Solar angle: 4,8,20,30
Building axis: 0,30,60,90,120


6.4


5.3

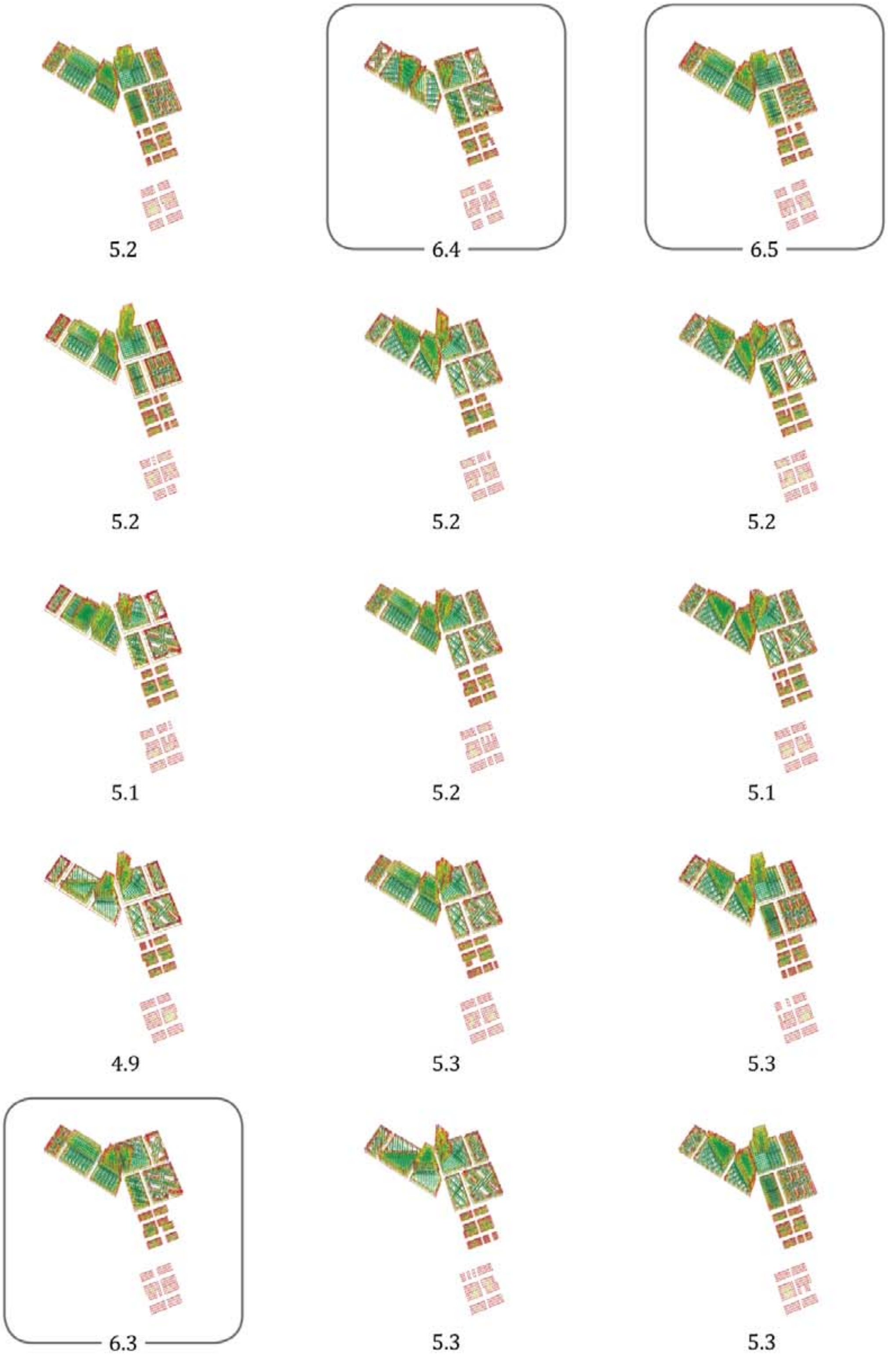

5.1


5.0


5.4

4th

Street ratio: 1,2,3
Surface coverage: 42-47
Solar angle: 4,8,20
Building axis: 0,30,60,90



5th

Street ratio: 1,2,3
Surface coverage: 42-47
Solar angle: 4,8,20
Building axis: 0,30,60,90

6th

Street ratio: 1,2,3
Surface coverage: 42-47
Solar angle: 4,8,20
Building axis: 0,30,60

7th

Street ratio: 1,2,3
Surface coverage: 42,44-47
Solar angle: 4,8,20
Building axis: 0,30,60

Figure 53 Genotype and phenotype population samples.

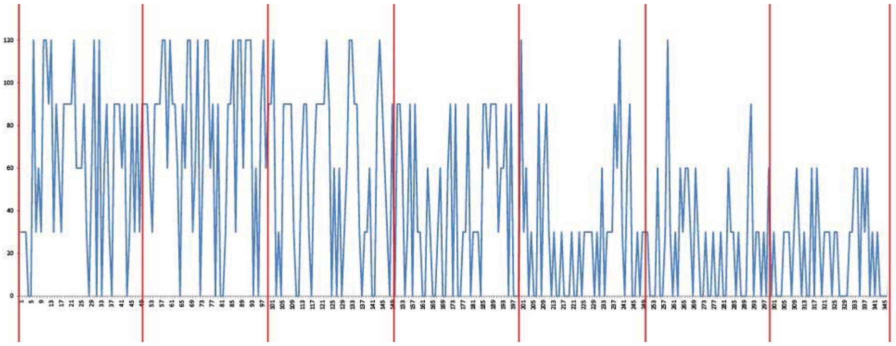


Figure 54 Building axis values for seven populations.

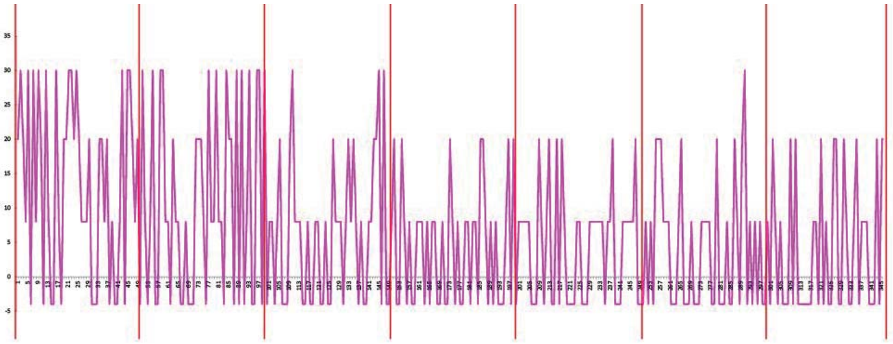


Figure 55 Solar angle values for seven populations.

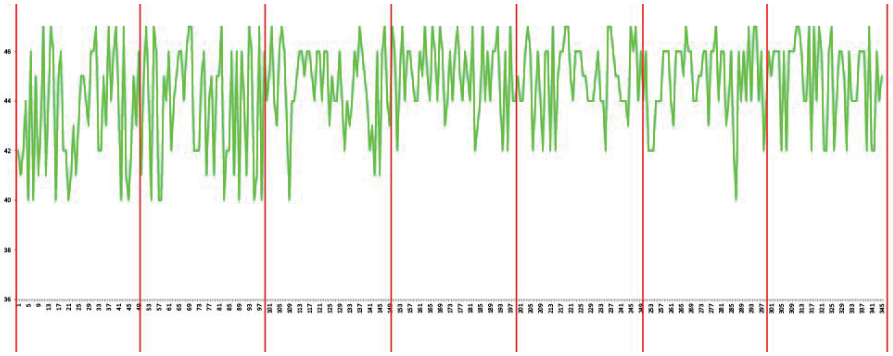


Figure 56 Surface coverage values for seven populations

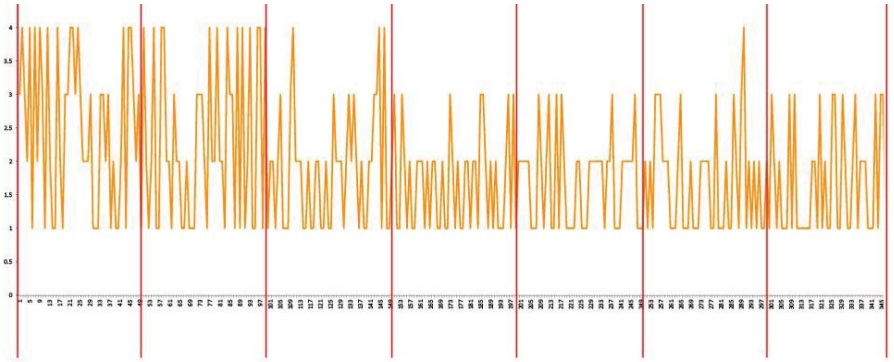


Figure 57 Street ratio values for seven populations.

5.3.2 Evaluation

In this subsection I will evaluate the achievement of the thesis goal in terms of the resulting typology solution space defined by the optimization algorithm.

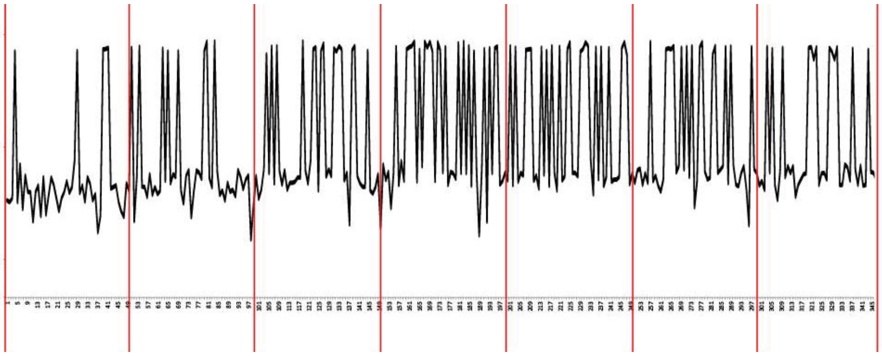
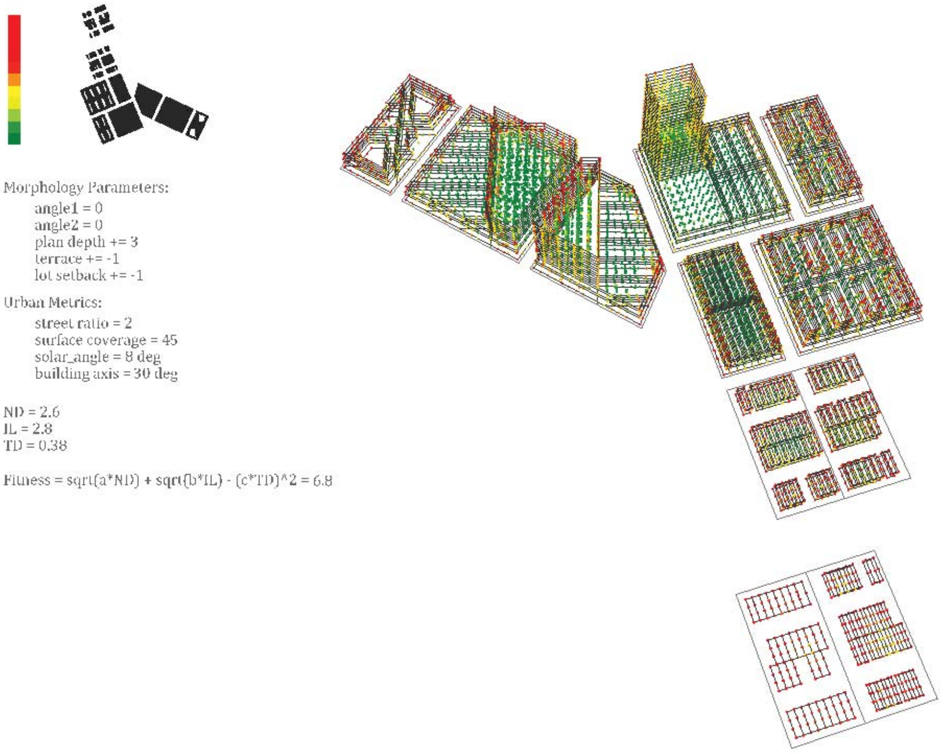


Figure 58 Fitness values for seven populations.

The graphs to the left illustrate the plotted fitness metrics — representing the generated solution space in terms of net density, irradiation and target density — of seven populations. The plotted fitness metric above illustrates that, despite the low amount of calculated populations, there were noticeable improvements in overall fitness values in the later populations relative to earlier populations. The produced values ranged between 6.854 and 5.141, with an average value of 5.96. Assuming optimal performance as any value greater than or equal to 6.75, the population with the solution space with the highest mode of optimal values was population five, with 16 optimal values.

Going back to Radford and Gero (1980, 75), optimization provides prescriptive information unlike the other two computational design methods. Data mining the resulting values allows us to establish the combination of genotypes, or morphological variables, that correspond to both the highest and worst performing fitness value.



Morphology Parameters:

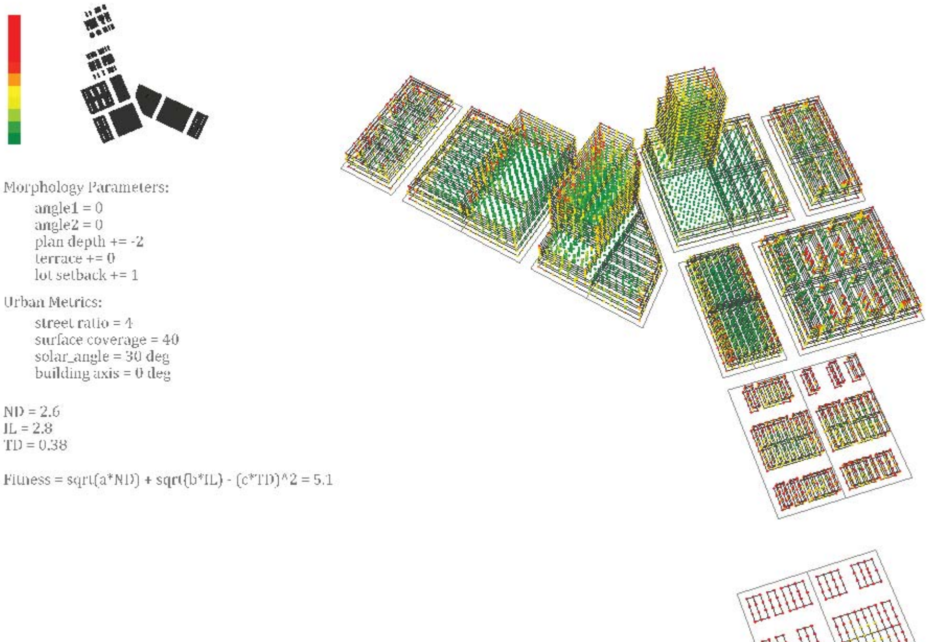
angle1 = 0
angle2 = 0
plan depth += 3
terrace += -1
lot setback += -1

Urban Metrics:

street ratio = 2
surface coverage = 45
solar_angle = 8 deg
building axis = 30 deg

ND = 2.6
IL = 2.8
TD = 0.38

Fitness = sqrt(a*ND) + sqrt(b*IL) - (c*TD)^2 = 6.8



Morphology Parameters:

angle1 = 0
angle2 = 0
plan depth += -2
terrace += 0
lot setback += 1

Urban Metrics:

street ratio = 4
surface coverage = 40
solar_angle = 30 deg
building axis = 0 deg

ND = 2.6
IL = 2.8
TD = 0.38

Fitness = sqrt(a*ND) + sqrt(b*IL) - (c*TD)^2 = 5.1

Figure 59 Typology of (top) highest and (bottom) lowest fitness values.

High Fitness Value = 6.854454

- Street ratio: 2:1
- Surface coverage: 45%
- Solar angle: π/24
- Building axis: π/6

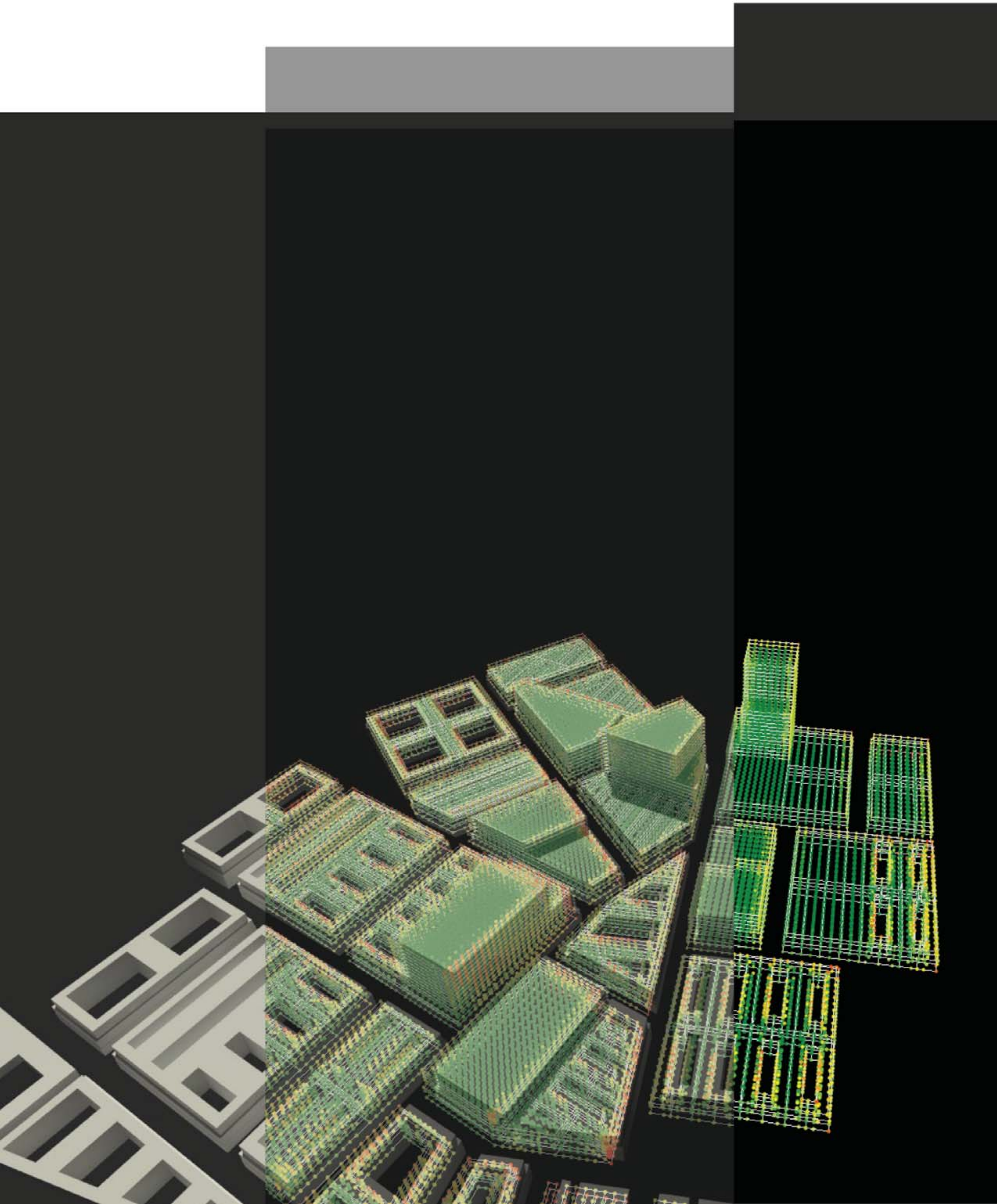
Low Fitness Value = 5.14104

- Street ratio: 4:1
- Surface coverage: 40%
- Solar angle: π/6
- Building axis: 0π

This gives the user prescriptive information for the design of high-density, low-efficiency housing typologies. Specifically, the optimization algorithm suggests a combination of a low street-ratio, high surface coverage, low solar angle, and a building mass oriented π/6 radians from due north.

Based on the generated solution space of 350 typology samples, we can say that density has a variation of 22.78% and solar irradiation 6.73% based on the combinations of different values of morphological properties. Without further energy simulation the energy implications of these metrics cannot be valued. However, we can make some assumptions for the purpose of calculating a ballpark estimate. In §3.2 the light percentage of energy and space heating demand was found to be 10% and 60% of the net energy demand for UK housing respectively. Let us assume that the proof-of-concept can replace these energy loads through passive means by 6.73%. Note that this is done purely to understand, in very broad terms the potential scale of energy impact —the 6.73% reduction for lighting and heating assumes unrealistic, ideal energy dynamics. With this in mind, the ballpark estimate indicates that the proof-of-concept can potentially reduce the operational energy usage of a specific neighborhood by 4.71%, given a density variation of 22.78%.

To put this value in perspective, Strømann-Andersen and Sattrup note in their study that a 3.6% reduction in energy usage from urban design alone is considerable for an already energy-optimized building, and that this, "...corresponds to an increase in the thickness of insulation of the entire building facade from 125 mm to 170 mm)." (2013, 67). Furthermore as this reduction is passive, it requires no extra cost in the form technical solutions. Thus the energy impact derived by optimizing morphological relationships in this application test potentially adds justifiable energy savings to city fabric.



6 Conclusion

The proof-of-concept enables the strategic reduction of light energy demand during the early design stages of urban massing through passive methods. Given the overall reduction of heat demand in the building energy budget, and the passive energy potential afforded by exposure to the external environment (Ratti et al, 2005, 12) daylighting mapped to occupancy zoning serves as a rudimentary proxy[1] for tackling building energy efficiency in general. The proof-of-concept achieves this by encoding and optimizing typology shape grammars according to daylighting and density considerations. Specifically the design system allows the user to locally control illuminance and FAR values through parametricized type grammars that vary key typology characteristics such as the building orientation, lot setback, terracing setback and solar obstruction angles.

Strømann-Andersen and Sattrup (67, 2013) established that type design with equivalent densities can vary interior DA by 15%. The thesis proof-of-concept reduced solar irradiation by 6.73%, which while marginal yields significant energy savings over the course of the 50 to 100 year lifetime of groups of buildings.

In broader context the proof-of-concept and thesis research is a response to the need to coordinate the interaction of energy optimization strategies between buildings, at neighborhood by means of the computational customisation of typology function and shape. To reiterate, the energy impact of typology differences at equivalent densities is significant: Rode et al (2014, 63) found a variation of 600% in heat energy demand and Strømann-Andersen and Sattrup (2013, 73) found a variation of 3.6% in yearly energy consumption. Yet most urban energy models do not account for the consequences of different typology choices, and urban modeling tools do not to integrate state-of-the-art environmental and energy simulation methods.

Figure 60 Large scale implementation of optimal type relationships..

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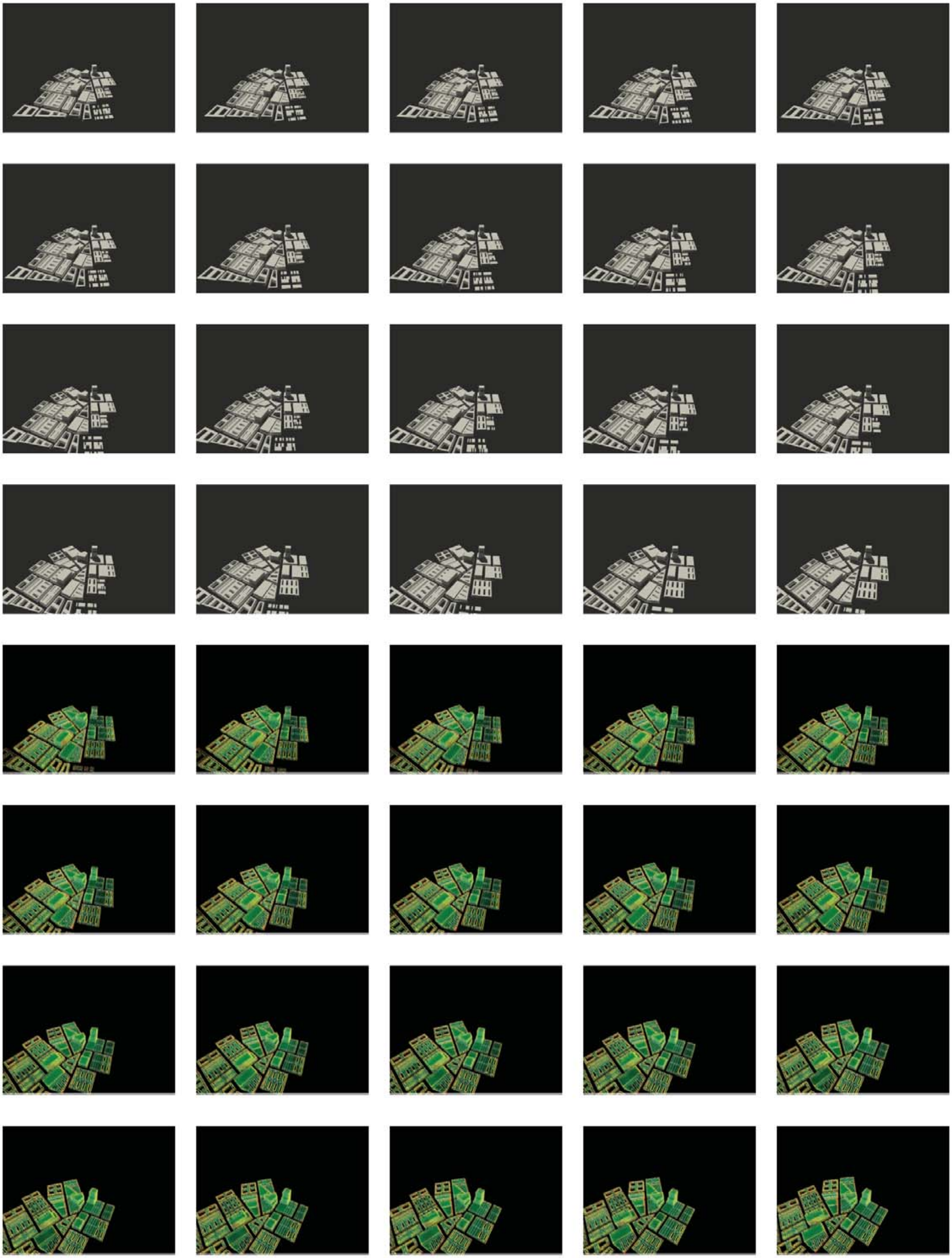
[1] Caveat: daylighting metrics do not give us a way to gauge where excessive external loads might increase the overall building energy, and thus cannot capture certain energy trade-off nuances that an integrated building energy modeling would.

The projected rate of urbanization compounds the danger of this gap in dedicated urban design tools. In the coming years cities will account for 90% of global growth and 60% of total energy consumption (Larson 2013, xix). This growth will be concentrated in developing contries where often, the availability of relevant expertise is limited Municpalities and urban planners therefore will face the crunch of designing high-performaing cities, in contexts with limited energy resources and expert feedback.

An opportunity therefore exists to intervene with high-tech methods of designing low-tech optimization strategies. To this end the proof-of-concept tool has been packaged as a series of components for Grasshopper3D, the visual scripting interface for the Rhinoceros3D CAD modeler and licensed under the open-source GNU General Public License.

Figure 61 Densification dynamics of optimal type relationships.



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Appendix

Please see https://github.com/saeranv/cactus for the most up to date copy of the Cactus script.