Bibil

A Performance-Based Framework to Determine Built Form Guidelines

ABSTRACT
City built-form guidelines act as durable constraints on building design decisions. Such guidelines directly impact energy, comfort and other performance conditions. Existing urban design and planning methods only consider a narrow range of potential design scenarios, with rudimentary performance criteria, resulting in suboptimal urban designs. Bibil is a software plugin for the Rhinoceros3D/Grasshopper3D CAD modeler that addresses this gap through the synthesis of design space exploration methods to help design teams optimize guidelines for environmental and energy performance criteria over the life cycle of the city. Bibil consists of three generative and data management modules. The first module simulates development scenarios from street and block information through time, the second designs appropriate architectural typology, and the third abstracts the typologies into a lightweight analysis model for detailed thermal load and energy simulation. State-of-the-art performance simulation is done via the Ladybug Analysis Tools Grasshopper3D plugin, and further bespoke analysis to explore the resulting design space is achieved with custom Python scripts.

This paper first introduces relevant background for automated exploration of urban design guidelines. Then the paper surveys the state-of-the-art in design and performance simulation tools in the urban domain. Next the paper describes the beta version of the tool’s three modules and its application in a built form study to assess urban canyon performance in a major North American city. Bibil enables the exploration of a broader range of potential design scenarios, for a broader range of performance criteria, over a longer period of time.
INTRODUCTION

Urban design and planning guidelines have a determinant role in the economic, environmental and experiential performance of cities. Once implemented, land-use planning, street grid layouts and built form controls are difficult to overturn, and therefore can drive performance conditions over broad spatial and temporal scales. However, it is difficult to quantify and communicate the performance trade-offs inherent in such high-level design guideline decisions to specialists and non-specialist stakeholders alike. This, in part, is because contemporary methods and tools available to urban designers and planners do not seamlessly integrate generative design, analysis, and decision making tools that help them nimbly model, optimize, and communicate spatial and temporal planning guidelines. Instead city development processes are driven by overly aesthetic and parochial political concerns and are informed by inadequate environmental simulation methods. This paper explores how integrating such tools can help city planners, designers, and stakeholders design better performing cities through time.

A typical process for generating built form guidelines today consists of design teams manually defining and modeling a limited range of feasible candidate solutions for street grid layouts, development potential per parcel, and building archetypes. This is traditionally dictated by a combination of municipal zoning and performance constraints, and rule-of-thumb assumptions made by city officials, senior designers, planners or consultants. Since useful performance metrics for comfort, energy or environmental performance require sophisticated thermal load or energy analysis simulations which require costly expert knowledge and computational resources, performance analysis has traditionally been limited to shadow studies for the limited range of candidate solutions. The resulting design solutions and performance analyses are then presented and refined through several cycles of city stakeholder meetings—changing candidate variables or even objectives. If development potential is unrealistically accounted for, developers often lobby to successfully build beyond established built form controls, which over many years may trigger a new round of built form controls to post-rationalize new growth.

This research addresses several concerns associated with this process. First, the design generation process for urban fabric including street grids and building archetypes through time relies on hidden heuristics or assumptions made by the design team that can lead to unsystematic searches and underperforming guidelines. Second, aesthetics, density, and rudimentary ground level shadow studies are the only conditions assessed, and thus given disproportionate weight in the broader question of human comfort and design trade-offs. Only computationally costly, expert-driven methods can yield more useful comfort, environmental, and energy metrics informed by the interaction of the urban built environments with complex thermal and airflow dynamics. Third, the lack of systematic methods for considering the evolution of urban systems over time and rudimentary environmental simulations results in an inability to optimize for both.

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<th>GIS Integration</th>
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Finally, these processes lack systematic methods for gathering the results from multiple scenarios to help design teams understand performance trends and optimize their guidelines.

This paper describes systematic and explicit methods for generating built forms and modeling their evolution through time, and consistent and robust process integration and multidisciplinary optimization tools to quantify and communicate the results of performance simulations. A partial list of process requirements for city design and decision-making tools include the following:

- Generative Modeling building archetypes within zoning constraints
- CAD Integration
- Generative Parcel Generation
- Development Simulation
- Simulation Integration (in particular the automation of material, occupancy, and thermal zone definitions)
- Solar Analysis (shadows, insolation)
- Transient Thermal Load Analysis
- Energy Simulation
- Solution Space Structuring, Exploration and Evaluation.

**BACKGROUND AND CONTEXT**

Dedicated urban-scale form generation tools such as AutoCAD Civil 3D, CityCAD, City Induction and CityEngine apply a degree of generative computation to produce urban built form scenarios but do not include sophisticated methods for managing and simulating how this form will change and perform through time. Meanwhile, dedicated urban-scale performance tools serve only an evaluative role, with limited generative capacity. This includes tools for energy, environmental and transit analysis, such as the Energy and Environmental Prediction model, the Solar Energy Planning tool, SUNtool, Young Cities, and the Urban Modeling Interface. The table in Figure 2 summarizes our analyses of several available methods with respect to the requirements. The next section describes the Bibil method.

**METHOD**

Bibil is a software plugin for the Rhinoceros3D/Grasshopper3D CAD modeler that models potential urban design scenarios and explores the performance trade-offs between them. Figure 3 illustrates the Bibil workflow, which addresses key challenges for modeling and communicating urban performance by automating and integrating three modules: time-based simulation methods, procedural shape generation, and creating an analytical model for simulation engines.

This section breaks down the three sequentially linked modules that make up Bibil. Figure 4 illustrates the three modules (Development, Architectural and Analytical) and their integration to produce detailed microclimatic simulation results.
Development Simulation Module

The parcel division and growth module is concerned with geometric repercussions of urban growth. This includes the subdivision logic of land, organization of the block and growth of parcels located in it. The inputs are in the form of a parsable file and include a vast number of numerical values like street widths or permissible Floor to Area Ratio (FAR), organized according to zones like commercial or residential. FAR is calculated as the ratio of total area of built floors to total area of the lot. The input file may be considered an external configuration file which instructs the program about logic for subdivision and feeds specific values to guide the growth simulation.

The algorithmic interpretation of urban processes for this module begins with the input of a block region. A region consists of several parcels, which may be organized in various geometrical configurations. Each parcel is hypothetically subdivided into cells. Each cell may be considered an independent entity, only the cells are active in the overall system because they receive values from the system, and grow or die. In the final expression of the model, the cells remain invisible. However, the growth of a parcel is the result of the cumulative growth of cells. Thus, cells are an invisible agent that accept values from the region and their growth is expressed as a geometric development in parcels. Avenues and streets subdivide the region and contribute to the value of each
cell. This is the initial and persistent value based purely on the cell’s location. The FAR of the region grows over time. A change in FAR affects the cells which govern the development of parcels and result in a change of geometry. It may be assumed that cells always try to build parcels that result in maximum FAR. In this way the design team can automate the tedious task of generating parcels for development in CAD software, while controlling specific parcel shapes and size using the input file.

Time is interpreted in two ways. A linear flow of time governs the system (Figure 5). The change in FAR is expressed as a function of time. The internal mechanism of a cell is governed by a cyclic function of time (Figure 6). As the cell’s time increases, its growth is more probable. This probability is increased by its location value. As soon as a cell grows to the nearest FAR, its internal time is set to zero. It is mandatory for the cells to grow at the end of its time cycle. Apart from the cellular activity, the parcels can independently merge. Only adjacent parcels can be combined. One parcel may merge with only one parcel in one iteration. Or only two individual parcels may join. This activity is possible if the parcels share a side.

Architectural Model Module
The architectural model module interprets the street and parcel network, zoning guidelines, and user-inputted typology parameters to procedurally generate architecturally-correct typologies. This module uses a grammar-based algorithm that specifies incremental typology development by recursively applying shape transformation rules to defined geometries. Specifically, initial street geometries are treated as the root of a data tree structure, and subsequent shape transformations procedurally triggered by automated or user-inputted grammars are generated as leaves of the data tree. Thus, as illustrated in Figure 4, the parcel geometries are split to compose a perimeter block (Court Type), step-backed according to street adjacencies to produce tower podiums (Podium Type), and then extruded to generate Slab towers (Tower Type). The advantage of the procedural data tree approach is twofold. First, grammar-based design transformations can reliably replicate compositionally correct ‘design languages’ with minimal user input. Secondly, within the context of urban design generation, shape transformations can reference prior geometric or zoning information associated with the urban boundaries or neighboring structures by backtracking and traversing the node structure. In this way the architectural module efficiently produces architecturally-correct urban design compositions that take into account the street and parcel network, zoning guidelines, and user-inputted typology parameters.

Analytical Model Module
The analytical model converts the resulting architectural models into a lightweight representation of thermal zones for energy analysis and thermal load simulation in EnergyPlus via the Honeybee plugin for Grasshopper3D (Roudsari and Pak 2013). As has been noted, simulation data pertaining to energy, environmental and comfort performance available from EnergyPlus can better inform urban design decisions, especially in high-growth contexts. However there are two key challenges in deriving detailed performance simulation outputs from EnergyPlus that have prevented their integration with existing urban design tools. First, a Building Energy Model (BEM) requires detailed non-geometric inputs pertaining to material, occupancy, HVAC systems, and boundary conditions that are traditionally determined and inputted manually by an experienced energy modeler. Secondly, running an energy simulation or thermal load simulation at the scale of multiple buildings is prohibitively time-consuming.

The analytical model addresses these challenges through the use of several energy-centric procedural grammars that automate commonly used heuristics applied by experienced energy modelers (Figure 7). Energy data is managed by matching architectural typology reference information from the U.S. Department of Energy (DOE) prototype buildings for new construction. These prototype models include energy input data for multiple building types in 17 climate locations consistent with ASHRAE 90.1 standards for buildings.

To speed up the energy simulation process, the designer must identify and separately input contextual urban fabric from
Time and Individual growth of each cell in global time.

Individual cell’s time in the same parcel.

Converting the Architectural Model into the Analytical Model, and simulating performance values. This consists of: (1) Defining the massings to be studied, (2) simplifying and separating the context massings, (3) extracting representative floor levels, (4) splitting perimeter and core zones, (5) defining boundary, material and envelope conditions, (6) simulating performance values for representative floors and finally (7, 8) interpolating the results for the entire mass.

buildings to be modeled. These are then simplified into bounding box geometries to reduce time spent checking shading surfaces. In EnergyPlus, ‘Zone Multipliers’ take the simulated thermal loads in a defined thermal zone, and multiply it by other, similar thermal zones. The simulated and multiplied thermal loads are then sent to the simulated HVAC system to derive system energy outputs (U.S. Department of Energy 2014). The multiplication of thermal loads avoids costly and redundant load calculation for thermal zones with relatively similar conditions. Studies have shown how this method allows even high-rise buildings with 200 thermal zones to be represented with as little as 3 floors or 12 thermal zones, greatly speeding up the simulation process without losing accuracy (Ellis and Torcellini 2005).

Similarly, in Bibil, the buildings to be simulated are divided into a few representative thermal zones corresponding to common load conditions for load calculations. Bibil’s analytical module automates the process of clustering similar zone conditions together to extract representative thermal zones. This entails identifying potential thermal zones with similar program, material, shape conditions, as well as similar interaction or exposure to the exterior microclimate. Specifically, the module identifies floor levels with similar or the same program, geometric dimensions, materiality, material adjacencies to other zones, orientation, and elevation. These floors are further subdivided into perimeter and core geometries to account for orientation-specific thermal loads. Horizontal zone surfaces that are against another zone’s bottom or top surface are presumed to be adiabatic to account for the minimal heat transfer between stacked thermal zones.

CASE STUDY
This section demonstrates an implementation of Bibil to determine built form guidelines through the systematic exploration of the microclimatic consequences of various typologies, and development potential.

Background and Context
The Bibil tool was developed and tested during the development of built form guidelines in a major North American city. Figure 8 illustrates sixteen typologically representative “Character Areas” that were defined for the four square kilometer urban fabric, and a proposed design solution ranked according to its relative performance to other candidate solutions. Through the course of eight months, research, design, and city official teams analyzed and ranked neighborhood built form options, and then participated in the corresponding drafting of relevant policy recommendations for approximately 2,200,000 square meters of residential, commercial and office built form. High-level objectives and workflows for built form prototyping, ranking and recommendations were developed for each “Character Area” with the local urban design team and city officials. Built form was to adhere to existing precedents for construction feasibility, market feasibility, gross floor area (GFA) targets, environmental performance, adherence to zoning constraints, performance standards. Precedents for built form was primarily informed from three sources: relevant Ontario Municipal Board feedback to proposed Zoning Amendment Applications, performance standards from the “Avenues and Mid-Rise Buildings Study and Action Plan” (City of Toronto Planning Division 2010) and “Tall Building Design Guidelines” (2013).

Objective
As high density, multi-unit housing is the fastest growing building type in the city (City of Toronto 2016), emphasis was placed on
determining built form controls to rationalize the vertical growth according to quantitative performance simulation for occupants of the outdoor public realm at street level and the occupants of units in buildings. To assess this, a typical urban canyon condition was chosen in one of the neighborhood ‘Character Areas’ and Bibil was used to assess the thermal effect of varying development and typological standards within the canyon. Specifically, the objective was defined as maximizing the gross floor area (GFA) while minimizing the extreme thermal conditions as measured by the area weighted temperature at ground level and building surface temperature facing the urban canyon by varying typology parameters, grouped into four categories:

- Archetype: relating to tower, slab typologies, within a park or on a podium type
- Podium height: the height (7.5 to 31.5 meters) of the built mass extrude at grade typically with little or no setback from the street lot line
- Setback and Stepback: the distance (0–6 meters) a built mass is recessed from the street lot line at grade, and above grade, respectively

The GFA, ground surface temperature, and envelope surface temperature were in addition given weights of 1.5, 0.5, and -1.5, respectively. Surface temperature was used as a proxy metric to indicate potential urban heat island and thermal comfort performance in this beta version of Bibil for two reasons. First, outdoor comfort values are not calculated by EnergyPlus, and therefore require custom or computationally costly methods to calculate additional comfort parameters such as the mean radiant temperature. Secondly, the outside surface temperature from EnergyPlus takes into account the conduction effects of material exposed to transient solar conditions (U.S. Department of Energy 2014), which is an improvement over the current state-of-the-art for performance metrics in urban design software for indicating local heat flux as well as relative changes in the temperature range. These qualitative and quantitative objectives were subsequently encoded into parameters, variables, constants, and fitness values to drive the Bibil plugin.

Analysis
This section summarizes the results from the initial design space exploration. The table and images (Figures 10–12) represent the simulated solution space and top three design solutions. Notable trends in the highest performing typologies are the preference for podium-based typologies, relatively high podiums, and the highest development iteration. Setback and stepback dimension do not seem to have a high correlation to resulting performance. The design outcomes also indicate the strengths and weaknesses of the tool for the design frameworks for urban design guidelines chosen. While the top three performing solutions were clearly superior in the context of the output values chosen, they wouldn’t be considered “well designed” urban schemes. This suggests the role of the tool is to challenge design frameworks chosen and suggest directions to explore rather than to suggest singular optimized solutions.

The form generation tool and its integration with simulation was immediately integrated with project team workflow. The automation of these two components increased speed in two ways: first by, generating initial test options in a matter of seconds versus minutes, and secondly by allowing the subsequent revisions of parameters to be done instantly, versus manually rebuilding the models. The parametric nature of the tool allowed
it to be brought to meetings with city officials, and dynamically
generate or modify solutions in response to feedback in real-
time. However, the exploration of the multi-dimensional solution
space was ultimately never implemented with the design project
team due to the following factors:

- Concern about the greater complexity and time investment in
generating large design solution spaces
- Confusion about what multi-objective exploration is, and the
benefits of the approach to the project
- The status quo of urban design defined by city didn’t strictly
require high performing solutions
- The more qualitative values of structured space exploration
(higher quality urban massing in terms of multiple objectives)
is less clear than the tangible value (time savings, increased
accuracy) of automating the process of form generation to
simulation
- The status-quo urban design process places a large emphasis
on qualitative objectives: contextual appropriateness,
aesthetic integration, and the political. In particular urban
planning and design in the city continues to struggle with the
problem of the “Tragedy of the Commons,” i.e., high-rise and
mid-rise building types are politically difficult to implement
where low-rise residential buildings exist.

Conclusion
In summary, this paper has introduced the relevant background
for performance-oriented urban design guidelines. The paper
surveyed the state-of-the-art in design and performance
simulation tools in the urban domain. The gap between urban
design and performance simulation was identified as a significant
bottleneck for structured design space exploration of different
urban design solutions. Bibil was introduced as a process integra-
tion tool that linked urban design generation and performance
simulation through three modules. These consisted of genera-
tive and data management methods for time-based simulation,
procedural shape generation, and abstracting analytical models
for thermal load and energy simulation engines. The application
of the tool in a built-form study to assess urban canyon perform-
ance in a major North American city was demonstrated, and
trends and relationships of optimal performance were identified,
as well as a review of the results and integration with the urban
design team.

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**Line Graph of candidate design solutions arranged from worst to best performing.**


Saeran Vasanthakumar is an Intern Architect and Researcher. His research interests lie in the process integration of advanced shape computation methods with energy and environmental simulation. He is currently a Building Performance Researcher with the KieranTimberlake Research Group, and previously worked as a Researcher with the Perkins+Will Design Process and Energy Labs.

Nirvik Saha is a Ph.D. student in the School of Architecture at Georgia Institute of Technology. His research investigates the formulation of a precise definition of topological and physical relations between spaces in an architectural and urban context to automate the search for an elegant solution. Nirvik is a research assistant at the Digital Building Lab (DBL) where his involvement is centered around developing computer graphics and web based applications for layout optimization.

John Haymaker serves as Perkins+Will’s Director of Research. John works closely with a team of researchers, designers, and academics to expand the firm’s knowledge base in pursuit of state-of-the-art design solutions. He also oversees Perkins+Will’s Research Labs, Innovation Incubator program, and nonprofit research arm, AREA Research, which conducts studies on the built environment and publishes its findings for free public use. Previously a professor of civil engineering at Stanford University, and a professor of architecture and building construction at Georgia Institute of Technology, John has contributed more than 80 professional and academic articles on topics such as design process communication, optimization, and decision-making.

Dennis Shelden is the Director of the Digital Building Lab and an Associate Professor at Georgia Tech. An expert in applications of digital technology to building design, construction and operations, his experience spans across research, technology development and professional practice including multiple architecture, building engineering and computing disciplines. Prior to joining Georgia Tech he was a co-founder and CTO of Gehry Technologies, directed technology, research & development at Gehry Partners, and was Associate Professor of Practice in the Design & Computation program at MIT. He is a licensed Architect and holds a BS in Architectural Design, an MS in Civil & Environmental Engineering, and a PhD in Design & Computation from MIT.